Depth Analysis for Sensitivity Pattern Section in the Electrical Resistivity using the 2D Computerized Modeling Method

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ABSTRACT

This paper presents the analysis of depth of investigation factors which are (**Zm**/**a**) and (**Zm**/**L**). The medium depth of investigation (**Zm**) from the sensitivity pattern of different arrays influences the array selection which is good enough for planning infield surveys. In this paper, the average maximum for data level **n** value for inline dipole-dipole, pole-dipole and Wenner-Schlumberger for a good subsurface investigation is 6. Then, the spacing of current and potential electrode pair which is **a** value must be increased. The 2D sensitivity section using the computerized modeling method for each array is able to assist the user in choosing the appropriate array for a practical survey planning after carefully balancing factors such as the cost, investigation depth and resolution. Among the matters for array selection that should be considered are (1) the signal strength, (2) sensitivity of the array to horizontal and vertical changes in the resistivity pattern, (3) investigation depth and (4) horizontal data coverage. Beside than that, the use of appropriate constraint parameters and proper array selection will lead to a better processing and interpretation work in order get reliable and acceptable results. In additional, this paper introduces a new hybrid array called Andy-Bery array. In the application, this new hybrid array is successful and reliable in imaged the conductive block model with it's actual dimension.

KEYWORDS: Tomography; Analysis; Sensitivity; Computerized modeling; Resolution

INTRODUCTION

The electrical methods such as resistivity method and induced polarization have been used widely in environmental and engineering subsurface investigation. These electrical methods are environmentally friendly, which is non-destructive method and also low cost of investigation compared to drilling method. However, better understanding about the advantages and disadvantages of these electrical methods can assist in data processing and interpretation works. The good selection of array for infield survey and proper constraint parameters in processing work will lead to good results in the interpretation. Thus, ignorance of these matters in the Earth's subsurface investigation will cause wrong interpretation of results. For example, the dipole-dipole array is widely used in resistivity and induced polarization surveys because of its characteristic of low EM coupling between the potential and current circuit. However, the disadvantage of this array is the very small signal strength for large data level (**n**) values.

The research was carried out with the objectives; to developing a table for medium depth of investigation (**Z_M**) factor that can help in planning infield survey and determining the maximum **n** value their effective imaging depth. This paper also discussed in general on the sensitivity pattern of five different arrays which are inline dipole-dipole, pole-dipole, Wenner-Schlumberger, Wenner alpha, Wenner beta and Wenner gamma arrays.

METHODOLOGY

Electrical resistivity and induced polarization tomography methods were a good geophysical tool for imaging the Earth's subsurface. Seismic refraction method also a good geophysical for imaging the Earth's subsurface (Bery, 2013; Bery and Saad, 2013a). Recently, these tomography methods have been used in the subsurface characteristic study (Jinmin et al., 2013; Nordiana et al., 2013) and slope monitoring study (Bery and Saad, 2013c; Bery et al., 2014). Beside than that, the resistivity tomography was also used in imaging the man-made buried bunkers (Bery and Saad, 2013b). In this paper, the computerized tomography is used to study the sensitivity pattern for all selected arrays. The electrical arrays used in this study are dipole-dipole, pole-dipole, Wenner-Schlumberger, Wenner alpha, Wenner beta and Wenner gamma. Then, the medium depth of investigation is determined for all selected arrays.

Figure 1 shows a plot of this function. Note that it starts from zero, then increases to it's maximum sensitivity value and then decrease asymptotically to zero. The medium depth of investigation is shown in Figure 1. This function plot is constructed based on Equation 1.

$$F_{1D}(z) = \frac{2}{\pi} \bullet \left[\frac{Z}{(a^2 + 4Z^2)^{1.5}}\right] \qquad \text{(Equation 1)}$$

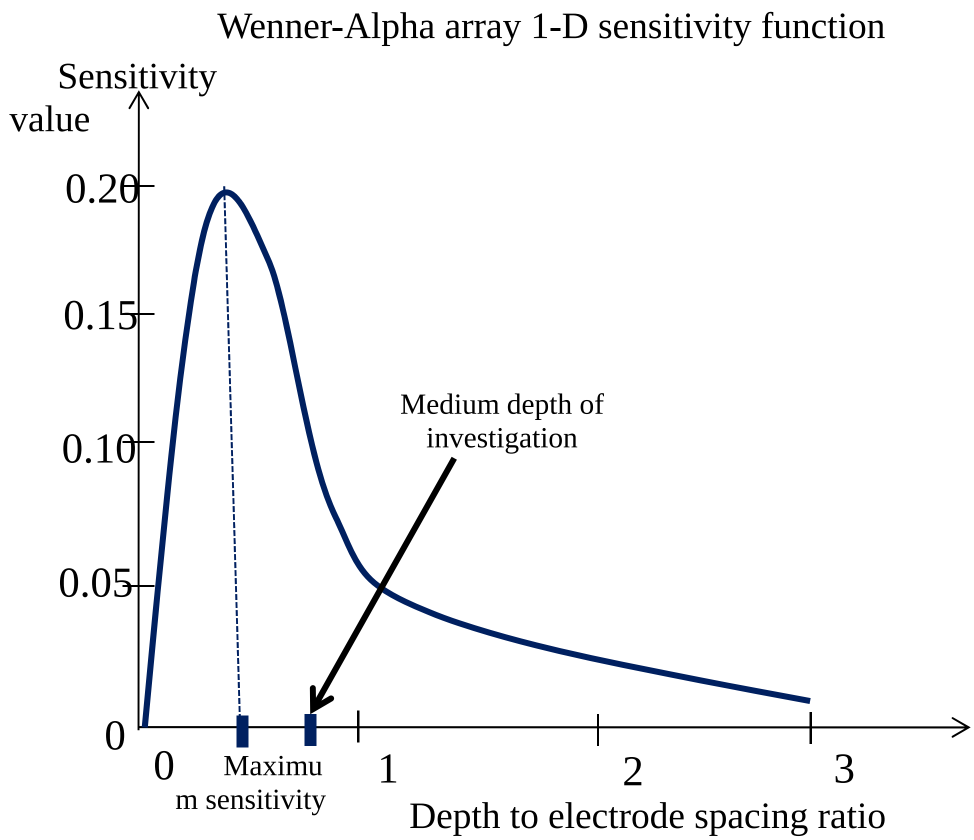

Figure 1: The sensitivity function plot for the Wenner-alpha array.

This is the depth above which the area under the curve is equal to half the total area under the curve. According to layman's terms, this upper section of the earth above the 'medium depth of investigation' has the same influence on the measured potential as the lower section. This tells us approximate deep we can reach with an array. This depth does not depend on the measured apparent resistivity or the resistivity of the homogeneous earth model. It should be noted that these depths are strictly only valid for a homogeneous earth model. This might be good enough for planning infield survey. However, any large resistivity contrasts near to the surface can change the actual depth of investigation.

RESULTS AND DISCUSSION

The 2D sensitivity section for all studied electrical arrays is discussed in this section. The 2D sensitivity section for each array able to assist in choosing the appropriate array for a practical survey planning after carefully balancing factors such as the cost, investigation depth (target), resolution and practicality. Among the criteria for array selection that should be considered are (i) the signal strength, (ii) sensitivity of the array to horizontal and vertical changes in the resistivity pattern, (iii) investigation depth and (iv) horizontal data coverage.

The medium depth of investigation (**Z_M**) for the Wenner alpha array is 0.5190 m with **a** and **n** values is 1. Meanwhile, for the same **a** and **n** values for the Wenner beta and the Wenner gamma arrays, their values are 0.4159 and 0.5953 respectively. This 2D sensitivity section for all these three arrays are shown in Figure 2. The Wenner-Schlumberger array with a value of 1 able to give medium depth of investigation (**Z_M**) value of 0.9249 m at **n** value of 2. Meanwhile, this array with **a** value of 1 and **n** value of 5 gives medium depth of investigation of 2.0927 m (Figure 4a). Beside than that, the midpoint and depth of data point were also shown in Figure 2 for each array. The inline dipole-dipole array has medium depth of investigation (**Z_M**) of 0.4159 with **a** and **n** value of 1 respectively. This (**Z_M**) value give 1.7300 m when **a** value is 1.0 m and **n** value value is 6. The pole-dipole array has (**Z_M**) value of 0.5169 m for a and n values of 1. However, this (**Z_M**) value is 2.6108 m when **a** is 1 and **n** value is 7. Their 2D sensitivity pattern section for these two arrays are shown in Figure 4b and 4c.

The Wenner-Schlumberger array is a combination two different arrays which is Wenner alpha array and schlumberger array. This hybrid array is the combination of Wenner alpha array and schlumberger array. This is proven by datum points distribution is similar between Wenner alpha and schlumberger arrays combination with Wenner-Schlumberger array (Figure 3). Thus, this array can be considered as co-linear and asymmetric array. However, for the geometric factor **k**, this hybrid array is still using schlumberger array's geometric factor (Figure 6).

The Wenner alpha array has good signal strength compared to other arrays. Figure 2a shows the sensitivity pattern of Wenner alpha. It shows that the higher the sensitivity value, the better respond the region to the electrical method. The region between C1-P1 as well as P2-C2 electrodes has large negative sensitivity values near the surface (Figure 5). This means that if a small body with a high resistivity that the surrounding is placed in these negative zones, the measured apparent resistivity value will decrease. This phenomenon is called 'anomaly inversion'. Meanwhile, if the high resistivity body is placed in between the large positive sensitivity values region that is P1-P2 electrodes, the measured apparent resistivity will increase. The arrangement of common arrays and their geometric factor **k** used in electrical resistivity and induced polarization methods is shown in Figure 6.

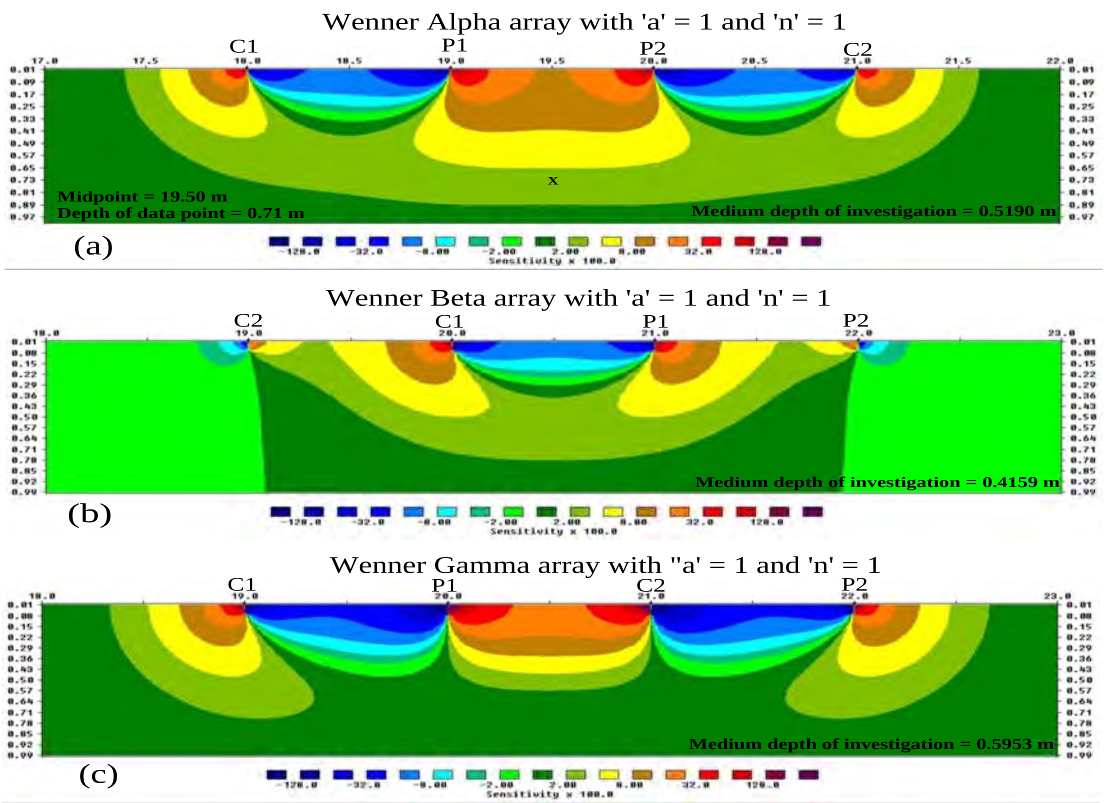

Figure 2: 2D sensitivity pattern section for (a) Wenner alpha, (b) Wenner beta, (c) Wenner gama and (d) Wenner-Schlumberger arrays.

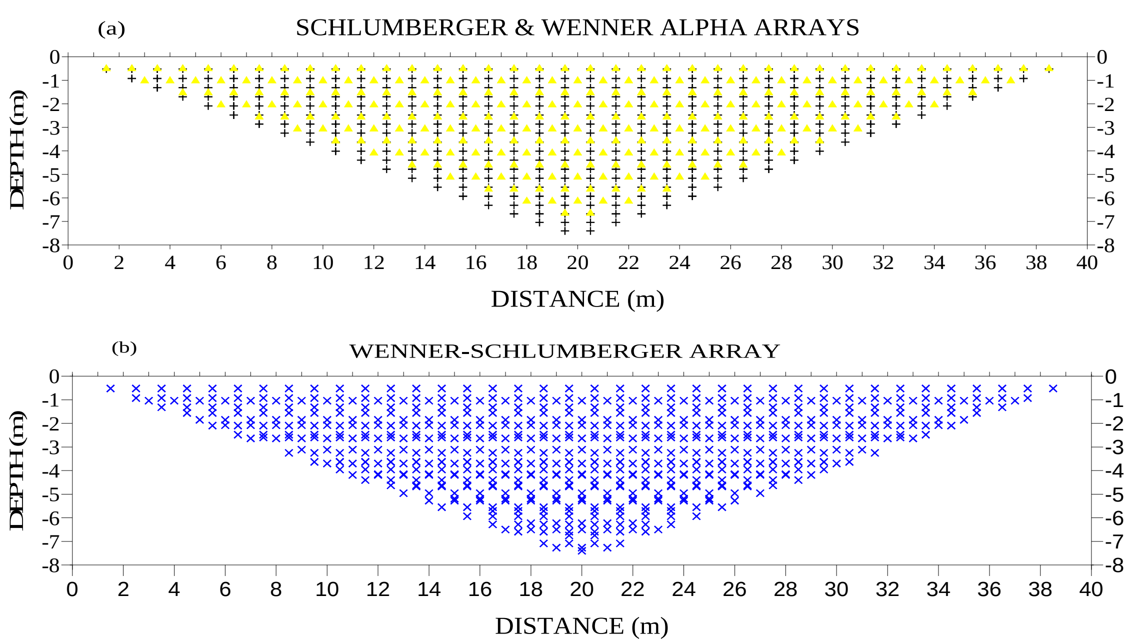

Figure 3: The development of Wenner-Schlumberger array (b) from combination of **a** and **n** values in data points Schlumberger and Wenner-alpha arrays (a).
[Z max = -0.519m; Z min = -7.399m]

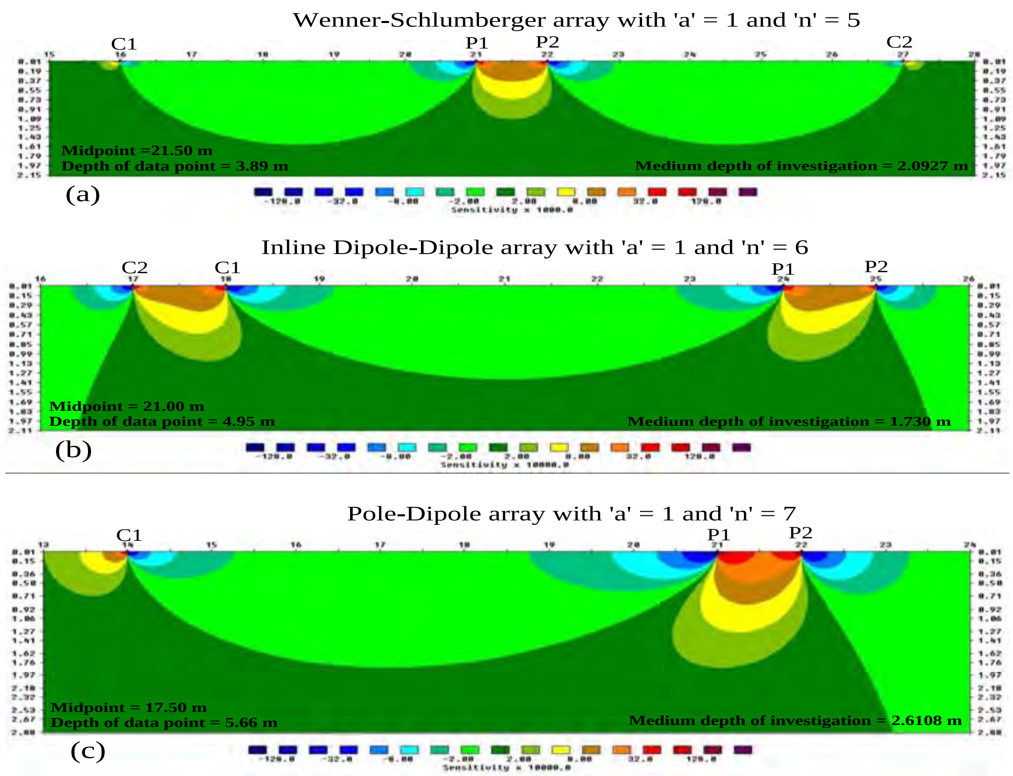

Figure 4: The 2D sensitivity pattern section for (a) inline dipole-dipole array and (b) pole-dipole array, with various *n* values.

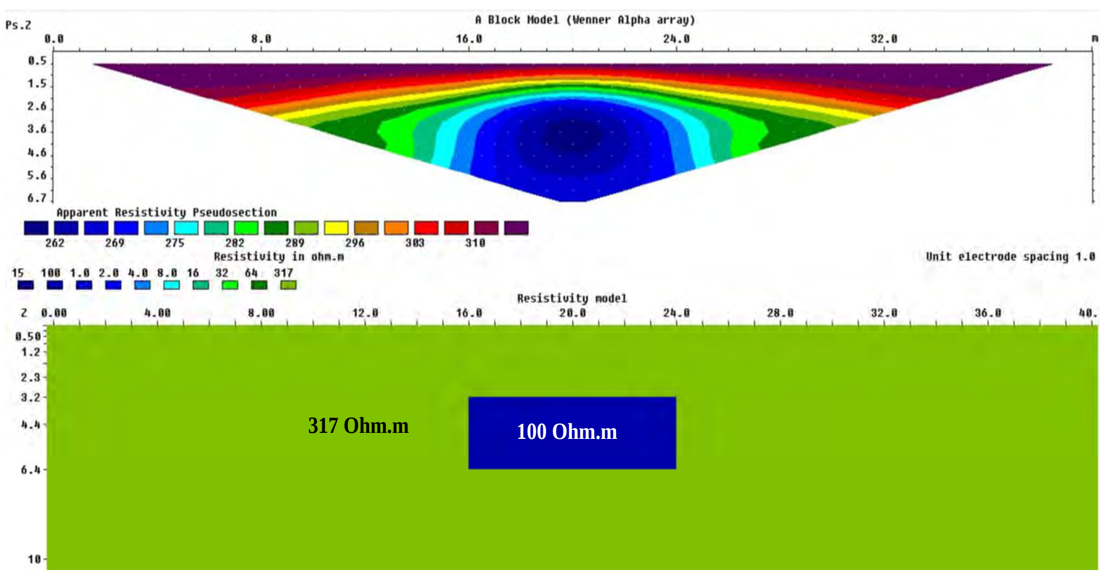

Figure 5: Apparent resistivity pseudosection using Wenner alpha array (above) and the actual block model (below) used in this computerized tomography. The block model has a resistivity value of 100 Ω.m and surrounded by material with a resistivity value of 317 Ω.m.

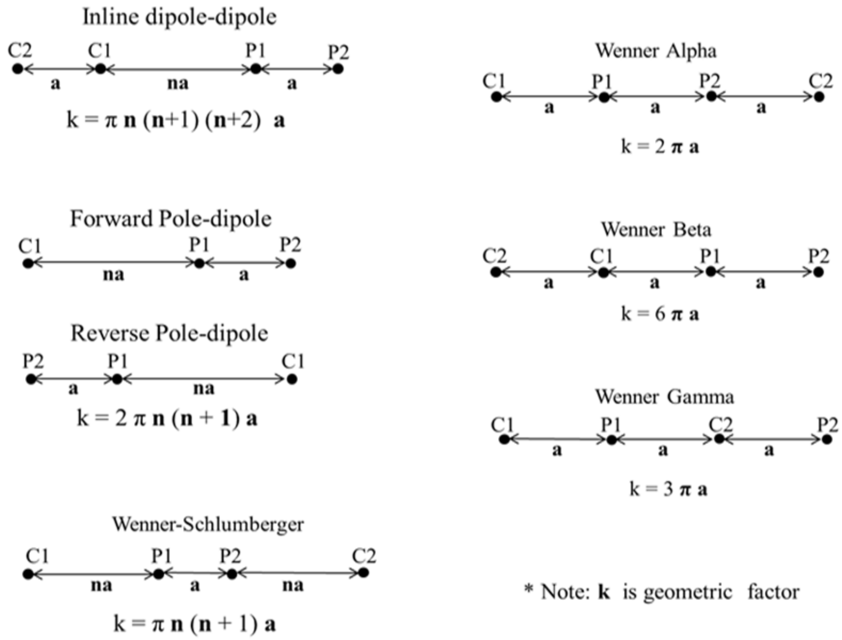

Figure 6: The arrangement of common arrays used in electrical methods.

From the computerized tomography, the data set is saved in the RES2DINV program format for the inverse resistivity modeling. Figure 7a shows the inverse resistivity modeling section for the Wenner alpha array. This inverse resistivity section is successful in imaging the actual shape of the block model. For this inversion program, the inversion constraint is selected in order to give a reliable and acceptable result is shown in Table 4. The absolute error of this inverse model is 0.52 %. This result shows that a block model is imaged well. However, the actual depth is shifted a bit than the actual depth from the surface.

For the second array, we used a new hybrid array which is combination of Wenner-beta and dipole-dipole arrays called Andy-Bery array. This hybrid array is formed by the combination of **a** and **n** values datum points of Wenner-beta and dipole-dipole arrays. This Wenner-beta array start with data level **n** of 1 which is Wenner-beta array. Then, when **n** value increased to 2 and onward, it starts using dipole-dipole array. The constraint parameters used for the inverse modeling method is shown in Table 1. From the inverse model resistivity, this array is able to mapped well edges of the block model (100 Ω.m). The inverse model resistivity produced by this Andy-Bery array is reliable and acceptable because this array able to image the actual dimension of the block model (Figure 7b) compared to Wenner-alpha array (Figure 7a).

Table 1: The constraint parameters used in the inversion model.

Constraint Parameters	Value / Decision
Initial Damping Factor	0.05
Minimum Damping Factor	0.01
Factor to increase damping factor	1.10
Optimize the damping factor	Yes
Forward modeling method	Finite-difference
Least-squares constraint	Robust

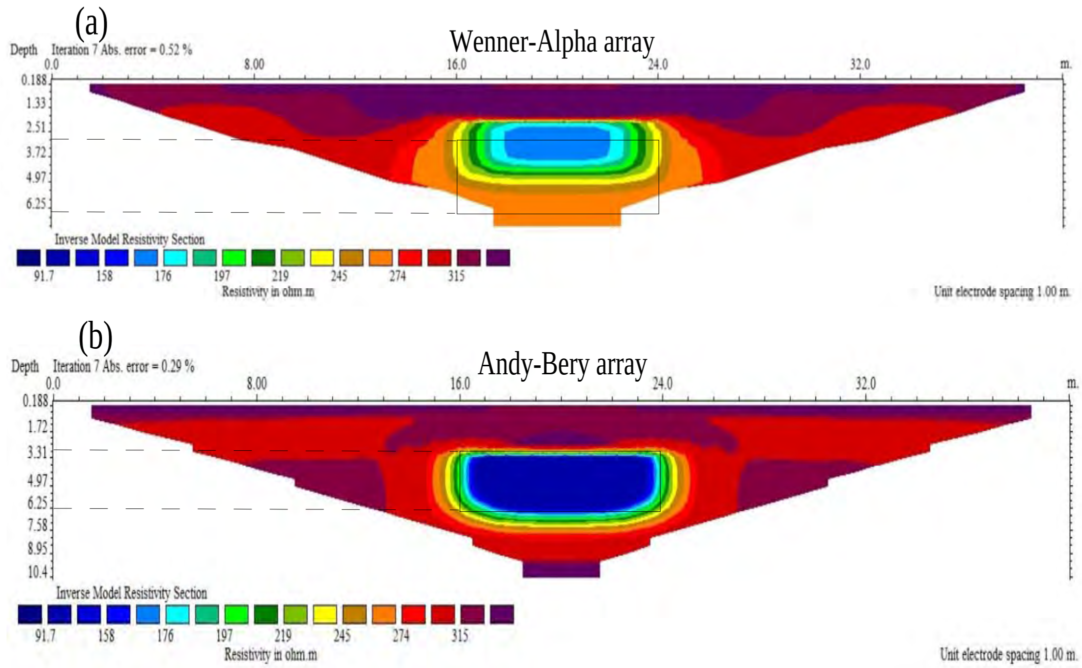

Figure 7: The inverse resistivity model section using the Wenner-alpha array (a) and Andy-Bery array (b). The dash black line is the actual depth and the solid black rectangle is the actual dimension and depth of the block model used in this 2D computerized modeling method.

From the Figure 7b above, it shows that Andy-Bery array is a suitable electrical resistivity array for mapping a block model with an absolute error of 0.29 % (also refer to Figure 5 for actual model's shape). In conclusion, this Andy-Bery array is sensitive to horizontal changes in resistivity. Thus, this hybrid array is suitable in mapping vertical structures such as man-made buried bunkers and cavities.

Table 2 and 3 gives the medium depth of investigation ($\mathbf{Z_M}$) for the different arrays. Meanwhile Table 4 is a depth of datum point ($\mathbf{Z_D}$) analysis. This ($\mathbf{Z_M}$) able to gives an idea of the depth to which we can map with a particular array. To determine the maximum depth mapped by an array, multiply the maximum **a** value which electrode spacing or maximum array length **L** by an appropriate depth factor given in Table 2 and 3. For example, if **a** spacing used by the Wenner alpha array is 50 m (or maximum **L** is 150 m), then the maximum depth mapped via this array is 25.95 m (≈ 26 m). These tables can be used as an estimation tool in the infield survey planning.

The maximum value for data level **n** for a practical electrical imaging is 6 for inline dipole-dipole, pole-dipole and Wenner-Schlumberger arrays. Beyond this maximum **n** value, the sensitivity for these 3 different arrays is not relevant. Thus, it will produce a bad effect on the data set and increase the percentage error.The overcome this problem, the active electrode spacing a should be increased. Meanwhile, for Wenner alpha array, this problem is not occurring. The Wenner alpha , Wenner beta and Wenner gamma arrays have a constant data level **n** of 1. Table 4 can be used as an estimation tool for maximum depth of investigation for the datum points with the consideration there is good electrodes contact to the ground and good sensitivity of the electrical equipment. This can avoid negative reading in apparent resistivity . Then, this will reduce the total of datum points.

Table 2: Medium depth of investigation (**Z_M**) factor analysis for inline dipole-dipole and pole-dipole arrays

Array Type	**n**	**L**	**Z_M**	**Z_M / a**	**Z_M / L**	**Z_M / n**	Geometric Factor, **k**
Inline Dipole-Dipole	1	3.0	0.4159	0.4159	0.1386	0.4159	18.8496
a : 1(=1.0 m)	2	4.0	0.6972	0.6972	0.1743	0.3486	75.3982
	3	5.0	0.9616	0.9616	0.1923	0.3205	188.4956
	4	6.0	1.2202	1.2202	0.2034	0.3051	376.9911
	5	7.0	1.4759	1.4759	0.2108	0.2952	659.7345
	6	8.0	1.7300	1.7300	0.2163	0.2883	1055.5751
	7	9.0	1.9832	1.9832	0.2204	0.2833	1583.3627
	8	10.0	2.2357	2.2357	0.2236	0.2795	2261.9467
	9	11.0	2.4878	2.4878	0.2262	0.2764	3110.1767
	10	12.0	2.7396	2.7396	0.2283	0.2740	4146.9023
Pole-Dipole	1		0.5169	0.5169		0.5169	12.5664
a : 1(=1.0 m)	2		0.9142	0.9142		0.4571	37.6991
	3		1.2882	1.2882		0.4294	75.3982
	4		1.6448	1.6448		0.4112	125.6637
	5		1.9843	1.9843		0.3969	188.4956
	6		2.3063	2.3063		0.3844	263.8938
	7		2.6108	2.6108		0.3730	351.8584
	8		2.8978	2.8978		0.3622	452.3893
	9		3.1678	3.1678		0.3520	565.4867

Table 3: Medium depth of investigation (**Z_M**) factor analysis for Wenner-Schlumberger, Wenner alpha, Wenner beta and Wenner gamma arrays

Array Type	n	L	Z_M	Z_M / a	Z_M / L	Z_M / n	Geometric Factor, **k**
Wenner-Schlumberger	1	3.0	0.5190	0.5190	0.1730	0.5190	6.2832
a : 1(=1.0 m)	2	5.0	0.9249	0.9249	0.1850	0.4625	18.8496
	3	7.0	1.3177	1.3177	0.1882	0.4392	37.6991
	4	9.0	1.7061	1.7061	0.1896	0.4265	62.8319
	5	11.0	2.0927	2.0927	0.1902	0.4185	94.2478
	6	13.0	2.4782	2.4782	0.1906	0.4130	131.9469
	7	15.0	2.8631	2.8631	0.1909	0.4090	175.9292
	8	17.0	3.2476	3.2476	0.1910	0.4060	226.1947
	9	19.0	3.6318	3.6318	0.1911	0.4035	282.7433
Wenner Alpha	1	3.0	0.5190	0.5190	0.1730	0.519	6.2832
a : 1(=1.0 m)							
Wenner Beta	1	3.0	0.4159	0.4159	0.1386	0.4159	18.8496
a : 1(=1.0 m)							
Wenner Gamma	1	3.0	0.5953	0.5953	0.1984	0.5953	9.4248
a : 1(=1.0 m)							

Table 4: Depth of data point (**ZD**) factor analysis for inline dipole-dipole, pole-dipole and Wenner-Schlumberger arrays

Array type	n	L	Z_D	Z_D / a	Z_D / n	Z_D / L
Inline dipole-dipole						
	1	3.0	1.41	1.41	1.41	0.470
	2	4.0	2.12	2.12	1.06	0.530
	3	5.0	2.83	2.83	0.94	0.566
a = 1(=1.0 m)	4	6.0	3.54	3.54	0.89	0.590
	5	7.0	4.24	4.24	0.85	0.606
	6	8.0	4.95	4.95	0.83	0.619
Pole-dipole						
	1	2.0	1.41	1.41	1.41	0.705
	2	3.0	2.12	2.12	1.06	0.707
a = 1(=1.0 m)	3	4.0	2.83	2.83	0.94	0.708
	4	5.0	3.54	3.54	0.89	0.708
	5	6.0	4.24	4.24	0.85	0.707
	6	7.0	4.95	4.95	0.83	0.707
Wenner-Schlumberger						
	1	3.0	1.06	1.06	1.06	0.353
	2	5.0	1.77	1.77	0.89	0.354
a = 1(=1.0 m)	3	7.0	2.47	2.47	0.82	0.353
	4	9.0	3.18	3.18	0.80	0.353
	5	11.0	3.89	3.89	0.78	0.354
	6	13.0	4.60	4.60	0.77	0.354
Array Type	**a** (m)	**L**	Z_D	Z_D / a	Z_D / n	Z_D / L
Wenner Alpha						
	1	3.0	0.71	0.710	0.71	0.237
	2	6.0	1.41	0.705	1.41	0.235
	3	9.0	2.12	0.707	2.12	0.236
n = 1	4	12.0	2.83	0.708	2.83	0.236
	5	15.0	3.54	0.708	3.54	0.236
	6	18.0	4.24	0.707	4.24	0.236
	13	39.0	9.19	0.707	9.19	0.236

CONCLUSION

The depth of investigation factors (**Z_M**) and (**Z_D**) analysis via computerized tomography is successful in developing a table for medium depth of investigation (**Z_M**) factor that can help in planning infield survey and determining the maximum **n** value their effective imaging depth.

The proper selection of electrical array for survey and used appropriate constraint parameters in the processing will lead to a better processing and interpretation work. Then, a good electrical tomography result can be produced. For example, to mapping sedimentary layers, a good decision is not to use the dipole-dipole array because this array is insensitive to vertical changes in resistivity. If a bad array selection is made for the survey, it will produce a wrong data processing and interpretation. Thus, the objective of the survey has failed. Beside that, the proper selection of constraint parameters in the inversion also able to lead to a good inverse model resistivity for a reliable and acceptable interpretation. In conclusion, this geophysical method is a good tool for imaging the Earth's if the user understands well and know the advantages and limitations of the method itself while, vice versa can be happen too.

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