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Study on the distortion of apparent resistivity curves caused by the 'infinite' electrode space of a Pole–Pole array and its correction

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ABSTRACT

The Pole–Pole (PP) array is widely used for measurements that incorporate two-dimensional (2-D) and three-dimensional (3-D) multi-electrode electrical resistivity surveys, although an effective equilibrium has not yet been achieved between two factors, the location of 'infinite' electrodes and the data utilisation of the effective resistivity, which affects the detection accuracy; thus, the data collected under the conditions of 'infinite' electrodes that are as finite as possible are maximally effective. Studies have shown that the optimum 'infinite' electrode distance must be greater than 20 times the current-potential electrode distance AM; this value is much greater than the currently used value of 5 to 10 times AM. However, limitations imposed by landforms and topographic conditions, such as mountainous areas and coal mine roadways, often prevent the 'infinite' condition from being satisfied. In this study, a field test was designed and performed by adopting a particular PP array to collect sounding data under different 'infinite' electrode distances, and the differences were analysed in the apparent resistivity curves calculated with different geometric coefficients. The results reveal that when the 'infinite' electrode space is finite relative to AM, significant distortion may occur, and a minimum inflection point may appear in the sounding curve of apparent resistivity that is calculated with the geometric coefficient K_{pp}. Although the data past the minimum inflection point of $\rho_{s\text{-}mpp}$ curve lose their value for the sounding application, a portion of the first segment of the distorted curve can be used, therefore, a correction formula under the condition of non-infinite electrode (Bing and Greenhalgh, 1998) space in a PP array is derived based on traditional electric field theories and formulas of apparent resistivity under different electrode arrays. The error analysis after correction indicates that the data utilisation ratio in the corrected effective apparent resistivity is significantly improved, and all the data that appear before the minimum inflection point can be effectively corrected. Additionally, the error between the corrected apparent resistivity and the value under an ideal state (when BM is at least 20 times AM) is less than 5%. Engineering application cases are conducted to validate the effectiveness of this correction formula, and the results indicate that this formula can be applied to process the resistivity sounding data affected by the 'infinite' electrodes.

1. Introduction

Direct current (DC) electrical prospecting has produced many methods, including DC electrical sounding (DC methods), two-dimensional DC resistivity surveys (2-D R), three-dimensional DC resistivity methods (3-D R) and Electrical Resistivity Tomography (ERT). Currently, 2-D surveys are relatively mature. Although 3-D resistivity methods have not yet reached the same level of usage as 2-D surveys, they are inspired by the many advantages of yielding high detection accuracy, being informative, providing direct viewing and facilitating convenient analysis; furthermore 3-D resistivity methods are also experiencing rapid development (Patella and Mauriello, 1999; Boulanger and Chouteau, 2005; Papadopoulos et al., 2010; Loke et al., 2013). With the continuous optimisation of multi-electrode arrays, 3-D surveys have very widespread application prospects; in recent years, they have extensively played important roles in fields such as mineral exploration; hydrological; environmental; engineering applications; agriculture; soil science; archaeology; and cultural heritage (White et al., 2001; Legault et al., 2008; Magnusson et al., 2010; Jia et al., 2012; Chambers et al., 2011; Di Maio and Piegari, 2011, 2012; Heincke et al., 2010; Lebourg et al., 2005; Udphuay et al., 2011; Rao et al., 2014; Loke et al., 2015; Seger et al., 2009; Greve et al., 2011; Wake et al., 2012; Orfanos and Apostolopoulos, 2011; Ercoli et al., 2012). Regardless of which electrical prospecting methods are used, it is necessary to select the most suitable electrode array according to the prospecting purpose and the geological environments that the target encounters. There are many types of arrays, which have their own advantages and disadvantages. Among them, PP has played a key role in 2-D and 3-D surveys.

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In the traditional 2-D resistivity methods, Dipole–Dipole (DD) produces relatively small potential differences and good coupling effects (Bodmer and Ward, 1968), and Pole–Dipole (PD) has a relatively high detection accuracy in the transverse direction (Bing and Greenhalgh, 1998; Loke et al., 2010; Niu et al., 2013). PP has the highest detection depth (Robain et al., 1999; Loke et al., 2001; Drahor, 2006) and a higher resolution in the vertical direction than PD and DD (Neyamadpour et al., 2010). Nonetheless, PP has relatively poor transverse discrimination, and is vulnerable to ground noise (Loke et al., 2001; Seaton and Burbey, 2002).

Regarding 3-D survey applications, PP is widely used in the early stages of development, primarily due to the low number of electrodes used over this period, the relatively smaller model used in inversion calculation, and the advantage of its directivity in survey line layout and inversion. With the increased number of electrode used in 3-D surveys and the super-large scale development of calculation models, optimisation technologies based on GPU calculations for multiple electrode arrays have become mainstream for 3-D surveys development; notably, DD and W-S have been widely used in 3-D ERT exploration. However, the use-area of electrode arrays is also regional; China and France have frequently used PP in 2-D ERT methods, while India prefers to use Wenner (W), and the majority of European countries use DD and W. With respect to 3-D ERT, China also uses PP, whereas many European countries usually choose DD and W-S (Perrone et al., 2014). Presently, with the development of the tl-ERT methods, PP is also widely applied (Jia et al., 2012).

Many experts and academics, such as Loke et al. (2013), Park and Van (1991), Hiromasa (1992), Zhang et al. (1995), Loke and Barker (1996a), Park (1998), Xiong and Ruan (2003), Brinon et al. (2012), and Jones et al. (2014) have conducted numerous comparative experiments, data inversions, and theoretical analyses for the application of PP, indicating that PP has become the most commonly used electrical surveillance array for measurements in 2-D and 3-D multi-electrode electrical surveys.

However, the accuracy of sounding data collection with the PP array remains limited because of the requirement regarding the 'infinite' electrode location. The literature states that this 'infinite' distance should be 10 to 20 times longer than AM distance (Keller and Frischknecht, 1966; Telford et al., 1990); such an 'infinite' distance should also be respected between B and N (Robain et al., 1999). According to the studies by Park and Van (1991), Robain et al. (1999), and Kim et al. (2007), in practical applications, the two 'infinite' electrodes B and N are not placed at infinite locations under this ideal state because of limitations due to field landform conditions. These scholars believe that in the PP array with 2-D and 3-D electrical methods, if the influence of the 'infinite' current electrode B is so small that it is negligible relative to the electrical potential generated by the current electrode A on electrode M, this location can be viewed as infinite; in addition, if A on electrode N is so small that it is negligible relative to M, this location can also be considered infinite, and its electrical potential can be viewed as 0. The traditional view that the currently adopted 'infinite' electrode space is greater than 5–10 times AM can satisfy the aforementioned condition (where B and N are symmetrically distributed on two sides of the survey line) (Chen and He, 1980; Zhang et al., 2014).

The 'infinite' electrode position will affect sounding data collected by either 2-D or 3-D electrical method, and studies have been performed to determine the impact of 'infinite' electrodes. Robain et al. (1999) reported that in most cases, the resultant apparent resistivity curve is strongly distorted because of the impact of 'infinite' electrodes B and N; they designed a particular finite array providing results that are as close as possible to those of the ideal PP array when two conditions that are weaker than an infinite location are fulfilled: (1) the 'infinite' electrodes are placed symmetrically on both sides of the in-line electrodes with a spread angle of 30°; (2) the length of the 'infinite' distance is at least 20 times the greatest distance between in-line electrodes. Razafindratsima and Lataste (2014) estimated the error made in ERT when a PD array is used and reported that the remote electrodes influence the electrical sounding data through two factors: Q (the remote distance divided by the half of the distance between the first and the last in-line electrodes) and α (the angle between the line BM—joining the remote electrode and the centre of all in-line electrodes—and the line joining all inline electrodes). A minimum Q value of 5 is necessary, whereas for the apparent resistivity, a minimum Q value between 2 and 5 would be sufficient if $\alpha = 100°$; a mean spread value of 100° yields the weakest error in the geometrical factor.

Only the most favourable layouts for the positions of different 'infinite' electrodes have been studied, which include the azimuth and distance of 'infinite' electrodes corresponding to the survey line; the most suitable range of 'infinite' electrode space has been determined by comparing the apparent resistivity and inversion results. In the above studies, a correction analysis was not performed on the data that contained distortion. In practical field applications of PP arrays, B and N are far from satisfying the range defined above, especially for detecting the water richness in the underground rock layers of coal mines. Because of the constraints of limited underground roadway space, the two 'infinite' electrodes B and N of the PP array used in the 3-D prospecting of working surfaces can only be placed in nearby roadways; thus, a large amount of the affected data cannot be used in the data processing, which causes loss of the advantages afforded by using large amounts of data and wide detection ranges for the PP array. Consequently, this study aimed to deduce a correction formula, determine the sounding data affected by 'infinite' electrodes by conducting the correction processing, and attempt to increase the detection accuracy by increasing the effective amount of data in the 2-D and 3-D electrical methods.

Because of the limited number of studies conducted on the influence of 'infinite' electrodes on the measurement accuracy of the PP array, this study primarily included the following aspects.

(1) A field test scheme was designed and applied to obtain sounding data and analyse the impact of the 'infinite' electrodes on the apparent resistivity values under different 'infinite' electrode spaces. Various parameters, such as the geometric coefficients of different electrode arrays, were determined; in addition, the apparent resistivity values calculated with different geometric coefficients were defined.
(2) A correction formula was derived to correct the apparent resistivity influenced by 'infinite' electrodes under non-infinite conditions. A comparison of the apparent resistivity curves before and after correction was performed and an error analysis of the corrected resistivity data was used to compare the difference between the corrected and standard data.
(3) The practical value of this correction methodology was validated by the geophysical prospecting results of two engineering application cases.

2. Materials and methods

2.1. Field test design

Currently, scholars hold differing views on the optimal location of the 'infinite' electrode arrangement. Indeed, when the PP array is chosen, the problem is to move the B and N electrodes as far away as possible to approach their theoretical location at infinity. Although it is generally not specified, it should be noted that, in this field test, we refer to the distance between electrodes B and M as the 'infinite' electrode space, which satisfies the equation 2BM = 2NM = BN. The state when BM is at least 20 times AM is defined as the ideal condition; at this point, the 'infinite' electrodes have no impact on the sounding data.

The layout of electrodes for the field test PP array is illustrated in Fig. 1, where B is the 'infinite' current electrode; N is the 'infinite'