Integrated Geophysical Application to Investigate Groundwater in a Wind Power Station of Mountainous Area: A Case Study in Xuefeng Mountain Area of Hunan Province, China

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Abstract: Groundwater is an essential source of drinking water in water-deficient regions. The authors mainly discussed the groundwater exploration of a wind power station in granite mountainous area, and integrated geophysical methods (i.e. vertical resistivity electrical sounding method with a three-electrode configuration and frequency selection method of natural electric field) were used to carry out in-site exploration work. Firstly, the authors carried out three-electrode resistivity sounding profile work, and studied 2D finite element inversion. The 2D resistivity distribution characteristics and the favorable well position of sounding profiles had been obtained. On the basis of the resistivity sounding work, the frequency selection method of natural electric field (FSMNEF) was further developed on the original geophysical profiles. The precise position of the well was determined by the small volume effect of FSMNEF, and the sounding of FSMNEF was used at this position to determine the depth of the abnormal body. Subsequent drilling results validate the effectiveness of geophysical methods, the resistivity anomaly of geo-electrical cross-sections of three-electrode sounding is very intuitive, and FSMNEF has high accuracy in horizontal positioning and depth judgment of the aquifer, and is convenient for construction. The application results show that FSMNEF is an efficient, cost-effective tool for groundwater exploration, the field crews are small, and it has been extremely useful when coordinated with background hydrogeology or other geophysical methods.

1 INTRODUCTION

Groundwater is an important part of freshwater resources and is the most important source of fresh water in many parts of the world. The groundwater is relatively poor in the granite region (Li et al, 2017), so it is generally believed that the granite area is a forbidden area for water exploration, and it is very difficult to look for groundwater yield more than 100 t/d in the granite region. For this reason, some geologists have carried out related research work on the occurrence characteristics of groundwater in the granite region and its exploration problems (Huang et al, 2005; Mahmoudzadeh et al, 2012; Madhnure et al, 2016; Shi et al, 2016). The groundwater in granite areas mainly occurs in fault fracture zones, and a small part of them occur in the weathered layers. In addition, there is also a small amount of groundwater in the tectonic fissures or joint fissures. Duan (1999) believed that the water content of weathered layers and fault fracture zones in granite areas could be detected by geophysical methods, therefore, a combination of shallow seismic refraction method and vertical electrical sounding method was proposed and used to obtain better exploration results in Guangdong, Hainan, Zhejiang Province of China. Taking the Qingdao area as an example, Zhao (1990) discussed the problems that should be paid attention to when searching for groundwater sources in granite areas. Qiao (1988) studied the types of granite fissure water and its occurrence characteristics in Heilongjiang Province and Hulun Buir League region of China. Cao et al. (2006) carried out water exploration practice in granite areas by using surface nuclear magnetic resonance method (NMR).

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According to a large number of water resources exploration results in Hebei, Inner Mongolia, it showed that NMR could detect groundwater within 100 m depth in complex strata containing granite. Li et al. (2009) used the integrated geophysical methods such as induced polarization method and audio frequency geoelectric field method to determine the spatial distribution characteristics of the water storage structure in granite area and judge the water content of the structure, so as to determine the spatial distribution of groundwater. Their work achieved satisfactory results (Li et al, 2009).

In the granite area, the lithology of granite is compact, the porosity is small, the groundwater is generally deep, the influence of surface is small, and the water quality is excellent, so it has certain economic development and utilization value (Dai, 2001). Therefore, exploration and use of groundwater in granite regions is a difficult but yet a significant issue. The objective of this paper was to highlight the utility of resistivity sounding method and the frequency selection method of natural electric field (FSMNEF) for the successful exploration of groundwater in a granite area. According to the application effect, the experience of groundwater exploration in the granite area was summarized, and the effectiveness of the comprehensive method was illustrated. It is of great guiding significance to the hydrogeological work, the exploration and utilization of groundwater resources in granite areas in the future.

2 STUDY AREA AND METHODS

2.1 Study Area

The site of groundwater exploration is located in a small hilltop area near Baoding mountain, Shuikou township, Suining county, Hunan province, China. Datang International Power Generation Co., Ltd. is building a wind power station here, as shown in figure 1 and figure 2.

Suining county is located in the southwest of Hunan province. Shuikou township is located in the northwest of Suining county. This location belongs to the Xuefeng mountain range, and it is relatively remote and the terrain is relatively high. The wind power station construction site is basically located near the top of a small mountain with an elevation of about 1,100 m in figure 2. The surrounding mountainous area is lush with vegetation. Its geographical coordinates are latitude 26°51’42’’N and longitude 110°13’28’’E, as shown on figure 1. The average yearly minimum temperature is 5.7℃ and January is the coldest month. The average yearly maximum temperature is 26.7℃ and July is the hottest month. Average annual rainfall in this region is about 1,320 mm.

From the perspective of regional structure (Figure 3), the working area is located in the central south section of Xuefengshan uplift belt in the third uplift of the Neocathaysian. The NE trending folds and faults are relatively developed, which may be the local turning position of the Neo-Cathaysian structure. The NNE trending folds and faults are very developed, and the associated NW, NNW, NEE and EW trending faults are also developed, all of them belong to the tectonic system of Neocathaysian. The lithology of the study location is Indosinian quartz-monzonite (γ51) (Figure 3).

During the exploration work of FSMNEF, the power station facilities have been basically completed, but they are not yet running. There is no current in the high-voltage cable in figure 2, and the temporary power cable is used for the construction of the power station in the field. The width of the slope shown in figure 2 is about 120 m, and the power station covers an area of about 120 m×130 m. In order to ensure the living needs of 5 to 6 staff members in the future operation of the power station, it is necessary to find groundwater in or near the land acquisition scope of the power station. The owner's requirement for water quantity is more than 15 t/d. Prior to geophysical work, engineering geologists identified two wells locations in the nearby gullies based on hydrogeological conditions (Figure 1). The drilling depth of ZK1 is 60 m, 0-4 m is a diluvium, 4-13 m is a fully weathered or strongly weathered granite, 13-30 m rock is relatively broken, 30-40 m rock is relatively complete, and below 40m is complete granite. The drilling depth of ZK2 is 68 m, 0-5 m is the strong weathered granite, and the rock fissure of 5-40 m is relatively developed, but the crack opening angle is not good, and the rock of 40-68 m is relatively complete. The water yield of ZK1 and ZK2 is about 3 t/d, it cannot meet the demand of the power station. In order to further find the groundwater source, the authors use three-electrode vertical electrical sounding configuration and FSMNEF for comprehensive exploration.

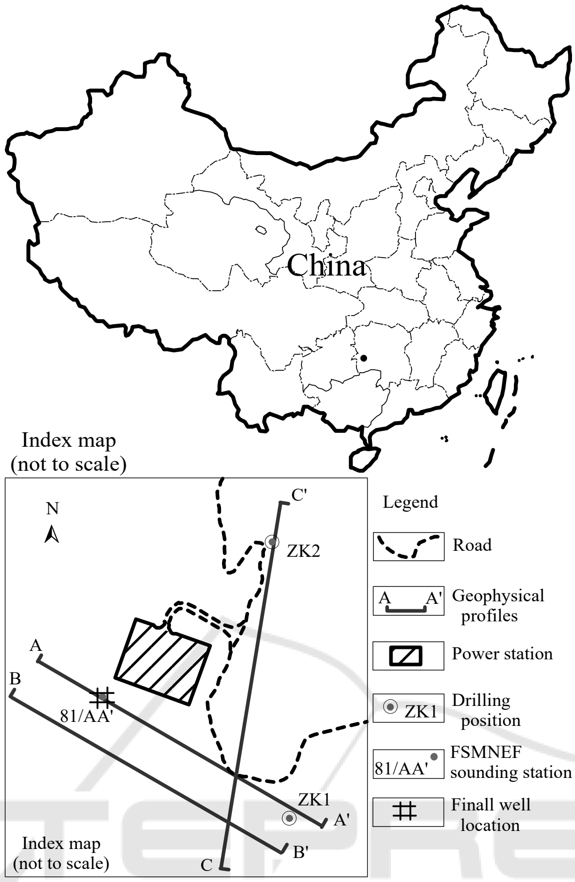


Figure 1. Map showing the location of geophysical works in the wind power station.

2.2 Methodology

2.2.1 Three-electrode Electrical Sounding Method

The conventional vertical electrical sounding method of the Schlumberger configuration is to increase the electrode spacing successively at the same sounding point on the ground, and detect the change of the apparent resistivity along the vertical direction from shallow to deep at the sounding point, and infer the change of vertical geological structure through the analysis of electric sounding curve or electric sounding section. The conventional vertical electric sounding (VES) needs to move current electrode A and B in opposite directions simultaneously during exploration. It is time consuming and cost prohibitive. The difficulty of work increases when the terrain is undulating and the vegetation is very developed. It may be also restricted by buildings and venues when working near a town. At this time, the three-electrode vertical electrical sounding configuration is more convenient and applicable.

Figure 2. A field photo of the wind power station.

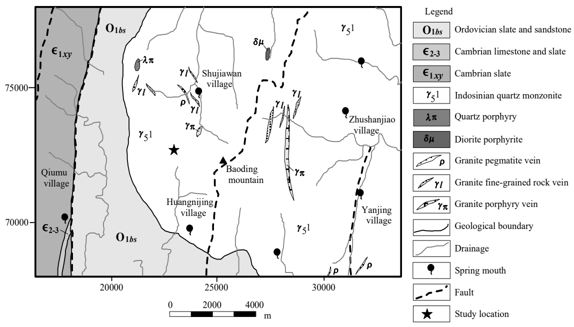


Figure 3. Regional hydrogeological map of the study location.

The two current electrodes (A, B) and the potential electrodes (M, N) of the three-electrode electrical sounding configuration are separated (Figure 4), which can reduce the electromagnetic interference. The current electrode B is located at infinity, the midpoint O of the potential electrodes (M, N) is the sounding point, and electrodes A, M, N arranged in a straight line (Xiang et al, 2011). In practice, it is usually only necessary to move the current electrode A. Therefore, compared with the conventional vertical electrical sounding method, the workload is reduced, and the site adaptability of the sounding method is improved. The sounding point spacing on the profiles is 20m, and the instrument is DDC-5 electric instrument. The on-site work of the three-electrode VES was completed in April 2016 for a total of 15 days, and 60 VESs had been completed.

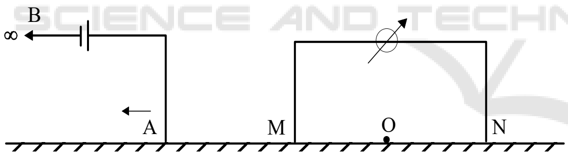


Figure 4. Three-electrode configuration schemes.

2.2.2 Frequency Selection Method of Natural Electric Field (FSMNEF)

The FSMNEF is developed by the telluric current method and the audio-frequency magnetotelluric method (AMT). It is proposed by Chinese scholars and a complete set of exploration equipment has been developed. As far as the surface of the earth is concerned, the natural electromagnetic field can be regarded as a plane electromagnetic wave incident perpendicularly to the surface, and the relationship between the magnetic field intensity $\boldsymbol{H}$, the magnetic induction intensity $\boldsymbol{B}$, the electric field intensity $\boldsymbol{E}$, the electric displacement $\boldsymbol{D}$, the current density $\boldsymbol{J}$ and the free charge volume density q are subject to Maxwell's equations. According to Maxwell's equations, the skin depth (depth of penetration, investigation depth) δ of plane electromagnetic wave in passive region can be estimated as:

$$\delta = 503.5\sqrt{\rho/f} \tag{1}$$

where δ is the depth in meter, ρ is the resistivity value ($\Omega \cdot \mathrm{m}$) of underground media, and f is the frequency used in Hz.

When the underground resistivity ρ is constant, the higher the working frequency f, the shallower the electromagnetic wave penetration; and conversely, the smaller the working frequency f, the deeper the electromagnetic wave penetration. When the frequency f is constant, the greater the resistivity ρ, the deeper the electromagnetic wave penetrates, and the smaller the resistivity ρ, the shallower the electromagnetic wave penetrates.

The relationship between wave impedance Z_{xy} and the apparent resistivity ρ_S can be further derived from Maxwell's equations:

$$\rho_S = \frac{1}{5f}\left[Z_{xy}\right]^2 = \frac{1}{5f}\left(E_x/H_y\right)^2 \tag{2}$$

where E_x and H_y are the orthogonal horizontal electric field component (mV·km-1) and magnetic field component (nT) respectively at the surface. Some scholars believe that H_y can be ignored in groundwater exploration and certain specific directions.

The parallel movement method is adopted in-site measurement for FSMNEF, namely, the electrodes M and N move along measuring lines or profiles with 20 m or 10 m electrode spacing, as shown in figure 5(a). The measuring point spacing is 5 m, and the abnormal section it is reduced to 2 m. The potential difference △V of the horizontal component of natural electric field at different frequencies between two electrodes is measured, and the midpoint O of M and N is the recording point. The acquisition instrument used for FSMNEF is the self-developed MFE-1 natural electric field frequency selector. The field work was completed on 26-28 June 2016 for a total of 3 days.

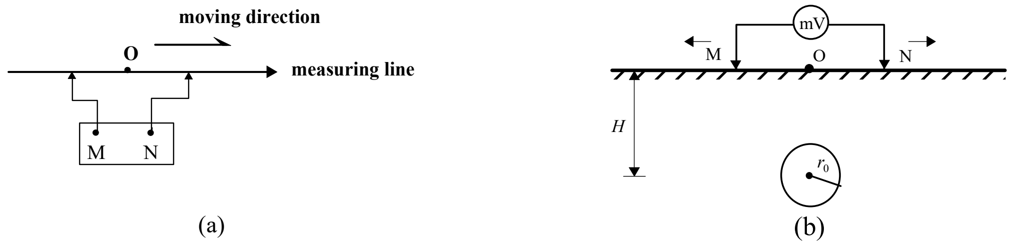


Figure 5. (a) A schematic diagram of a profile detection configuration; (b) a sounding configuration of FSMNEF

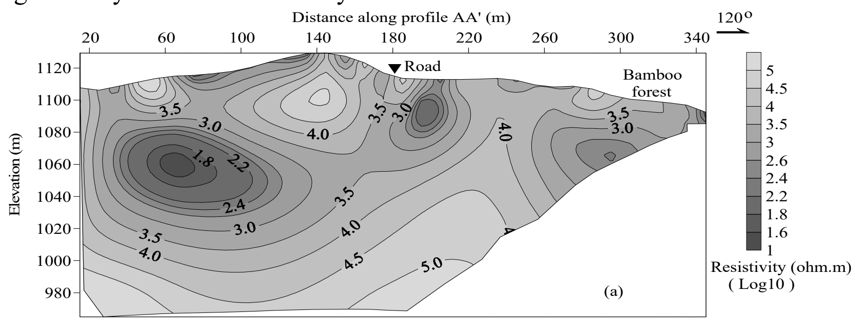
In recent years, vertical electrical sounding of FSMNEF has been used by some practitioners in groundwater exploration (Liang, 2016). This sounding configuration is similar to the conventional vertical electrical sounding, with the measured geophysical anomaly point O as the center, and the electrodes M and N synchronously move outwards respectively (the distance is usually 5m, and 1m in a particular case), the exploration depth gradually increases with the increase of the electrode spacing MN, see figure 5(b). The sounding of FSMNEF technique provides information on the vertical variations in the potential difference of the ground with depth.

The FSMNEF has been successfully applied to groundwater exploration and other engineering geological exploration in limestone areas (Yang at al, 2013), but its field source is very complicated. According to the authors' previous research results (Yang et al, 2016), the authors think that the field source of FSMNEF comes from the interaction of alternating electromagnetic fields generated by the natural factors outside the earth and the alternating electromagnetic fields produced by human factors on the earth's surface. Anthropogenic electromagnetic fields are generally regarded as interference noise in the application of AMT, but compared with AMT, the anthropogenic electromagnetic fields can be regarded as the far field because the exploration depth of FSMNEF is usually smaller (generally < 150 m). Therefore, the horizontal alternating magnetic field and the horizontal alternating electric field formed by natural and anthropogenic factors act together on the underground geological body to form the anomaly of FSMNEF. Their effect is the same as AMT, satisfying formula (1), (2).

3 GEOELECTRICAL MEASUREMENTS AND INTERPRETATION

In order to determine the target area for water exploration, three vertical electrical sounding (VES) profiles were arranged (Figure 1), sixty VESs were recorded with the three-electrode configuration in this study area; 2 of these profiles were selected for evaluation in this paper. The survey profile AA' and the survey profile BB' are located at the foot and the half-waist step of the slope in the southwest of the power station respectively. The survey profile CC' is outside the land acquisition scope, the direction is basically along the road, and it intersects with the survey profile AA' and BB' obliquely.

The measured apparent resistivities were used to compute electrical resistivity tomograms using RES2DINV inversion software. This program uses a finite-element calculation for the forward problem and solves for subsurface resistivity using an iterative Gauss-Newton smoothness-constrained least-squares algorithm (Mcclymont et al, 2011). The 2D inversion results obtained for the two electrical resistivity tomography (ERT) profiles of survey profiles AA' and BB' are presented in figure. 6. The contour of the graph is plotted as the logarithm of resistivity in figure 6.



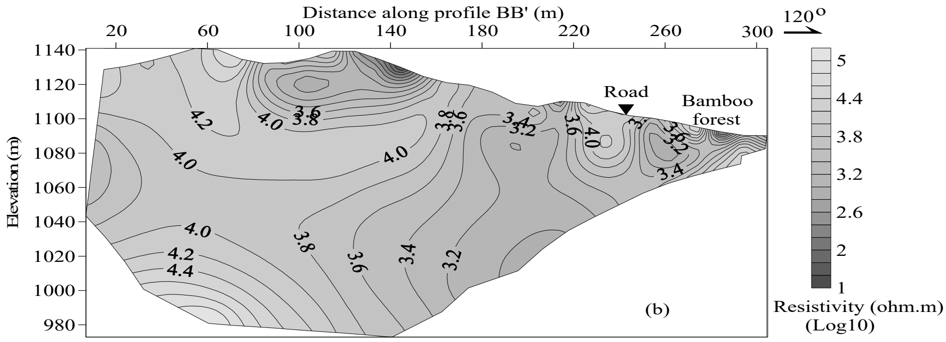
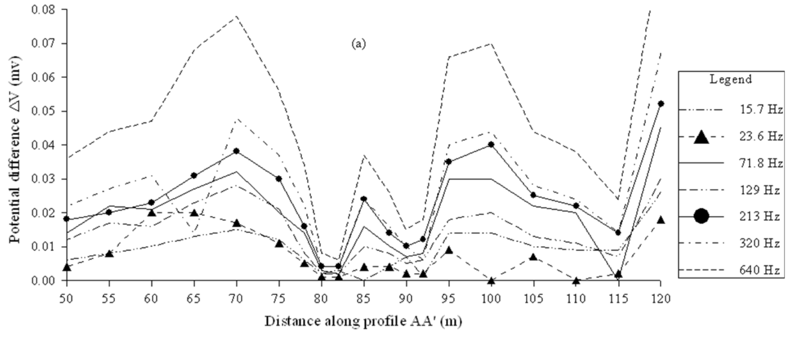


Figure 6. Views of the 2D inversion of the 2D ERT data observed of (a) survey profile AA' and (b) survey profile BB'.

Three relatively low resistivity anomaly areas were found on the profile AA', as shown in figure 6(a). Among them, the low resistivity anomaly near the profile of 50-100 m and the elevation of 1060 m is very obvious. Combined with the local geomorphology, the anomaly is close to the gully at 25 m of the survey profile. It is inferred that the abnormal section has large water content, and the anomaly may be related to the catchment of the gully. But due to the small area of the catchment on the site, and the exploration work in the spring, during which the rain is relative abundant, it is necessary to consider the influence of rainwater on the anomaly. There is also a shallow buried relatively low resistivity anomaly area near the profile of 200 m and the elevation 1080 m. It is estimated that the buried depth of the anomaly is less than 30 m. This position is located in the saddle of the two hilltops, and it can be inferred that the water content is strong, but it is outside the land acquisition scope. The bamboo forest is in the surface area of 290-340 m of survey profile AA', where there is an alluvial gully with strong water content, so it is a relatively low-resistance area. Due to the influence of surface water in the bamboo forest gully, and outside the red line of the land acquisition scope, the bamboo forest area is not an advantageous well site. The aforementioned borehole ZK1 is located near the vicinity 300 m of the survey profile AA', and the drilling depth of 60 m is basically a dry well, the lithology buried below 13 m is relatively complete granite.

Compared with survey profile AA', there is no very obvious low resistivity anomaly area on profile BB', as shown in figure 6(b). The profile BB' passes through the middle step of the slope in figure 2. Except for the bamboo forest area, the measuring point elevation of the survey profile is generally larger than that of the survey profile AA'. The measuring points near the slope are closer to the hilltop (Figure 2), and the water content in the slope decreases, which leads to the increase in the resistivity and the relatively low resistivity anomaly is not very obvious, but there are 3 relatively low value anomalies (Figure 6(b)). Firstly, there is a shallow low-apparent resistivity anomaly near the profile of 100 m and the elevation of 1120 m. It is located in the depression area of two hills in the middle of slope step in figure 2. It is presumed that the water content is strong below this position, and the anomaly has a certain correlation with the position anomaly near the profile AA' of 200 m in figure 6(a), because both anomalies are located in the depressed area of the slope. There is a relatively low resistance trend near the profile of 200 m, this anomaly is located at the side of the road and at the saddle of the two hills. The 260-300 m section of profile BB' is located in the bamboo forest, where there is an alluvial valley. There is a small amount of water in the shallow covering strata, but there is not necessarily groundwater in the deep because the borehole ZK1 on the previous survey profile AA' has been verified.



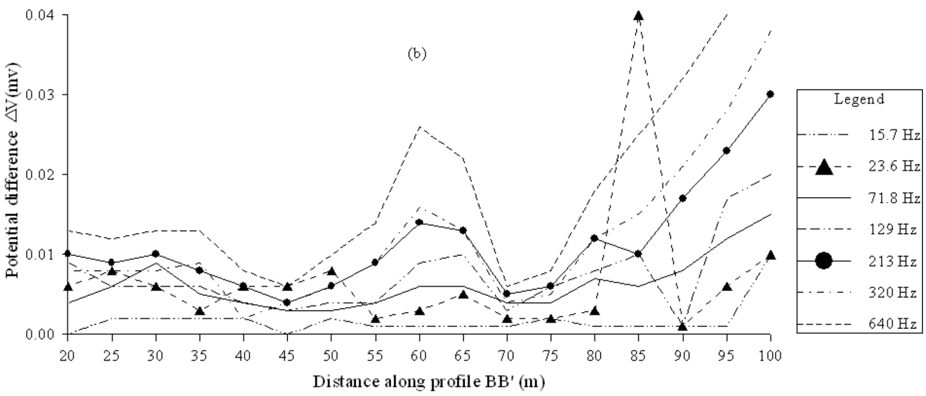


Figure 7. Results of FSMNEF on (a) survey profile AA' and (b) survey profile BB'.

According to the results of three-electrode electrical sounding, the resistivity anomaly near the 50-100 m section of survey profile AA' and the buried depth of about 40 m is the favorable position for water prospecting.

Figure 7(a) and figure 7(b) show the partial detection results of FSMNEF on survey profile AA' and BB', respectively, and the data next to the curve in the figure represents different detection frequencies. After 115 m of profile AA' and 90 m of profile BB', the curve increases obviously. It is caused by the interference of the cable used for temporary construction on the ground. Therefore, the data results which are interfered after 115 m of profile AA' and 90 m of profile BB' are omitted here and not drawn out. According to the results of FSMNEF, there are two obvious low potential anomalies in profile AA', namely near 81m and 91 m. The two anomalies were observed carefully in the field work, that is, the measuring point spacing was reduced from 5 m to 2 m. The reliability of the anomaly is determined. The anomaly of 81 m is more obvious than the anomaly of 91 m, and the relative amplitude of the anomaly is larger, and the synchronization of the detection results at different frequency is better, as shown in figure 7(a). In addition, the reliability of the low potential anomaly at 115 m of the survey profile AA' is affected by the interference of the nearby power supply.

The anomalies of FSMNEF on survey profile BB' mainly appear near the profile of 45 m and 70 m, and relative amplitude of the anomaly at 70 m is more obvious and the anomaly is more reliable. According to the position relationship between the survey profile AA' and BB', it is presumed that the anomaly at 70 m of the profile BB' is associated with the anomaly at 81 m of profile AA'. The survey profile CC' is roughly parallel to the construction road up to the mountain (Figure 1), and there is a high-voltage power supply line along the road, so the FSMNEF is not performed on the profile.

According to the results of FSMNEF method and vertical resistivity sounding, the position of the FSMNEF anomaly at 81 m is overlapping with that of resistivity sounding anomaly of 50~100 m on profile AA', which further determines the reliability of FSMNEF anomaly at 81m, and the point of 81m is finally determined as well location. For this reason, the vertical electrical sounding of FSMNEF is further carried out at this site (ie, point 81/AA'), and the sounding curves are shown in figure 8. It same as those shown in figure 7, the data next to the curve in the figure represents different detection frequencies. The FSMNEF sounding is similar to the conventional vertical electrical sounding of the Schlumberger configuration, but there are no current electrodes (AB) at this time. The potential electrodes (MN) are symmetrical with respect to the sounding point O and spacing of MN gradually increases, and potential differences $\triangle V$ of different frequencies are measured at different electrode spacing (Liang et al, 2016). It can be seen from the sounding curves of figure 8 that the FSMNEF sounding curves of 15.7 Hz, 23.6 Hz, 71.8 Hz and 129 Hz have relatively low potential anomalies around MN=20 m. According to the experience of, there is an approximately equal relationship between the electrode spacing MN and the detection depth H is, that is $MN/H \approx 1$ (Liang et al, 2016). Therefore, it is assumed that the buried depth of the aquifer is about 20 m.

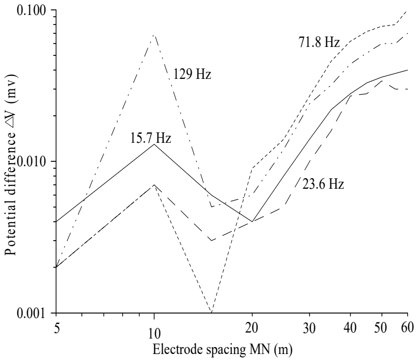


Figure 8. Sounding curves of FSMNEF at 81/AA'.

Figure 9. Drilling cores for 28m depth.

Figure 9 shows the core after drilling at point 81/AA', in which there are water-bearing fractures at 23-26.5 m segment, and the core is relatively fragmented and incomplete. The pumping test result shows that the water output of the well is about 30 t/d, and the final drilling depth of the well is only 30 m because the water requirement (>15 t/d) is satisfied. It can be seen that the ratio of electrode spacing MN (=20 m) of low potential anomaly reflected by FSMNEF sounding curves to the average buried depth H (=24.75 m) of water-bearing fractures is about 0.8.

4 CONCLUSIONS

According to the effect of groundwater prospecting practice in this granite area, the use of integrated geophysical technologies is an effective method for groundwater exploration in granite areas. As far as exploration results are concerned, the profile of three-electrode electrical sounding can delineate the range of low-resistivity anomalies and draw an intuitive geoelectrical cross-section of the survey profile. The horizontal volumetric effect of FSMNEF is small, and the horizontal position of the water-bearing structure can be determined accurately and meticulously, which is convenient for accurate positioning of well position.

From the exploration results of FSMNEF sounding method, it has similar exploration effects as the conventional direct current sounding of the Schlumberger configuration, that is, the exploration depth increases with the increase of potential electrodes spacing (MN). The authors believe that this is due to the existence of stray current in the ground. This is also a question worthy of further study in the future.

From the in-situ work, the conventional resistivity method is more troublesome, the workload is large, the volume effect is strong, the topography effect is serious, and curves are distorted. But FSMNE overcomes the defects of conventional geophysical prospecting methods which are complex and cumbersome in the in-situ work, and FSMNE has the advantage of cost effective, rapid and quick survey time, strong site adaptability and less ambiguity interpretations of results when compared to other geophysical survey methods, it has a good prospect of development and application. At the same time, FSMNE is an electromagnetic method which is susceptible to the artificial electromagnetic interference in the field. This is a problem that needs pay attention to it.

In addition, the FSMNE sounding is a new sounding method put forward by Chinese researchers in practical application recently, and it has achieved good results in practice (Liang et al, 2016). However, the inversion of data is still in the stage of empirical interpretation, and the theoretical research of this method needs to be further studied.

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