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Study on multiple induced polarization parameters in groundwater exploration in Bashang poverty alleviation area of Heibei Province, China

LIU Zhi-yuan, TAN Ding*, CHEN Zhi-bin, WEI Yun-fei, CHAI Quan, CHEN Xiao-hang

Hebei Institute of Geological Survey, Shijiangzhuang 050001, China.

Abstract: The study examines a water exploration and poverty alleviation project in Guyuan county. The study analyzes correlations between aquifers and multiple induced polarization (IP) parameters, including resistivity, polarizability, deviation, half decay time, water-bearing factors, and Kc, a new parameter refined in this study. Based on the study, the well was placed accurately, and its maximum water inflow reached 30 m^3/h. Kc value highlights the rate of change at early stages of IP secondary field. Kc value served as a quick indicator in this groundwater prospecting and is validated in practice. Progress has been made in finding new parameters in exploring water with IP method. Thanks to the project, local people have access to water and poverty alleviation has scored some achievements.

Keywords: Bashang; Induced polarization parameters; Decay rate; Secondary field

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Introduction

Since 1950s, scholars from United States and the Soviet Union started to use IP method in exploring groundwater and scored meaningful achievements (LI Jin-ming, 1993). After 1960s, Shaanxi Geology and Mining Geophysical and Geochemical Prospecting Team first identified the close relation between decay properties of excitation potential and groundwater (1969). Shanxi water conservancy system proposed comprehensive parameters which mainly focus on observing polarizability and excitation ratio (LIU Guo-hui, 2007; LU Yun-xiang, 2011). ZHANG Yao-ying (1989) noted the dispersion parameter F, and LI Jin-ming (1993) put forward the rate of deviation, another parameter. LIU Guo-hui *et al*. (2007) proposed water-bearing factors. All of these suggest that the relation between time properties of induced polarization and aquifers is increasingly acknowledged.

YANG Jin (1998) processed and examined the data of exploring water with IP method. LI Shu-wen *et al*. (2000) launched an applied research on IP anomalies. LONG Fan *et al*. (2002) summarized the actual cases of using IP method when troops prospected water. SONG Hong-wei *et al*. (2009) analyzed the actual cases of using ultra-high density resistivity method and IP method in exploring water in Hebei Province. ZHANG Bin *et al*. (2012) studied using IP method in groundwater prospecting. WANG Ping *et al*. (2013) explored water in Qingshuihe, a water-scarce region, by using a combination of geophysical prospecting methods and scored significant achievements. CAO Guang-qi *et al*. (2014) successfully applied power method to water resource prospection in Darfur of Sudan. LIANG Jian-gang *et al*. (2014) attained achievements in using IP method in groundwater prospecting. DENG Ya-ping (2016)

*Corresponding author. E-mail: 453063025@QQ.com

introduced the application status of geophysical methods in examining underground structures and plume contamination. Krishna Kumar Kotra (2016) conducted integrated assessment for the Thandava River basin in India, and used vertical electrical soundings, soil samples, rainfall data and water samples to evaluate groundwater in a more comprehensive and verifiable way. ZHANG Zhen-jie *et al*. (2018) used an optimal combination of direct electric sounding methods to explore water and scored achievements in pediment gobi area of the Hexi Corridor. LU Fang *et al*. (2019) studied the relation between gneiss rock fissure of Taihang mountains and IP decay parameters.

Water scarcity of Bashang region of Hebei province limited its economic development and the problem needs to be addressed immediately. In light of previous studies, this study put forward and refined the new parameter-Kc. The study examined the response characteristics of aquifers and multiple IP parameters, and successfully located the well.

1 Geological conditions

1.1 Strata

The study area is located in north-western Hebei Province and at the structure junction between Shanxi ridge and Yan Mountain fold. The area has three stages of development: Basement formation, cap rock development, and activation. In the basement formation stage, the stratum was located in the southern region and the scale was small. It mainly involved the development of Palaeoproterozoic Hongqiyingzi residue rock group, and the lithologic character was simple. It mainly consisted of biotite plagioclase gneiss and amphibole plagioclase leptynite. In cap rock development stage, the coverage was extended. The sedimentary strata from the top town were Mesozoic Cretaceous Beigou formation, Yixian formation, and Zhangjiakou formation. Activation period covered the whole area. The strata mainly consisted of Mesozoic Quaternary river and lake facies sedimentary stratum. Lithology types were mainly claystone and sandstone conglomerate, creating a favorable condition for storing groundwater. Magmatic rock has complicated lithologic characters. It possesses ultramafic, basic, and acidic characteristics (Bureau of Geology and mineral development of Hebei Province, 2013).

1.2 Structure

The study area is located in the middle of northern uplift zone of Huabei and Huabei-Guyuan fracture zone (NE). The region borders Kangbao-Weichang fracture zone (WE) to the north and passes Shangyi-Chicheng fracture zone in the south. As a result, the study area and its periphery have well-developed fault structures. The southern area mostly includes north-east fractures, and the middle area mainly includes north-east and nearly south-north fractures. The northern area includes north-east and north-north-east fractures and derivative secondary fractures that pass them. In the area, multi-stage fractures cut and influenced each other, forming favorable passages for transferring groundwater and creating favorable conditions for bearing and storing groundwater.

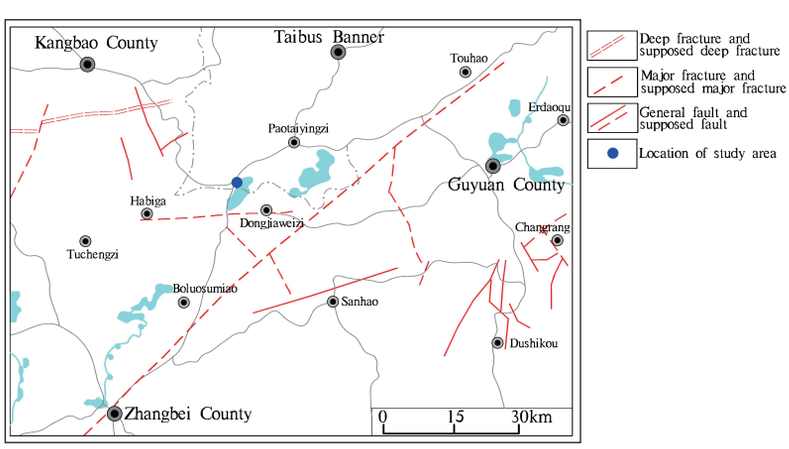

Fig. 1 Structures of north-western Heibei Province (ZHANG Ya-dong, 2006)

1.3 Hydrological conditions

The study area is located in the north-eastern Zhangjiakou city and is known as Bashang. The area borders Inner Mongolian Plateau to the north-west and borders Yan Mountains to the south. There are undulated hills in the northern part of the area, and the whole area is cut by Yin Mountains from east to west. The overall terrain is high in the south and low in the north, and flat in the east and steep in the west. The study area has continental monsoon arid or semi-arid climate. In summer, it rains for a short period of time, and it is windy and rarely snows in winter. Precipitation varies in the area, and generally, the area suffers from severe water shortages.

The study area has developed geological structures. Cenozoic Quaternary overburden is widely distributed, and its thickness ranges from a few meters to dozens of meters. Generally, there are two types of groundwater occurrence in this area. The first type is Quaternary pore water. Major aquifers are gravel, pebble bed, and weathered fissure layer at the top of bedrock. The key is to find low-lying areas with undulated underlying bedrock. Water content is determined by porosity and the size of the catchment area. The second type is bedrock fissure water. Its water content is determined by the size of fractured structure and its nature. Generally, tension faults can store water.

1.4 Physical properties

As illustrated in Table 1, Quaternary overburden is significantly lower than bedrock. Since the study area is relatively flat, low-lying areas with undulated underlying bedrock has the biggest catchment area and it is the favorable water-bearing location. The physical characteristics lay a foundation for electrical work.

Table 1 Common values of rock and soil stratum's physical properties

Name	Soil	Clay	Silty Clay	Silty sand	Sand	Gravel	Strongly weathered zone	Complete bedrock	Pure water
Resistivity (Ω.m)	30	20	50	60	70	80	110	>200	30~100

2 Methodology

Induced polarization (IP) is based on the fact that different geological bodies have different induced polarization effects. The method is an effective technique to indirectly prospect groundwater and address geological problems through analysis and examination of different strata's IP effects (strength and rate of decay of the secondary field).

According to multiple experiments of LI Jin-ming (1994), intensity of induced polarization field of water-bearing rocks is related to discharge speed and water-bearing status (humidity). On the sand layer with medium level of water abundance, it is likely to observe high polarizability and half decay time. On the saturated sand layer, anomalies are not likely to be measured. In this study, Bashang region suffers from severe water scarce, and water exploration is conducted in unsaturated strata. Multiple IP parameters and their relation to groundwater are examined:

① Apparent resistivity ρ_s ② Polarizability η_s

③ Half decay time S_t is most sensitive to water-bearing strata. The more water the strata bear, the longer the half decay time.

④ Deviation r is closely related to groundwater abundance. Generally, r decreases with increasing water content.

⑤ Water-bearing factor is F_w. F_w=S_t/r. When humidity is high, S_t is high and r is low, and as a result, F_w is higher. High granularity of the aquifer usually means high water content, and in this case, S_t is high and r is low, and consequently, F_w is higher. F_w parameter takes into consideration the half decay time St and deviation parameter, and is highly reliable. F_w parameter is directly proportional to water content. When granularity is high, F_w parameter increases with increasing humidity. When granularity is low and water content is at the medium level, a maximum value appears. Generally, F_w increases with increasing humidity (LIU Guo-hui, 2007).

⑥ The decay rate of polarizability K_c. K

reflects the overall slope of the discharging curve within the measurement time.

$$K = -\left(\frac{\partial \triangle V_2(t)}{\partial \lg t}\right)_{\text{average}} = -\frac{1}{n}\sum_{i=1}^{n}\frac{\partial \triangle V_2(t_i)}{\partial \lg t_i} \quad (1)$$

Where: $\triangle V_2(t_i)$ is the difference value of secondary field. t_i is time difference, and n is time of periods (LI Jin-ming, 1993).

To better apply the method and enrich the parameters in theory and in a simple and effective manner, it is defined that K_c describes the decay rate of polarizability at the early stages of the discharge. $\triangle t$ is between η_1 and η_3. $K_c=(\eta_1-\eta_3)/\triangle t\times 10^3$, and the unit is %/s. K_c value highlights the decay rate of secondary field at the early stages of IP. At the early stages of secondary field, the signal is strong, and anti-interference ability is higher than that in the overall time. In this way, the observation errors due to low intensity at the later stages of the secondary field can be avoided. In accordance with the electrochemical principles, the relevance between K_c value and aquifers decreases with increasing water content.

3 Application examples

In the workspace, Quaternary overburden is widely distributed, and the terrain is flat. In light of the type of groundwater of the area, the groundwater exploration aims to identify aquifers in low-lying areas with undulated underlying bedrock. Firstly, by measuring the profile of IP intermediate gradient, the researcher quickly identified five IP anomalies with low resistivity and high polarization. The low resistivity is directly proportional to quaternary thickness, and high polarizability shows a positive correlation with water abundance. Then the researcher carried out IP soundings around IP anomalies, and further examined the vertical electrical characteristics. Finally, the researcher used multiple IP parameters to analyze and identify the water abundance and located the well.

3.1 Device parameters

(1) IP intermediate gradient. DWJ-3B micro-electro-mechanical equipment was used and its supporting IP transmitting system was produced by Beijing Earth Long Science and Technology Co., Ltd. Delay was set to 40 ms and integral was set to 200 ms. The statistics was read twice. Power supply cycle was 16 s, and power supply pulse width was ±4 s. Power supply polar distance AB=1200m, and MN=40m. Range of observation was kept within the middle 2/3 of AB. Anomaly areas (with low resistance and high polarizability) were initially identified.

(2) IP soundings. To further examine the vertical electrical distributing features of anomaly areas, IP soundings were carried out around five IP anomaly areas in the profile, and the collected parameters were consistent with the profile of IP. Symmetrical quadrupole device was used. Power-supply polar distance AB was equally spaced according to logarithm as illustrated in Table 2.

Table 2 Polar distance of IP symmetrical quadrupole device

AB/2(m)	3	6	9	12	15	20	...	60	80	100	120	150	210	300
MN/2(m)	0.5	0.5	0.5	0.5	5	5	...	5	5	10	10	10	10	10

3.2 Comprehensive study

In light of the type of groundwater in the region, this groundwater exploration focused aquifers in low-lying areas with undulated underlying bedrock. Firstly, by measuring the profile of IP intermediate gradient, the researcher quickly identified five IP anomalies with low resistance and high polarization. Then the researcher carried out IP soundings around the anomalies, and further examined the vertical geo-electrical characteristics. Finally, the researcher used multiple IP parameters and geological information to analyze and identify the water yield property, and located the well.

As illustrated in Fig. 2, 1 200~1 400 m in the profile of IP intermediate gradient is a classic JD2 region with low resistivity and high polarizability, and the area with low resistivity matches the area with high polarizability. It is initially assumed that JD2 anomaly area is a favorable condition for exploring water. To further examine its vertical geo-electrical distribution, IP soundings and profile measurement were carried out in anomaly area.

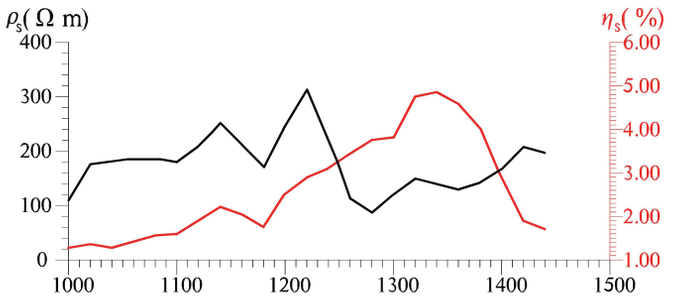

Fig. 2 Profile of IP intermediate gradient

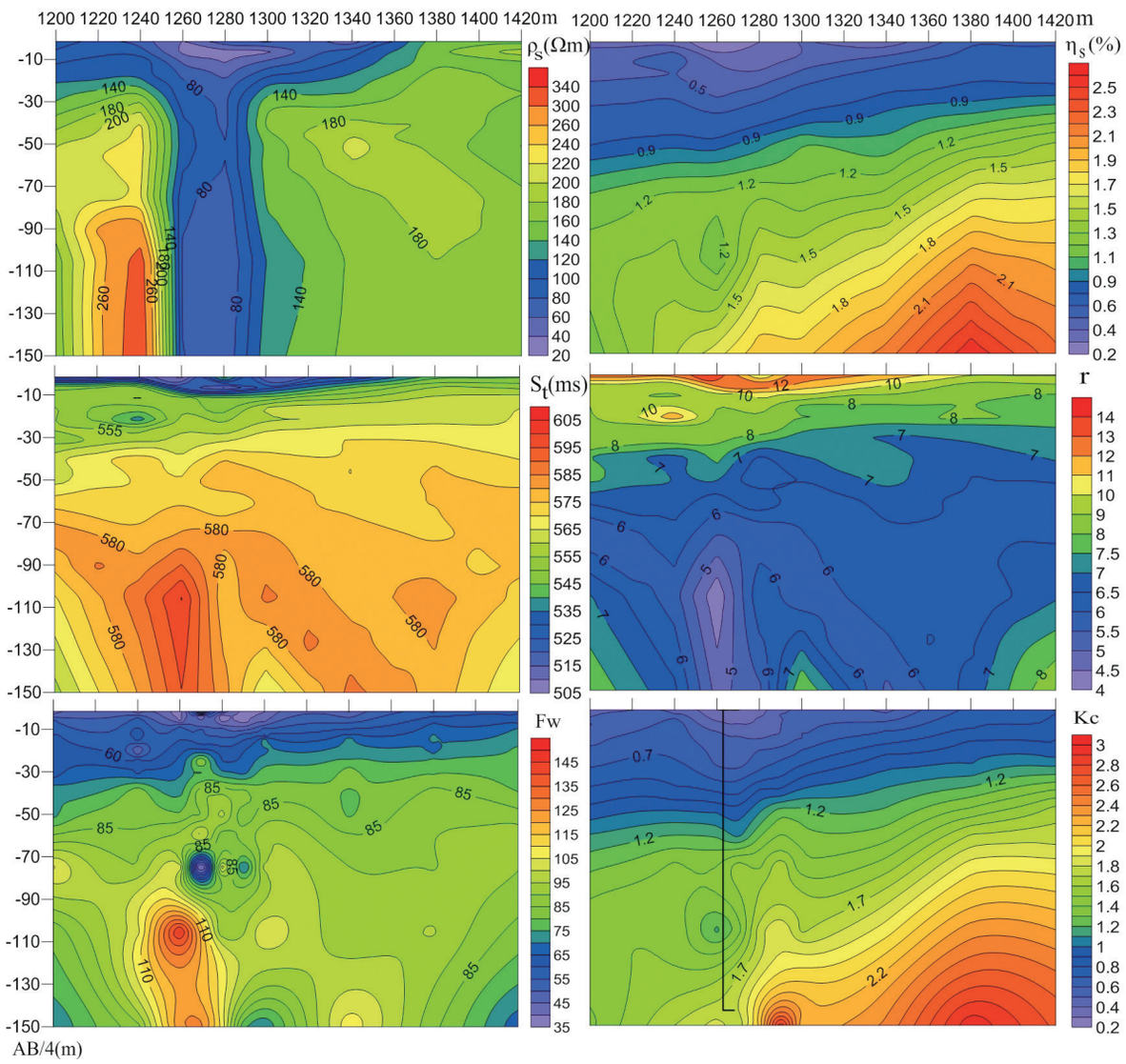

Fig. 3 Profile contour map with multiple IP soundings parameters

Apparent resistivity ρ_s, polarizability η_s, half decay time S_t, deviation r, water-bearing factor F_w, and decay rate of polarizability K_c. To accurately place the well, the profile of IP soundings was carried out in JD2 anomaly area. Dot pitch was 20 m, and intensive measurement was implemented at 1 270 m. As for the relation between AB/2 polar distance and depth, empirical coefficient 0.7 was usually adopted. Hebei Institute of Geological Survey's experience in mineral exploration suggests that AB/4 polar distance is usually closer to the actual depth. For that reason, the soundings adopted the AB/4 polar distance in mapping. Detailed analysis of Fig. 4 is as follows:

(1) 1 240~1 300 m is an obvious low resistivity zone with its center between 1 260~1 280 m. It is initially assumed that this is a water-bearing fractured zone covered by Quaternary overburden.

(2) In regard to the low resistivity zone's polarizability, slightly higher polarizability can be observed between 1 270~1 280 m and when AB/4>70 m. Based on experience, location with high water yield property is between 1 270~1 280 m.

(3) High value of half decay time usually suggests high water yield property. In this study, the high half decay time is observed at 1 260 m and when AB/4>70 m, but this location is deviated from the location suggested by slightly higher polarizability.

(4) According to Li Jinming's studies (1994), low deviation is negatively correlated with water content. Anomaly area with low deviation is also between 1 260 m and when AB/4>70 m, which is consistent with implications of half decay time. The location indicated by small deviation is 20 m away from the location indicated by half decay time.

(5) Water-bearing factor F_w is high between 1 250~1 270 m in the project and when AB/4>70 m. The maximum value occurs at 1 260 m and when AB/4=100 m. According to practices of LIU Guo-hui (2007), the maximum value corresponds with water-bearing fracture zone. The location indicated by half delay time is only slightly deviated from the location suggested by deviation, but the location suggested by polarizability is deviated from locations indicated by others.

(6) To accurately place the well and highlight the decay rate of the secondary field, this study refined the K into K_c (decay rate of apparent polarizability at early stages of discharge). Between 1 260 m and 1 270 m in profile, an area with low K_c value from the top to bottom can be observed. The minimum value appears at 1 260 m and when AB/4=100 m. The minimum K_c value corresponds with the maximum value of water-bearing factor, and it is presumed that it suggests a water-bearing fracture zone. In theory, K_c corresponds with water-bearing zone. K_c clearly corresponds with water-bearing factor. The location K_c indicated is only slightly deviated from those indicated by water-bearing factors, half decay time, and deviation, but it is more deviated from the location suggested by apparent polarizability.

The designated area of low resistivity is large, and the center indicated by slightly higher polarizability is 1 280 m. The locations indicated by high decay half time are basically the same with those indicated by low deviation, and the center is 1 260 m. Water-bearing factor F_w suggests that the center is 1 270 m, but when AB/4 is over 100 m, the center approaches 1 270 m. Low Kc value indicates a center between 1 260 m and 1 270 m and the shallow center is 1 270 m. When AB/4>70 m, the indicated center is 1 260 m, and when AB/4>90 m, it clearly corresponds with the maximum value of F_w. Consequently, the well is located at 1 265 m with a depth of 150 m, and the maximum water inflow was about 30 m^3/ h. The study finds that S_t corresponds with r. F_w corresponds with K_c, but locations indicated by the four parameters are deviated from the locations indicated by η_s to varying degrees.

4 Conclusions

(1) K_c, a parameter refined on the basis of previous studies, is validated in practice. K_c served as a quick indicator in the groundwater exploration and is validated in practice. Headway has been made in finding new parameters in exploring water with IP method.

(2) By analyzing and examining different IP parameters, the researcher accurately located the well, and the well's maximum water inflow reached 30 m^3/h. The study addressed the water scarcity problem and contributed positively to the poverty alleviation work of Bashang of Heibei Province.

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