Characterize hydraulic properties of fault zone using pumping test data and electrical resistivity data in Xinchang Region, China

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Abstract

Obtaining the hydraulic conductivity characteristics of widely distributed fault zones is the key to evaluating potential underground nuclear waste repositories. However, there are currently certain limitations on the methods for such data collection. In this study, electrical resistivity tomography (ERT) was combined with pumping test data to obtain the distribution of hydraulic conductivity in fault zones. The hydraulic conductivity of the aquifer was obtained through 30 pumping tests in seven pumping wells, and the results were then fitted with the aquifer resistivity obtained by the ERT at the corresponding positions to establish the relationship between the resistivity and the hydraulic conductivity, according to which the hydraulic conductivity characteristics of the fault zone can be obtained using the resistivity value. The results show that for the sandstone area with a small hydraulic conductivity, the result of exponential fitting is more accurate (R2 = 0.97) than that of linear fitting and power fitting. The hydraulic conductivity calculated based on the established R-K relationship has an error of less than 10.50% compared with that measured by the pumping tests, and the Nash-Sutcliffe efficiency coefficient is 0.96. Furthermore, the spatial distribution of the hydraulic conductivity of the fault zone in the study area was calculated based on this relationship, providing a basis for more accurate and low-cost descriptions of groundwater and solutions transport in the fault zone.

Introduction

The fault zone is a type of geological structure that is widely distributed in the crust(Caine *et al.* , 1996; Wibberley *et al.* , 2008). Its existence damages the continuity and integrity of the rock mass, which results in changes in the hydraulic connection between aquifers and thereby controls the occurrence and transport of groundwater(Mase and Smith, 1987; Bense *et al.* , 2013; Hayward*et al.* , 2019). The study of the hydraulic characteristics of fault zones is an important part of the safety evaluation of geological disposal sites for high-level radioactive waste(Pollock, 1986; López and Smith, 1996; Evans *et al.* , 1997; Tondi *et al.* , 2016). However, because the fault zone is often not obviously exposed on the ground surface, it is very difficult to make a correct judgment about the spatial distribution of the fault zone based solely on the information obtained from the surface, which brings difficulties to the safety evaluation of underground nuclear waste disposal sites (Dipple*et al.* , 1990; Otsuki *et al.* , 2003; Collettini *et al.* , 2009; Li *et al.* , 2013). Fortunately, the development of electrical resistivity tomography (ERT) provides new tools and methods for the identification of underground structures (Zhou *et al.* , 2001; Kemna *et al.* , 2002; Singha and Gorelick, 2005; Jougnot*et al.* , 2018; Tso, 2019). Numerous researchers have used ERT to identify fault zones and fracture networks. Taylor and Fleming (1988) studied the fracture network characteristics of the rock and clay in Wisconsin by using the resistivity measurement method and proved the feasibility of using this method to identify the fracture network in the medium. Slater *et al.* (1996) used a borehole ERT to identify preferential flow paths in bedrock fissures at a quarry in the UK. Mondal et al. used ERT to detect underground hidden fracture and fault zones in the fracture distribution area of the bedrock. To achieve accurate detection, Suzuki *et al.*

(2000) integrated ERT with the controlled-source audio-magnetotellurics to conduct a comparative study on the morphology and occurrence of four faults in the north island of Japan. The results showed that the latter is very effective in delineating the strata structure within a depth of several hundred meters near the faults, while the former can identify the stratigraphic bending structure generated by the faults in more detail. Ganerød*et al.* (2006) used ERT, the seismic reflection method, and the very low frequency method to detect fractures in bedrock, and the results showed that the data acquired by ERT can more clearly identify the characteristics of the thickness, width, and depth of the fractures in the tunnel bedrock. Many studies (Francese *et al.* , 2009; Robinson *et al.* , 2016; McLachlan *et al.* , 2017; Palis*et al.* , 2017) also showed that ERT can be used to determine the vertical and horizontal contact relationships between different geological units with a high spatial accuracy.

Therefore, ERT has the advantages of fine detection, variable spatial scale, sensitivity in the detection of fault zones and fracture networks. However, due to the increasing requirements for fault zone identification accuracy, there are still some shortcomings when single RET is used to obtain the hydraulic characteristics of fault zones(Hermans *et al.* , 2015; Chou *et al.* , 2016). To address this problem, many attempts (Olsen *et al.* , 1999; Francese*et al.* , 2009; Koch *et al.* , 2009; Lu *et al.* , 2017; Peng *et al.* , 2019) have been made to improve the identification accuracy by combining other geophysical exploration data. Due to the limitation of the geophysical method, complex fault zone exploration and geophysical data often lead to limitations in interpretation, and thus, the parameters of the hydraulic characteristics of the fault zone cannot be obtained. This study aims to combine ERT with pumping test data to obtain the hydraulic conductivity of the fault zone, which can provide a theoretical basis and data support for studies on the hydraulic characteristics of the fault zone and groundwater movement in nuclear waste repository areas.

Methodology

Study area

The study area is located in the Xinchang region of Beishan, China (Figure 1), and is one of the alternative sites for the establishment of underground nuclear waste repositories and laboratories. The topography is characterized by being high in the west, low in the east, high in the north, and low in the south, with some undulating terrain. The groundwater in the study area is generally mountain bedrock fissure water. The lower part of the Quaternary sand gravel alluvium is a bedrock weathering crust or tectonic fracture zone, which is rich in bedrock fracture water (Li *et al.* , 2012). The groundwater in the study area mainly receives vertical recharge from atmospheric precipitation. The groundwater enriched in gullies and depressions as well as fault zones and fracture zones are partly consumed by evaporation and partly discharged to the downstream runoff through gullies, fault zones, and fracture zones, and it finally flows to the basin or regional discharge point, thus constructing a complete groundwater circulation system. Due to the influence of the multiphase structure, the fault structure is well developed in this area and can be roughly divided into three tectonic systems, the NW-trending, EW-trending, and NE-trending tectonic systems, of which the NE-trending tectonic system is particularly developed (Xiao *et al.* , 2012; Li*et al.* , 2017). It can be seen from the water circulation path in this region that the fault zone in this area has a pronounced hydrogeological significance. Therefore, the in-depth study of the hydrogeological characteristics of the fault structure is the focus of hydrogeological work in the bedrock area and an important and arduous task in underground laboratory construction and repository site selection evaluation. In this context, the main purpose of this study is to complete a preliminary hydrogeological investigation. On the basis of the application of traditional hydrogeological methods and combined with modern hydrogeophysical imaging technology, the hydraulic characteristics of alternative sites are identified from the perspective of two-dimensional space, thus providing a scientific basis for the prediction of groundwater environment evolution and the evaluation of repository safety performance at the site.

2.2 Methods for the acquisition of fault zone properties

1) Electrical resistivity tomography method

In this study, two schemes were used to obtain the spatial distribution characteristics of fault zones in

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the study area. The first scheme was to directly use ERT and a large number of electrodes to obtain a large amount of data to achieve nondestructive exploration of the target body through resistivity images. The basic principle is as follows. First, a large number of electrodes are densely placed in the area to be surveyed, and these electrodes are connected via cable to the ground resistance measuring device with an electrode switching function. Because two electrodes are used for the power supply and two electrodes are used to measure the voltage, every four electrodes can obtain a resistance data. Because a large number of electrodes can have a large number of four-electrode combinations, multiple resistance data of the target body can be obtained at multiple locations. Second, according to the measured resistance data and electrode coordinates, the apparent resistivity value corresponding to each resistance value is calculated, and then the initial resistivity model of the target body is established based on these apparent resistivity values. Third, according to the actual measured current in the initial resistivity model, the finite element method is used for forward calculation to obtain the voltage value of each electrode combination. Then, by comparing the calculated and actual measured voltage values, the previously established initial resistivity model is modified via inversion. When the error between the calculated and measured values is sufficiently small, the corresponding resistivity model is considered the true resistivity distribution of the target body. Finally, the resistivity images of the detected fault zones can be obtained by means of discrete interpolation and smoothing. For more information on electrical resistivity tomography method, readers are advised to refer to the paper of Lu et al (2015). In this study, a total of 10 survey lines were set up around seven logging sites near the fault zone to obtain representative aquifer resistivity values. The E60CN 24-channel resistivity meter (made by GeoPen in Tsingdao,China) was used for resistivity measurements. A survey line was set up for each well log. The location of the survey lines is shown in Figure 1. There were 64 electrodes at a spacing of 2.5 m. The dipole-dipole configuration which showed a good resolution in both horizontal and vertical direction was used to acquire the apparent resistivity (Wilkinson *et al.* , 2012). Data acquisition was conducted at least three times, and the standard deviation was calculated until it was less than 10%, at which point the data were considered reasonable. The resistivity obtained from the inversion calculation of the apparent resistivity was derived as a resistivity file containing three-dimensional coordinates, so that the resistivity data of the aquifer could be filtered and analyzed. Then, the top, bottom, and lateral extents of the aquifer were determined according to the resistivity data of each survey line. The boundary of the aquifer was determined by averaging the high and low outliers.

2) Scheme with pumping test data

The complex structure inside the fault zone generally leads to different conductivity characteristics (e.g., hydraulic conductivity) from those of the surrounding rocks. However, the conventional pumping test can only obtain the average hydraulic conductivity of the aquifer, not the spatial distribution of the hydraulic conductivity in the fault zone region (Demir *et al.* , 2017). Therefore, this study combined the pumping test data and the ERT data to obtain the spatial distribution of the hydraulic conductivity of the fault zone. Figure 2 shows the flowchart of this scheme. The field hydraulic conductivity was calculated using the pumping test, and the data were fitted with the field-measured resistivity data to determine the quantitative relationship between the resistivity and the hydraulic conductivity. The resistivity data could then be converted into the spatial distribution of hydraulic conductivity, thus obtaining the hydraulic characteristics of the fault zone. In this study, a total of 30 pumping tests were conducted in seven well logs. The obtained data were calculated according to the Theis and Theis recovery scheme (Theis, 1935; Niwas and Singhal, 1981), and the hydraulic conductivity of the aquifer was determined by the average value calculated using the field test. In addition, the pumping test and the resistivity measurement were carried out separately. Therefore, the resistivity measurement results did not show the variations of the aquifer during the pumping process.

3. Results and discussion

Characterization of the fault sectors using ERT data

ERT measurements were recorded near the fault zone on August 24, 2010, using a dipole-dipole configuration. In total, 40 electrodes at a spacing of 2.5 m were used. The fault zone intersected with the survey line at 80 to 120 m, and the survey line and fault zone are at an angle of approximately 90 degrees. Given the dryness

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of the study area, the grounding of the electrodes and the accuracy of the raw data could directly affect the subsequent processing results. To ensure the quality of the measured data, the following measures were specifically taken during the collection of the field data: 1) before the measurement, the grounding resistance of each electrode in every array was checked and controlled under 2 kΩ· the watering method was used in the case of an excessively large grounding resistance; 2) in the measurement, the potential difference should not be less than 5 mV, and the current should be greater than 5 mA; in addition, the coverage measurement method was adopted for the electrode rolling data in the measurement process, and 50% of the data were re-tested for each rolling. The measured data were calculated by inversion using the method proposed by Lu et al (2017) to obtain the resistivity distribution of the fault zone in the study area.

Figure 3 shows the ERT exploration results in the study area. It can be seen from the figure that there are low-resistivity regions of 0-60 m and 130-200 m, with the resistivity below 600 Ω·m, while the resistivity in the region of 70-120 m was higher than 1100 Ω·m, exhibiting poor continuity between this region and the surrounding regions. It can be inferred that the lithology in this region is significantly different from that in the surrounding regions. According to the rock sample information of the borehole, this fault zone is dominated by fractured sandstone, which is mixed with gravel and rubble, so the resistivity is high. It is comprehensively determined that this region should be the one where fault zone is located, and the resistivity on the two sides of the fault zone does not differ very much. The fault zone does not show a significant dip angle near the surface but exhibits a pronounced trend of dipping toward the west at 5-30 m underground. However, under general circumstances, it is very difficult to determine the hydraulic conductivity characteristics of a fault zone simply based on the resistivity data, and the general pumping test can only generate results for the synthetic hydraulic characteristics of an aquifer. Therefore, this study combined the resistivity data with the pumping test data to obtain the relevant parameters of the hydraulic conductivity characteristics of the fault zone.

Relationship between the electrical resistivity and the hydraulic conductivity

According to the pumping test solution proposed by Theis (1935), the pumping data of seven aquifers in the study area were analyzed and calculated to obtain the hydraulic conductivity. Table 1 showed the pumping test configurations and calculated hydraulic conductivity of each well. The average field hydraulic conductivity at the seven sites was in the range of 1.62 to 4.12 m/d, with an average of 2.45 m/d. The standard deviation of hydraulic conductivity at each site was in the range of 0.34 to 3.12 m/d, with an average of 1.05 m/d. It can be seen that the calculation results are basically reasonable, and the permeability coefficient of the study area is in a small range, which is basically consistent with the rock properties in the area.

Sequently, the boundary of the aquifer near the pumping well was calculated and extracted from the ERT exploration results to calculate the average resistivity within the boundary of each aquifer, as shown in Table 2. The standard deviation is in the range of 2.14 to 331 Ω·m, and the average is 92.10 Ω·m.

The data were fitted using the data from 30 pumping tests at seven points and the average resistivity of the aquifer obtained from the seven ERT measurement sections. In this study, linear, exponential, and power fitting methods were used to fit the resistivity and hydraulic conductivity. Figure 4 shows the fitting results. The R^2 value of the linear fitting is the lowest ($R^2 = 0.8775$), and the R^2 values of the exponential fitting and the power fitting are relatively high (0.9723 and 0.971, respectively). The best fitting method may vary with the different lithological characteristics of the study area. Therefore, the exponential fitting result is used in this study as the relationship between the resistivity and the hydraulic conductivity, which is expressed as follows:

$$R = 8.14e^{1.23k}$$

where R is the average resistivity of the aquifer, and K is the hydraulic conductivity of the aquifer. According to this relationship, the hydraulic conductivity can be obtained by inputting the resistivity of the study area. The hydraulic conductivity of the aquifer is calculated based on the measured resistivity of the aquifer and is compared with that calculated using the pumping test. As it shown in Table 3, The calculated relative error is in the range of 1.6% to 10.5%, which is relatively small, and the Nash-Sutcliffe efficiency (NSE) coefficient

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of the two is 0.962, indicating that the calculation result is reasonable.

3.3 Characterization of the fault zone using the R-K relationship

According to the relationship between R and K, the resistivity distribution obtained from the exploration and interpretation of fault zone can be converted into the distribution of hydraulic conductivity, as shown in Figure 5.

It can be seen that the hydraulic conductivity distribution is similar to the resistivity distribution. The hydraulic conductivity values of the low-resistivity region of 20 m-70 m, the low-resistivity region of 130 m-180 m, and the high-resistivity region of 70-120 m are 3.2 m/d, 2.7 m/d, and greater than 3.7 m/d, respectively. The hydraulic conductivity of the fault zone region according to the resistivity exploration is 3.7 to 4.5 m/d, indicating a poor hydraulic conductivity. These results can further provide important parameters for the study of groundwater transport and the variability of aquifer media.

The identification of fault zone characteristics using resistivity has been widely used by many researchers. However, there are many uncertainties in ERT explorations. 1) During exploration, different electrode configuration schemes result in significantly different results. Although researchers have investigated the detection characteristics of different configurations, no unified quantitative conclusion has been reached, which poses substantial challenges to the identification of fault zone characteristics. 2) There is uncertainty in data inversion. At present, most inversion calculations rely on linear methods to solve nonlinear problems, causing certain accuracy problems. In addition, the inversion calculation results may be nonunique, thus increasing the difficulty of interpretation. To solve these problems, the dipole-dipole configuration method is used in this study, and this method is considered highly accurate due to the use of a large amount of data. The prior model proposed by Lu is used to improve the efficiency of the inversion calculation. However, due to some deficiencies and limitations of ERT, it is necessary to combine other data (such as other geophysical data) to obtain more accurate and detailed characteristics of the fault zone.

By combining the pumping test data with the resistivity data, the hydraulic conductivity characteristics of the fault zone region can be obtained, and the limitations of the separate use of pumping tests and resistivity explorations can be overcome. In this study, the hydraulic conductivity characteristics of the fault zone region were determined by establishing the R-K relationship, which can reduce costs. However, there are still some issues that need further discussion. 1) The R-K relationship is established only at the mathematical level, and its physical mechanism needs to be further studied through tests. 2) The applicability of the relationship may have some regional characteristics. A comparison with the relationship established by Jason shows that the method has good applicability in alluvial fan aquifers but may lead to some errors for sandstone areas with small hydraulic conductivity values.

Conclusion

In this study, the properties of fault zones were obtained using ERT and pumping tests. The results showed that the ERT exploration method can obtain some geometric characteristics of fault zones, such as the dip and width, but this method suffers from considerable limitations in terms of the acquisition of hydraulic conductivity characteristics of fault zones. By combining the pumping test data with the resistivity data, we established the quantitative relationship between the resistivity and the hydraulic conductivity to obtain the distribution of the hydraulic conductivity in the fault zone region. The results of this study have shown that, for the sandstone aquifer area, the results obtained by the power fitting are better than those obtained by the exponential and linear fittings. This relationship has certain regional characteristics. After the establishment of this relationship, the hydraulic conductivity characteristics of the fault zone can be obtained at a relatively low cost through nondestructive resistivity explorations, which is of great practical significance for the quantitative description of the groundwater movement process.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Table 1 The configurations and results for pumping test from each well

NO.	Hydraulic conductivity from pumping test (m/d)	The calculated hydraulic conductivity (m/d)	Relative error (%)	NSE
#1	1.27	1.15	9.43	0.962
#2	4.12	3.99	3.04	
#3	2.15	1.95	9.13	
#4	3.23	3.47	7.38	
#5	1.96	2.08	6.19	
#6	2.77	3.06	10.50	
#7	1.62	1.65	1.70	

Table 2 The electrical resistivity for each aquifer in field

Aquifer Number	The electrical resistivity for each aquifer in average (Ω·m)	Standard deviation
#1	33.50	8.75
#2	1108.24	331.00
#3	90.00	2.14
#4	580.00	124.00
#5	105.31	38.00
#6	351.27	124.00
#7	61.76	16.83

Table 3 The comparison of hydraulic conductivity from pumping test and R-K relationship

Figure Legends

Figure 1 The location of study area, pumping wells and fault zone

Figure 2 The scheme for characterizing fault zone with ERT and pumping test data

Figure 3 The electrical resistivity profile for the Fault zone

Figure 4 The fitting curves for R-K relationship by using different function

Figure 5 The hydraulic conductivity distribution for fault zone

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