Research of in-situ hydraulic test method by using double packer equipment

JI Rui-li*, ZHANG Ming, SU Rui, GUO Yong-hai, ZHOU Zhi-chao, LI Jie-biao
Beijing Research Institute of Uranium Geology, CNNC Key Laboratory on Geological Disposal of High-level Radioactive Waste, Beijing 100029, China.

Abstract: Double packer equipment for hydraulic test can be used to measure pressure of test zone directly, and it is frequently used to perform many kinds of hydraulic tests and take groundwater sample from borehole. The test method of this equipment mainly includes the test design, implementation, interpretation and synthetic analysis. By adopting the double packer equipment for hydraulic test, the parameter distribution of rock permeability along borehole can be acquired, as well as the connectivity, water conductivity and water bearing capacity of the disclosed structure and the chemical characteristics of the deep groundwater. It is a necessary method for the research and evaluation of the complex hypotonicity terrace site selection under geological conditions. This method is not only suitable for the geological disposal of high level radioactive waste, but also can be used in the site selection of underground facilities such as storage of petroleum and carbon dioxide. Meanwhile, it has a good application prospect in other hydrogeological investigation fields.

Key words: Lower permeability rock; Double packer equipment; Borehole; In-situ test method

Introduction

The high integrity of low permeability rocks usually generate rather enclosed hydrogeological units in the local area. The low permeability rocks, which are not tightly closed to the regional groundwater activities, can address the demands for hydrogeological conditions featured by little water contents, long-distance runoff and low hydraulic gradient and other high-level radioactive waste geological repository (National Nuclear Safety Administration, 2013). Therefore, these geological repositories can become the perfect candidates for the geological disposal sites of high-level radioactive wastes. Beishan area in Gansu Province has been selected as the key candidate site for geological repository, and granite is served as the host rocks (WANG Jun et al. 2006; SU Rui et al. 2007a).

The high integrity of rocks can generate rather enclosed hydrogeological units in the local area. Few people have achieved the hydrogeological investigation results in the Beishan area. In particular, there was no research found concerning the hydrogeological and hydrochemical characteristics in deep geological environment. The hydrogeological test by using double-packer equipment is one kind of well-developed borehole test technology for the purpose of acquiring rock permeability parameter and taking the original groundwater sample. This technology has been widely used in engineering geology, water resources investigation and evaluation, mineral exploration, environmental investigation and pollution control, and investigation of the geological disposal sites for the high-level radioactive (SU Rui et al. 2007b; WANG Hai-zhong et al. 2005; PANG Zhong-he et al. 2007; Adams J, 1994). Characters of granite including heterogeneity, anisotropy and low permeability pose a very high requirement for the equipment performance, in-situ test methods, data interpretation and comprehensive analysis of hydrogeological test performed in boreholes (WANG Jun et al. 2008). The double packer equipment installed...
Characteristics of target aquifer can then be obtained by implementing of hydrogeological tests in borehole. The original groundwater sample that reflects the hydrochemical environment of the target aquifer can also be taken from the target aquifer. Only one isolation point can be set when single packer equipment is installed in the borehole and the target aquifer cannot be isolated effectively. In contrast, there are two isolation points inside the borehole when double packer equipment is installed, and the target aquifer can then be effectively isolated. There are three or more isolation points inside the borehole when multiple packer equipment is installed in borehole.

Considering the fact that the costs of test equipment increase when more packers are installed, and procedure of the installation will be more complex, the double packer equipment is the perfect choice to meet the requirements for borehole test. Beijing Research Institute of Uranium Geology introduced the double packer equipment for hydrological test in 2005 through the Technical Cooperation project of International Atomic Energy Agency. Moreover, water injection equipment and original groundwater sampling interface were integrated in the double packer equipment. The double packer equipment has the deep-decline and low-flow water pumping capability. The original groundwater sample from certain aquifer can be taken from surface and the parameter measurement of permeability characteristics is combined to improve the capability of double packer equipment for hydrogeological tests in borehole. After the practical work in several projects, the well-developed whole-process work model of hydrogeological tests is established. The work model includes test design, preparation and implementation, data interpretation and comprehensive analysis, covers all procedures that should be included, and plays a positive role in the research on the evaluation of hydrogeological characteristics in deep geological environment through the geological disposal site of high-level radioactive wastes.

1 Principle of hydrogeological test by using double-packer equipment

The hydrogeological test equipment based on double-packer borehole can be divided into two parts, surface equipment and downhole equipment. These two parties create an integral whole in a real-time manner with other pressure transmission pipelines through cables, drill rods and pressure-tolerant nylon tubing. Of the surface equipment, the data collection equipment of pressure sensor is used to monitor pressure (or water head) changes in the section above the test section, test section and the section below test section. The high-precision electromagnetic flowmeter is used to measure the pumping (pressing) flow of test section during the test period (Fig. 1). The pressure control equipment is used for packer inflation and deflation, as well as the control of working states of Shut-in tool. The surface equipment also includes booster pump and industrial nitrogen. Based on the author’s practical experience for years, the hydrogeological test with the borehole depth not more than 600 m can choose the industrial nitrogen ($\leq 10$ Mpa, the maximum output pressure is about 6.6 Mpa) as the pressure source of packer equipment. The advantage of industrial nitrogen is the convenient pressure increase and decrease process. For safety reason, water should be used as the source of pressure for borehole deeper than 600 m (in such condition, high-pressure is needed for packer inflation).

Downhole equipment (Fig. 1) has the main components like packer, test tubing, Shut-in tool, drill rod, sensor carrier, sensor and pumping equipment. Two packers connecting with test tubing form a test section. In most cases, the lower isolation points of upper packer and the upper isolation point of lower packer are chosen as terminals of test section. The Shut-in tool within test section can be used to open or close the hydraulic connection between test section and ground. It’s the necessary component for Slug test, pulse test and water pressure test. Three sensors are installed along gage carrier to measure the pressure above test section ($P_1$), pressure in test section ($P_2$) and pressure below the test section ($P_3$). Specifically, $P_3$ can be read directly, and $P_1$ and $P_2$ can be transmitted to sensor through pressure pipe. This form of sensor installation is mainly used to check the packer’s sealing effects, increase the credibility of test data and discover the possible leakage during hydrogeological test in
borehole. The water pumping equipment includes small-diameter submersible pump and screw pump, whose ends are both connected with drill rods.

Fig. 1 shows the structure of downhole equipment inside borehole. The installation process follows the bottom-up and right-to-left order. After the equipment is installed, packer can be inflated and hydrogeological test can then be performed. The packer equipment is used together with submersible pump or screw pump to perform the water pumping test. In this way, any external interventions can be prevented and the original groundwater sample (PANG Zhong-he et al. 2007) can be taken from certain aquifer in borehole. There are two pressure input terminals in Shut-in tool, and terminals in Shut-in tool and packers are connected to pressure control equipment on surface through pressure tolerant nylon tubing. During Slug test, it’s only need to close this value, inject water into (or pump water from) the drill rod, and then open the Shut-in tool. As a result, there’ll be an instant change in the groundwater level within test section. If the Shut-in tool is closed again, then the subsequent test is pulse test. In China, the common practice is to place PVC tube and bucket into borehole to change the groundwater level, but it’s impossible to do this in a test section at a given depth range. When the water pressing ends during water injection test, the pressure recovery stage is started by closing the shut-in tool.

2 Hydrogeological test by using double packer equipment

The implementation of the hydrogeological test by using double-packer equipment in a test section usually involves several steps: (1) test design in which the length and isolation points of test section are determined based on the borehole drilling records, photos of rock cores, and sound wave-based televised measures for well measurement; (2) equipment installation in which the downhole equipment is installed at the expected depth according to the test design; (3) packer inflation to isolate test section and wait for the pressure balance within test section; (4) conduct test based on the chosen test method; (5) remove pressure from packer and conclude the test.

2.1 Water pumping test

The borehole-based water pumping test of low
permeability rocks is mainly used to evaluate the aquifer permeability and water-bearing capacity. The original groundwater samples are collected for each level. The aquifer inside the low permeability rocks usually has such features as inconsistent hydraulic connection and uneven water distribution. In this case, the continuous water pumping test may cause groundwater from different sources to get mixed in aquifer around the borehole, so the original groundwater hydrochemical environment in the rocks around the test section is changed. Swiss SKB (Sevensk Kärnbränslehantering AB) suggests the value of hydraulic conductivity $K > 10^{-6}$ m/s in fully penetration borehole as the basic condition for taking the original groundwater sample for each level (SKB, 2001).

Fig. 2 Diagram of pressure during pumping test in section Test03 of Borehole BS03

The stratified pumping test performed the hydrogeological test equipment with double-packer equipment has the similar process to the borehole mixed pumping test, a test method frequently used in China. These test methods both involve two parts, water pumping and pressure recovery. During the water pumping test, three sets of pressure data are used to identify the packer’s isolation effect and the phenomenon of leakage. (1) If $P_2$ and $P_1$ (or $P_3$) roughly get overlapped as the time variation curve moves during the test, we can know that the packers do not work well and the test section is not isolated effectively. (2) If $P_2$ and $P_1$ (or $P_3$) show the same trend during the test and $P_2$ increases higher than $P_1$ (or $P_3$), we can know that leakage happens. Take BS03 borehole-based Test 19 for example (Fig. 2). It’s clear that groundwater from section below flows up into test section after the water pumping test starts. Lower part of test section is a leakage aquifer, and there’s no hydraulic connection between the test section and section above. Then, when the changes of $P_2$ and $P_1$ during the suspension of water pumping test on two occasions are considered, we can then make sure that the packer has effectively isolated test section during the water pumping test and there’s no hydraulic connection between shallow groundwater and test section. The penetration coefficient within this test section can address the sampling requirements and provide the original groundwater sample for the isotope-based hydrochemical analysis (PANG Zhong-he et al. 2007).

2.2 Slug test

Slug test, also known as hammer test, is an important test method for studying the permeability of the middle and low permeability rocks. The test principle is to change water level in borehole instantaneously, and the water-level changes are recorded. After the treatment of the water level-time response curve (Fig. 2), it can be used to estimate the aquifer permeability coefficient (SU Rui et al. 2007b; Butler Jr J J, 1997). Taking BS03 borehole Test 26 for example (Fig. 3) water level of test section is changed by injecting water inside during the Slug test. The
main steps concerned include (1) installation of test equipment, (2) packer inflation to isolate the hydraulic contact between test section and other sections in borehole; (3) closing the Shut-in tool and injecting water into test section through drill rod; (4) opening the Shut-in tool and then water level in test section recovering; (5) waiting for the water level recovering to static water level and then finishing the test. When compared with the whole-hole Slug test with heavy objects inside drill hole or by raising water through bucket, the Slug test using double packer equipment can be conducted in certain depth range in the borehole. The Shut-in tool and packer can be used together to achieve water-level change instantaneously in test section. So the test proves to be faster, more convenient and flexible, more reliable in terms of test equipment and more adaptable to borehole condition.

![Diagram of pressure during slug test in section 26 of Borehole BS03](image)

**Fig. 3** Diagram of pressure during slug test in section 26 of Borehole BS03

### 2.3 Transient flow constant head injection test

The regular water injection tests, which are commonly used in China, are performed based on three-level pressure additional or five-level steps. The observation and stability standard, and P-Q curve mapping for the water flow and pressure during the test are based on the Procedures of the Borehole Water Pressure Tests for Hydraulic and Hydropower Projects. The characteristics of flow regimes are classified based on the type of P-Q curves and the formula is used to calculate water permeability and permeability coefficient within test section (WANG Hai-zhong *et al.* 2005; ZHANG Ming *et al.* 2014).

The transient flow constant head injection test is used in the granite formation in the Beishan area. The foreign experiences in water injection tests are considered and the in-situ practices are used to develop the test process: The water pressure lasts for 20-30 minutes. When the water pressure test gains the steady flow, the Shut-in tool is closed and the water level in test section starts to recovery to static water level (JI Rui-li *et al.* 2014; ASTM International, 2008ab; Hamm Se-Yeong *et al.* 2007; Cristian Enachescu *et al.* 2007). Very slow pressure recovery process is frequent in very lower permeability rocks, which often needs several hours and even longer to recover to static water level. The pressure difference of downward water pressure stage within the five-minute test section (20%) is set as the evaluation basis for determining whether the pressure recovery will continue or not. When compared to the regular water pressure tests in China, the main difference is that (1) the test process includes two stages, water pressure and pressure recovery; (2) only one pressure difference value is used in water pressure stage; (3) the flow changes during water pressure stage are recorded as time goes by.
2.4 Pulse test

Pulse test, also known as the closed Slug test, is a test technology used in the oil industry to estimate the natural pressure of oil reservoirs. Since the 1990s, this test technique, which is used to estimate the permeability parameter of low permeability rocks, have been widely used in the hydrogeological investigation of groundwater, and the investigation and evaluation of geological disposal sites of radioactive wastes.

Taking the pulse water injection test for example (Fig. 5), after the water level within test section is changed by opening the Shut-in tool, the Shut-in tool will then be closed again in a pulse test. From this time point, pulse test started. Referring to the method and standard of ASTM pulse test, when the coefficient of transmissivity of the test section is $10^{-11}$ m/s, pulse test will last for $10^6$ s (about 12 days) while Slug test will last for more than $10^9$ s (about 1 574 days) (ASTM International, 2008ab). Based on the pressure change within the test section prior to and following the SIT closure as indicated in Fig. 5, we’ll find that the pulse test usually lasts for a much shorter period than the pressure recovery.
period in Slug test.

2.5 Basis for the selection of test methods

The water pumping test, slug test (also known as glug test, hammer test and impact test) (SU Rui et al. 2007b; YUAN Guo-hong et al. 2009), water pressure test and pulse test can be used in the borehole of low permeability rocks. Each test method has its own technical characteristics and applicable conditions (Table 1). When the test methods are selected, it’s imperative to refer to the borehole geological condition, integrity of rock cores within test section, requirement for in-situ test time and financial investment, and instruments and equipment can be used. If original groundwater samples can be taken from the borehole, the in-situ test should start with the water pumping test, and then select other methods to continue the test after the groundwater samples are taken.

<table>
<thead>
<tr>
<th>Name</th>
<th>Technical characteristics</th>
<th>Coefficient of transmissivity (m²/s)</th>
<th>Coefficient of hydraulic conductivity (m/s)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water pumping test</td>
<td>Long test period</td>
<td>5×10⁻⁷–10⁻²</td>
<td>More than 10⁻⁶ (SKB, 2001)</td>
<td>Monitor the groundwater tracer and isotopic concentration to collect samples</td>
</tr>
<tr>
<td>Slug test</td>
<td>Simple operation, low cost, no need for water injection into borehole, and no change in hydrochemical environment inside borehole</td>
<td>10⁻⁸–10⁻⁴ m²/s</td>
<td>10⁻⁹–10⁻⁶ m/s (Mejias Miguel et al. 2009)</td>
<td>Uncertain test time and repeat at least twice for each test section</td>
</tr>
<tr>
<td>Unsteady flow water pressure test under given pressure</td>
<td>Uncertain test time, and water injection during test affects the hydrochemical environment inside borehole</td>
<td>10⁻⁹–10⁻⁴ m²/s</td>
<td>10⁻¹²–10⁻⁶ m/s (Mejias Miguel et al. 2009)</td>
<td>Include the pressure recovery stage and no need for steady flow</td>
</tr>
<tr>
<td>Pulse test</td>
<td>Simple operation, low cost, no need for water injection into borehole, and no change in hydrochemical environment inside borehole</td>
<td>10⁻¹²–10⁻⁷ m²/s</td>
<td>10⁻¹⁴–10⁻⁹ m/s (Mejias Miguel et al. 2009)</td>
<td>Uncertain test time and repeat at least twice for each test section</td>
</tr>
</tbody>
</table>

Notes: The coefficient of transmissivity is cited from the technical materials of heavy-duty packer equipment provided by the Swiss Solexerts Company.

Time costs of a transient flow constant head injection tests are almost the same, and work plan of the in-situ test will be easy to confirm by using this method. The injection method fits a large variety of applicable permeability parameters in test section. When the test is finished, the reference value of permeability coefficient can be obtained quickly. The applicable permeability parameters within test section have the similar scope of use for Slug test and transient flow constant head injection test, and time costs of Slug test are difficult to estimate. To address the requirements for on-site work plan, the method of transient flow constant head injection test involved in the site investigation of Beishan area in Gansu Province has been widely used. In this area, water consumption during drilling of some 600-m boreholes is about 10-20 tons, and water flow rate during the water pressure test with 12 m-long test section is often less than 0.01 L/min. sometimes, it’s hard to measure the change of water flow rate during water injection test. In that condition, in-situ test method model combining pulse test and water injection test at the same time is established to reveal the very lower permeability rocks (Fig. 6). In this test model, the pulse test starts first, and the pressure recovery rate within test section is observed five minutes later. (1)When the pressure recovery ratio reaches 20%
of the original pressure change value, the pulse test is concluded and the transient flow constant head injection test starts. (2) When the pressure recovery ratio doesn’t reach 20% of the original pressure change value, the pulse test will continue.

![Fig. 6 Test procedure flowchart of constant head injection test and pulse test](image)

**Fig. 6 Test procedure flowchart of constant head injection test and pulse test**

![Fig. 7 Interpretation of Slug test of section 26 in borehole BS03](image)

**Fig. 7 Interpretation of Slug test of section 26 in borehole BS03**

### 3 Analysis of test results

#### 3.1 Slug test

There’re more than fifty Slug test data interpretation theory models (including improvement models). The widely accepted and used models mainly include Hvorslev model, Cooper model, Bouwer model, Rice model and KGS model (SU Rui et al. 2007b) and the data interpretation software used in China and abroad, such as Aqtesolv, AquiferTest and FlowDim all include these theory models. Taking BS03 borehole Test 26 for example, the parameters and test data like length of test section and initial waterhead difference are input into the software Aqtesolv, and Bouwer and Rice methods are selected for type curve matching test data and their derivatives (Fig. 7), and hydraulic conductivity of test section \(1.849 \times 10^{-9} \text{ m/s}\) is then estimated. The initial water head difference \(y_0\) is almost consistent with the measurement value of test data.

#### 3.2 Transient flow constant head injection test

The data interpretation method for transient flow constant head injection test is described in detailed by the Comparison of the Data Interpretation Method of Water Pressure Tests under Given Pressure in New Fields. When the
water flow rate during water pressure stage gets steady, we can use Hvoslav formula, Moye formula and USBR formula to calculate (JI Rui-li et al. 2014; Hamm Se-Yeong, et al. 2007; Cristian Enacheu et al. 2007) the reference value of permeability coefficient within the test section so that we have a rough idea of the depth-based distribution characteristics of rock permeability inside the borehole. In the indoor analysis, Aqtesolv software is used to interpret the test data during the water pressure stage (the left part of Fig. 8) and during the pressure recovery stage (the right part of Fig. 8). When the theoretical curve-fitted test data are used, the water storage coefficient and the coefficient of transmissivity have the experience formula \( S = 0.0007 \cdot T^{0.5} \) (Johan Harrström et al. 2007) to estimate the reasonable reading of water storage coefficient and reduce the influence of human factors on data interpretation process.

When S-T experience formulas are used to fit the test data curve, the following steps should be followed. (1) The initial value \( S_0 = 10^{-6} \) is assigned to water storage coefficient, and this parameter is set as a constant in the fitting process and other fitting parameters are set as variables. (2) Match toolbox can conduct the manual adjustment of variables to make theoretical curve come close to the test data. (3) The automatic parameter-solving functions are used to solve all the variables. (4) The fitting-generated coefficient of transmissivity \( T_1 \) is substituted into the S-T experience formula to obtain \( S_1 \). (5) Like Step 1, \( S_1 \) enters into Aqtesolv software as the known number, and the coefficient of transmissivity is obtained through the automatic fitting. (6) Step 4 and 5 are repeated through multiple iterations until \( S_n \) and \( S_{n-1} \) become roughly consistent with each other.

**Fig. 8** Interpretation of constant head injection test of section 11 in borehole BS20

### 3.3 Pulse test

Pulse test can use one simple calculation method of permeability parameter (Ludvigson Jan-erik et al. 2007):

\[
T = \frac{Q_{ave(f)}}{dh_f} = \frac{(Q_{ave(p)} + C_{eff} \times dp/dt)}{(dh_f)}
\]

Where \( Q_{ave(p)} \) and \( C_{eff} \) are the equipment constants concerned,

- \( T \): Coefficient of transmissivity within the test section \((m^2/s)\)
- \( Q_{ave(f)} \): Average flow rate of peripheral rocks within the test section \((m^3/s)\)
- \( Q_{ave(p)} \): Flow rate generated by the change of packer volume \((m^3/s)\)

\( C_{eff} \): Water storage coefficient of effective boreholes within the test section \((m^3/Pa)\)

\( dp/dt \): Pressure change mean of test section during pressure recovery stage

\( dh_f \): Initial waterhead difference of pulse test \((m)\).

The test section in borehole BS22 in the Beishan area is a good case in point. This borehole has a diameter of 95 mm, and the diameter of packers before inflation is 86 mm and the length of test section is 12.45 m. When the initial water head difference of pulse test, namely \( dh_f \), is no more than 60 m, \( Q_{ave(p)} \) is \( 6.36 \times 10^{-9} \) \( m^3/s \) and \( C_{eff} \) is \( 1.60 \times 10^{-11} \) \( m^3/Pa \). So we can calculate and obtain \( T \), the coefficient of transmissivity within test section.
Table 2 Transmissivity calculation sheet of pulse test

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{\text{ave}(p)}$</td>
<td>$6.86 \times 10^{-9}$</td>
<td>m$^3$/s</td>
</tr>
<tr>
<td>$C_{\text{eff}}$</td>
<td>$1.60 \times 10^{-11}$</td>
<td>m$^3$/Pa</td>
</tr>
<tr>
<td>$\frac{dp}{dt}$</td>
<td>4.608</td>
<td>Pa/s</td>
</tr>
<tr>
<td>$Q_{\text{ave}(f)}$</td>
<td>$7.083 \times 10^{-9}$</td>
<td>m$^3$/s</td>
</tr>
<tr>
<td>$\Delta h_f$</td>
<td>32.010</td>
<td>m</td>
</tr>
<tr>
<td>$T$</td>
<td>$2.213 \times 10^{-10}$</td>
<td>m$^2$/s</td>
</tr>
</tbody>
</table>

4 Conclusion

The double-packer hydrogeological test system can be used to perform multiple types of in-situ tests, and can be especially used to take the original groundwater sample from target aquifer in borehole. The test system is very useful and valuable for hydrogeological investigation in low permeability formation.

The hydrogeological test using the double-packer system involves test design, test implementation, test data interpretation and analysis, and plays a positive role in site characterization and evaluation for the geological disposal of high-level radioactive wastes. This test can also be used in the site selection of oil reserves and underground projects like carbon dioxide disposal process and in other similar regional hydrogeological investigation.

References


