Preliminary evaluation of the rock mass permeability of a granite site based on sonic logging

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Abstract. It is of great value to reasonably obtain the permeability characteristic value of a site’s bedrock, especially for the deep rock mass space excavation, site layout design, and subsequent effective management of some major engineering sites. Previous studies have found that the permeability of water-bearing media decreases with depth, and the compressional wave velocity can be used to estimate the permeability coefficient. Taking a preselected granite site as an example, we used deep borehole acoustic logging technology to obtain the longitudinal wave velocity data at different depths. The empirical relationship between the longitudinal wave velocity and the permeability coefficient in the granite field was further used to obtain the permeability coefficient at different depths of a borehole in the study area; we then compared these data with in situ borehole water pressure test data and found that the empirical relationship between the longitudinal wave velocity values and the permeability coefficient values at different depths cannot be directly applied. For example, the permeability coefficient increased sharply at −405 m to −425 m, instead of continuing to decrease according to the previous law, the measured value was 1 orders of magnitude larger than the empirical value. Through comprehensive analysis of the borehole acoustic testing of the longitudinal wave velocity changes and the corresponding core data, it can be preliminarily determined that the permeability characteristics of the deep rock mass in this area are obviously influenced by the geological structure.

1. Introduction
The permeability coefficient is one of the most important hydrogeological parameters in the evaluation of bedrock permeability characteristics. The study of the permeability coefficient value is one of the bases for exploring underground water flow and nuclide migration rules, which is of important reference value for the design and construction of major underground engineering structures [1, 2].

The most direct way to study the permeability characteristics of rock mass is to select the in situ water pressure test, but the deep-hole-type equipment often needs to be customized [3], and each time a test process is completed, it takes time and effort to attain rich results. The borehole hydrological parameters need to pass a long test period; in addition, the special drilling TV and other drills are intuitive, but the price is relatively expensive, and only a few state-level scientific research units have the related instruments [4]. Geophysical technology has the characteristics of short cycle and relatively low cost, especially the introduction of physical wave technology. At present, a series of discussions
on the variability of the permeability coefficients of aqueous media have been carried out in combination with actual engineering [5, 6] in some experiments. Studies have shown that the rock mass permeability coefficient decreases with increasing normal stress [7, 8], which directly shows that the rock mass permeability coefficient decreases with increasing buried depth [9]. For example, Literature [10] found that some rock mass mean values and RQD mean values have good correspondence. Literature [11] used a large number of statistical datapoints from granite bodies in a pumped storage power station and different depths of longitudinal wave velocity. A correlation between the mean longitudinal wave velocity and the mean value of the permeability coefficient was found. As the depth increases, the acoustic wave velocity of the rock mass will increase significantly and the permeability will decrease, and the corresponding empirical formula can be constructed for similar fields for use in practical applications. Therefore, it is usually used as an indirect method to evaluate the quality of engineering rock mass, and it has the advantage of a simple test procedure for deep hole evaluation at a site.

In summary, combined with the research and development of waste geological disposal, it is necessary to evaluate the influencing factors of the permeability characteristics of the rock mass in the relevant field. The paper takes a preselected field as an example and uses the wave drilling technique to evaluate the characteristics of the deep rock mass. We hope that this study will provide new and more reference materials for the effective identification of the dominant factors of the spatial variability of rock mass permeability in major engineering sites.

2. Engineering background

In this paper, the focus site is located in the no man’s land in northwest China, at a waste disposal primary inland area. The climate is dry with little rain. Through geology and site survey, the disposal of the rock lithology was found to be relatively singular, with basically no alteration, mainly due to the density of granite. No obvious traces of modern tectonic movement were observed in fractures, and the crust is relatively stable [12]. A drilling project was arranged in the selected site area and completed around 2011. The drilling depth was about 600 m. A study on the basic rock characteristics of the borehole showed that the deep rock characteristics are similar to those of the surface and belong to the category of granite, and the depth included the waste disposal reservoir (500 m to 600 m) studied. Acoustic logging testing was carried out by using the borehole after its completion.

3. Test equipment and principle

Generally, drilling and coring techniques have shortcomings such as insufficient core recovery, unreliable core quality, and incapability of accurately obtaining the original occurrence of rock structure or fissure information. Acoustic logging tests are used in engineering surveys. They have been widely recognized as a technique for supplementing surveys to identify defects within the rock mass.

In the face of possible high water pressure and other practical problems, first of all, according to the logging depth and working conditions of acoustic transducers, we specially developed a set of underwater borehole acoustic logging transducers, namely, piezoelectric ceramic dual logging transducers. Furthermore, a special deep-hole cable for logging (a 600 m field test can be realized, but only a 400 m test was carried out in this paper) was customized according to our needs. Meanwhile, a set of acoustic multifunctional sonometers was customized as the data interpretation platform.

In order to ensure that the transducer was centered in the field test, a rubber centralizer was set on each transducer to guard against instruments becoming stuck due to the uneven borehole walls in some holes. Another set of custom-made steel frames with uniform and even falling sections ensured that the acoustic transducer could fall to a fixed position stably and record data.

We customized a set of cables; the length was 600 m, with a single cable (including one transmitting cable and two receiving cables) inside waterproof and insulating rubber. The acoustic transmitting module and double receiving module were placed in the ceramic body of the transducer.
Basic principle of acoustic logging: This test was carried out by means of a double-detection method, it is shown in Figure 1(a). We placed one transmitting and two receiving transducers on the axis of the borehole. The borehole was filled with water, and the ultrasonic wave from the transmitter $F$ entered the rock through the water and glided along the hole wall, reaching receivers $S_1$ and $S_2$, respectively. The propagation times $t_1$ and $t_2$ of sound waves from emission to $S_1$ and $S_2$ were measured on the ultrasonic instrument, then the wave velocity $v$ of the rock mass in the hole wall was calculated by the following equation:

$$V = \frac{\Delta l}{t_2 - t_1}$$  \hspace{1cm} (1)

where $\Delta l$ is the distance between the two receivers.

According to relevant research experience, 1 m was used as the test interval. After the completion of the test, the data obtained on site were returned to the laboratory for statistical collation and interpretation on the computer, it is shown in Fig. 1(b).

![Image](image1.png)

(a) Principle of acoustic logging  
(b) Interpretation of first-break waves  
Figure 1. Principle and interpretation of acoustic logging.

The first arrival point of a double wave is read by a double receiver of a sound wave, and the time difference between the two waves is read; the wave velocity is then converted according to the difference in distance between the measured acoustic transducer and the receivers.

4. Correlation analysis of ultrasonic wave velocity and geological factors in the site area

We used formula (1) to extract the longitudinal wave velocity of the borehole in the ranges of $-360 \text{ m}$ to $-430 \text{ m}$. The results after indoor data interpretation and correction are shown in Figure 2, where $V_p$ represents the longitudinal wave velocity; the wave velocity generally shows an increasing trend with depth (as shown by the red dotted line in Figure 2), and from $-360 \text{ m}$ to $-430 \text{ m}$ the wave speed increased by nearly 400 m/s, but in the range of $-405 \text{ m}$ to $-425 \text{ m}$, the acoustic wave velocity decreased sharply, from an average of 5500 m/s to 3600 m/s. It needs to be explained here that no further correction has been made to the wave velocity according to lithology, so it is the value of relative wave velocity. The obtained wave velocity data are based on the test results of some indoor samples, so they can be used for rough calculation.

![Image](image2.png)

Figure 2. The sound wave preliminary logging curve of the studied borehole (relative wave velocity values of some sections, no further correction).

The core data were retrieved for further verification. The lithology revealed by the whole borehole was dominated by monzonitic granite. According to the information published by the Beijing Research Institute of Uranium Geology, more than 100 fractures in the core were obviously divided into a tectonic fracture zone with a depth of $-408.90 \text{ m}$ to $-414.26 \text{ m}$, which is equivalent to the range defined by the sonic test. According to the RQD value, the rock quality is excellent, accounting for 87.38% of the total core, and 8.05% of the core is good.
Using the empirical relationship, given in formula (2), of the correlation between the mean value of the longitudinal wave velocity and the mean value of the permeability coefficients of granite depths proposed in reference [11], we perform some calculations:

\[
K = 3001.1 V_p^{-7.847}
\]  

(2)

where the unit of \(K\) is (m/d) and the unit of \(V_p\) is (km/s).

The average permeability coefficient of the fracture zone in the typical zone is \(1.0 \times 10^{-5}\) m/s. The mean value of the permeability coefficient corresponding to the wave velocity of the acoustic wave at different depths is \(1.0 \times 10^{-6}\) m/s.

According to the field penetration test data[13], the measured permeability coefficient of Test35 with a depth of \(-304.47\) m to \(-314.68\) m was \(9.49 \times 10^{-9}\) m/s, and the permeability coefficient of Test05 with a depth of \(-406.47\) m to \(-416.68\) m was \(1.4 \times 10^{-7}\) m/s; most of the other infiltration data were discrete, and most of them were between \(1.0 \times 10^{-10}\) m/s and \(1.0 \times 10^{-12}\) m/s. The calculated permeability coefficient of the broken zone wave velocity was about 1 orders of magnitude different from the measured permeability coefficient, while that of the other complete rock mass was 2 to 7 orders of magnitude different from the in situ water pressure. Therefore, the empirical formula proposed previously is not applicable to this area.

It is generally believed that the overall permeability of the borehole (discrete data tend to decrease as a whole) corresponds to the increase of the acoustic wave velocity of the borehole, and the fundamental reason for this phenomenon is that the fissure rate or porosity of the rock layer decreases with increased burial depth. However, according to the corresponding analysis of the abovementioned wave velocity and field hydrological test data, the relation between the permeability coefficient value and depth is not obvious. In essence, the geological structure, lithology, and gravity stress of the surrounding rock, the structural plane degree of consolidation, and other factors will affect the medium permeability. Currently, the leading factor in the control of space variability of rock mass permeability is not gravity stress: further combination with core data shows that the geological structure (faults) may play a dominant role. It can be seen from the above analysis that the acoustic logging wave velocity is sensitive to the tectonic rock mass, and the preliminary evaluation and division of the permeability in this area is reliable. Then, the corresponding values of wave velocity and permeability coefficient in this area can be summarized, and the corresponding characterization scheme is a feasible idea.

5. The value of acoustic logging in the detection of the permeability characteristics of a deep rock mass

Large foreign underground laboratories (such as Swedish laboratories) have joined the fault and fracture system with the coupling model of hydrological parameters through many years of systematic experimental research. It can be seen that it is necessary to establish a nuclear transfer and safe operation for the disposal library. In consideration of this, we need a more accurate hydrological prediction model, which requires a large amount of experimental data to be applied. At present, other countries have carried out experimental tests at different scales in real test sites along with further multifield coupling simulation work and have obtained good results. However, there are few prediction models for coupled water–conducting parameters of multiscale structural planes in China. They are still in the exploration model of the repository and the exploration mode of the disposal method. Seepage simulation inside the relevant fractures is more complicated and needs to be selected. An appropriate fracture model is used as the carrier. At present, which ever model is selected and used in the partial test, the calculation is not too complicated and the simulation is guaranteed to be true. This is still subject to debate and argument.

Due to the late start of related research in China, it is not difficult to think about the characteristics of the candidate site in the granite area as they relate to results obtained at home and abroad. More prominently, the related 3D model is even hindered by the establishment of refined parameter assignments with characteristic parameters. Therefore, it is urgent to solve large-scale structural planes such as faults and to rationalize the permeability coefficient values and the permeability characteristics
of small-scale structural planes to nuclide migration. Targeted impact experiments are particularly urgent. As mentioned above, the traditional test method is expensive, and the current direct conversion result of deep sonic testing is obviously not applicable to the evaluation of the site area or the correspondence is not satisfactory. Therefore, for research content and subsequent research thinking, the next step should be based on full consideration of the structural factors, the relevant data can be corrected, and then the acquisition of new acoustic test data and an empirical formula for the permeability characteristic parameters can be obtained. This should be useful for modeling the nuclide transport of large-scale structural planes within the site.

6. Conclusions
1. By analyzing a partial hole section of the deep rock mass, it was confirmed that the rock mass of the area is excellent in quality, and the quality is sensitive to the specific section of the rock mass. More specifically, one location (at a depth of −405 m to −425 m) had a reduced wave velocity of 3600 m/s in this interpretation, which also indirectly indicates the superiority of the rock mass quality conditions in the site area. It should be noted in this paper that the current data processing is only preliminary, and the acoustic data may need to be further corrected according to the lithology analysis.

2. Due to the existence of fractures or jointed zones and fracture development in the deep part of the rock mass, the existing acoustic wave velocity–permeability empirical formula cannot evaluate the permeability of the pre-selected granite body and should be specifically analyzed. However, the relationship between sound wave data and permeability is of reference value and can be further explored.

3. Because the speed of sound wave logging is convenient, it is not necessary to carry out large-scale penetration testing, and it becomes a means to indirectly compare the permeability change of deep rock mass, reduce the unnecessary workload, and initially control the site area. The water section is identified, but the complete rock mass is correlated, and then the acquisition of new acoustic test data and an empirical formula for the permeability characteristic parameters can be obtained. This should be useful for modeling the nuclide transport of large-scale structural planes within the site.

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