The Feasibility of Low Field NMR Technology in Geotechnical Engineering

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Abstract. In recent years, the nuclear magnetic resonance (NMR) technique has been applied in a relatively small scale, which includes soil, rocks, coals, concrete and so on. In this paper, the author indicate the theoretical background of NMR in short words and explain the measurement methods of T1 and T2 relaxation. Then the important parameters that have great impact of the result is emphasized. After introducing the representative research scope in soil, rocks, coals and concrete, the advantages and limitation of the NMR application are clear. Although the result of the NMR test is not accurate totally, the trend is correct and the accuracy is trusted in geotechnical engineering.

1. Introduction
The materials in geotechnical engineering always have complex porous structure, and these pores have great impact on the engineering characteristics. For the geotechnical material, there are various forms of pores existing like gaps, cracks and normal tiny pores, which are full of liquids and gases. Destructive behavior could change the arrangement of particles randomly, resulting in the weakening of physical and mechanical properties. Because the change of the microstructure characteristic is the reason of the macroscopic behavior, it’s crucial to make the rule clear [1-3].

NMR technology has been successfully applied in medical diagnostic, oil exploration, agricultural food science and biomedicine. At present, the observation of geotechnical materials microstructures is mainly based on image analysis techniques, like electron microscopy and CT scans which are limited to poor integrality [4]. In recent years, with the popularity of low field NMR technology, the problems of pores in geotechnical materials can be explained more clearly.

In fact, because of the influence of the parameter selection, the low field NMR machine is not as simple as it looks. The parameters value is acquired by experience during the operation, which means that the experimental results are influenced by individual experience.

2. Theoretical support

2.1. The origin of T2
The nucleus always spins around its own axis at a constant frequency. The magnetic field could be generated by spin, when the protons are odd and the neutrons are even. The H element in water in line
with this law, that we could estimate the water content by the number of the H element. So the way to get the number of the H element is the crucial problem to solve the question.

In general, each proton spins randomly arrange in random order, so that the magnetization vectors cancel each other out. Therefore, the water does not show a macroscopic magnetization vector. After put in the magnetic field, the protons enter the nuclear magnetic state (figure.1).

![Figure 1. Enter nuclear magnetic state](image)

The precession causes the magnetic field of each proton to have a directionally stable longitudinal magnetization vector and a rotating transverse magnetization vector. There are slightly more protons in the low-energy state than in the high-energy state, thus producing a macroscopic longitudinal magnetization vector. The magnetic resonance (MR) cannot detect the longitudinal magnetization vector, but the rotating transverse magnetization vector can be observed. Then we need a 90° pulse so that the microscopic transverse magnetization vectors of the protons are summed to produce a macroscopic transverse magnetization vector. Finally, the MR detects the rotating transverse magnetization vector which cuts the magnetic line of force.

After the RF pulse is stopped, under the action of the main magnetic field, the lateral macroscopic magnetization vector gradually decreases to zero, and the longitudinal macroscopic magnetization vector gradually returns to equilibrium from zero. The T1 value is the time when the macroscopic longitudinal magnetization vector recovers to 63% maximum value. And the T2 value represents the time required for the transverse magnetization vector to decay to approximately 37% maximum value.

2.2. The parameters that affect T2 value
Assuming the shape of the pore is ideally same as it set and the condition for the fast diffusion regime is satisfied, the diffusion time can be neglected. Then the relationship of pore radius R and T2 could be established:

\[
\frac{1}{T_2} \approx \rho_2 \left( \frac{S}{V} \right)_{pore} = \rho_2 \frac{\alpha}{R}
\]

(1)

In the formula (1), the \( \rho_2 \) is the surface relativity, which is determined by the test material. There is a linear relationship between the \( \rho_2 \) and R. The experimenter cannot ensure exact value of \( \rho_2 \) that could affect the absolute value of the pore radius. S is the surface area of the pore and V is the volume of the pore water. For the shape factor \( \alpha \), the pore of the material always is assumed as planar pores, cylindrical pores and spherical pores, the value of which are 1, 2 and 3 respectively.

2.3. The choice of pulse sequences.
A series of radio frequency pulses, gradient pulses and signal acquisition designed are arranged in a certain time series for different purposes, called pulse sequences. There are some used sequences that frequently used below (Figure 2).
The FID sequence is the simplest sequence to get $T_2$ that only contains cyclic 90° pulses. This consequence is inaccurate because of the non-uniform of the magnetic field. This problem can be solved by adding a 180° pulse between the 90° pulses, which is called Spin-Echo sequence. The CPMG sequence adds several 180° pulses between the 90° pulses so that the $T_2$ value gets more accurate. The IR sequence can be used to measure the $T_1$ relaxation.

3. Practical application

3.1. Rock text based NMR
The NMR technology can detect the damage of the rock under freeze-thaw cycles, which includes the surfaces changes and the porosity changes. Also the NMR images are obtained to observe the internal structure during degradation evolution. The results of the NMR text match up with actual observations. But it can be seen that, the image from NMR is dim [5]. Since the geotechnical sample does not easily reach fully saturation, the porosity is measured by the T2 relaxation time which will be equal to or slightly less than the effective porosity in the rock. Even though, the NMR technology provides a non-destructive testing method for rock experimental studies [6]. All in all, it obviously that NMR technology is mainly used in rock’s damage by external forces, hydration, temperature changes, and chemical reactions [7-8].

3.2. Soil text based NMR
Soil is consists of different particles so that it’s more likely to reach full saturation than rock. The water in the soil includes free water and adsorbed water, which has a great influence on the mechanical properties of the soil. The distribution of the pore size is one of the key problems for soil, which can be detected by NMR technique. The distribution of unfrozen water in soil is discussed combining with the T2 value curve from the microscopic point of view under the temperature change [9] and the adsorbed water content of the soil with the help of NMR is analyzed [10]. NMR is a direct and accurate method for studying the microstructure of materials. NMR can be used to test the pore structure of high water content soils such as silt. The variation of pore size and pore size distribution of silt under typical loading conditions could be performed [11].
3.3. Concrete text based NMR
As one of the most commonly used artificial building materials in the world, the concrete refers to the collective name of an engineering composite material in which an aggregate is cemented into a whole by a cementitious material. There are a lot of closed pores in the concrete which contain air or water. The closed pores in the concrete limit the application of the NMR to get a precise value of the porosity. However, the variation of the water content in certain condition could be tested. SHE AnMing and YAO Wu take the advantage of NMR to detect the hydration process of composite cement pastes blending fly ash and silica fume during the early age by the analysis of T1 evolution curves [12]. NMR technology can be used to detect the damage of concrete from freeze-thaw cycles [13-14].

3.4. Coals text based NMR
Coal is an ancient flammable mineral that plants buried in the underground undergoes complex biochemical and physical chemical changes. The low field NMR is used to detect the wettability by the distribution of different peaks’ of T2 [15]. Yanbin Yao el. develop an NMR-derived permeability model by explore the relationship of the coal permeability with the moisture migration characteristics [16]. Based on the NMR technology, the method for characterizing the methane adsorption capacity of coals is developed [17].

4. Conclusion
The domestic nuclear magnetic resonance test mainly uses the instruments that developed by Newmag company in Suzhou. The author has the chance to try the signage equipment in this company with soil samples from Hangzhou (Figure 3).

Figure 3. The pictures of NMR

NMR is a direct and accurate study of the microstructure of matter method. Inevitably, and there are instrumental errors and human operation errors during test. However, the choice of suitable parameters is also a crucial problem that influences the results of pore distribution test. According to the author's attempt experiment, the value of \( p_2 \) and the shape factor \( \propto \) are the uncontrollable errors for NMR test's application of geotechnics. Although the result of the NMR test is not accurate totally, the test trend is correct and the accuracy of the result is trusted in civil engineering.

All in all, the NMR technique provides equipment basics for seeking the regular pattern of geotechnical materials’ micro-structure. The selection of parameter is a fixed error that needs to be reduced. The effect of closed pores on experimental results should be fully considered for specific materials.

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