In-situ Void Ratio and Saturation Measurements Using Magnetic Resonance and Disturbed Sampling: A Case History

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Abstract

This paper presents a case history evaluating the application of Magnetic Resonance (MR) logging for in-situ measurement of volumetric water content (VWC), void ratio (e), and degree of saturation (Sr) in unsaturated soils. Laboratory validation was first conducted using oil sands tailings to assess the accuracy of MR-derived VWC against known sample properties, achieving strong correlations (R^2 up to 0.93). Field deployments were then performed across varied geological settings in Canada and Peru, including tailings, peat, sand, and rock. MR logging was supplemented with disturbed sampling and in-situ testing, such as piezocone penetration testing, to enhance soil characterization. Results demonstrate the potential of MR as a valuable geotechnical and hydrogeological tool for direct, non-invasive assessment of unsaturated soil parameters, despite current limitations from electromagnetic noise and tool sensitivity in complex materials. The study supports the continued refinement of MR methods for broader adoption in geotechnical investigations

Introduction

Magnetic Resonance (MR) logging is an emerging technique offering direct volumetric water content (VWC) measurement, with preliminary studies, such as those on copper tailings [1], showing promise. In unsaturated soils, VWC, when combined with known phase relationships and sampling, can yield, density [2], degree of saturation (Sr), and void ratio (e) values. Evaluating e and Sr in tailings deposits is informative for liquefaction assessments. Accurate assessment of VWC is also valuable in hydrogeological evaluations, where, alongside porosity, interpretation of the data can support determination of hydraulic conductivity. Cost effective, accurate, and timely in situ measurements of VWC would be invaluable for geotechnical and hydrogeological practice.

This study summarizes a previously published laboratory validation study and presents several field investigations utilizing MR logging, complimented with disturbed sampling and in situ methods, including piezocone penetration testing (CPTu) to enhance soil characterization. It includes findings from sites in Canada and Peru, considering a variety of materials including peat, tailings slimes, clean sand, treated tailings, and rock.

Fundamentals of Magnetic Resonance

MR, also commonly referred to as Nuclear Magnetic Resonance (NMR) and Borehole Magnetic Resonance (BMR), is a geophysical technique that measures the response of hydrogen nuclei to an applied magnetic field. When subjected to a strong external magnetic field, hydrogen nuclei in water molecules align with the field. A subsequent radiofrequency pulse disturbs this alignment, and the resulting decay of the induced magnetic signal over time (referred to as the 'T2' time), is used to determine VWC. The distribution of this decay can differentiate between bound water (bound onto soil particles) and mobile water (free to move within pores) [3], [4].

MR logging has been widely used for decades in the oil and gas industry to support petroleum exploration [5], [6]. Recent advancements in compact and cost-effective MR tools have enabled their application in groundwater studies, allowing for direct measurement of water content in situ [7], [4]. These systems are becoming common for informing environmental remediation, through characterizing aquifer properties [8], [9].

In saturated soils, the VWC provides a direct measurement of the porosity of the soil, through constitutive relationships the void ratio can be readily determined. Saturation exceeding 99.5% can be confirmed using the compression wave velocity (V_p) [10] from the seismic cone penetration test (SCPT) or borehole geophysical methods such as the downhole seismic test.

The degree of saturation can be determined from the VWC when the gravimetric water content (GWC) and specific gravity of solids (G_s) is known as shown in equation 1. Through phase relationships, and lab testing, the void ratio can be determined since the volume of solids (V_s) can be calculated and the VWC is known, as shown in equation 2.

$$Sr = VWC / \left(1 - \left(\frac{VWC}{GWC}\right) / G_s\right) \tag{1}$$

$$e = \frac{1 - V_s}{V_s} \text{ where } V_s = VWC \times \left(\frac{m_s}{G_s} / m_w\right) \tag{2}$$

Where m_s is the mass of solids and m_w is the mass of water and G_s is the specific gravity.

Laboratory Validation

At the University of Alberta, a two-phase laboratory validation study was conducted to evaluate the potential for MR obtained VWC measurements to determine the void ratio and degree of saturation of unsaturated tailings materials [11]. Testing was performed using a range of oil sands tailings materials, including coarse sand tailings (CST), fluid fine tailings (FFT), and froth treatment tailings (FTT), to evaluate how variations in composition impact NMR-derived VWC. Samples were tested in custom PVC columns of a known volume and mass, comprising two nested cylinders sealed with plates on either end. The outer cylinder was fully packed with the sample, while the inner cylinder allowed horizontal insertion of the NMR tool for measurement.

Two sets of control testing were performed. The first phase was undertaken to establish protocols to ensure that environmental noise and electromagnetic (EM) interference were adequately minimised when using the shielded instrument in air (VWC = 0) and water (VWC = 100). A low noise level was achieved through conducting testing in a basement laboratory with minimized external interference through shielding, grounding, and without fluorescent lighting. The second phase was conducted in a clean sand, where the saturation ratio was incrementally increased from 0% to target saturation levels of 25%, 50%, 75%, and 100%. Given that the sample mass, volume and specific gravity was known for each test it was possible to calculate a laboratory measured VWC and compare with the NMR derived VWC. The correlation for sand samples was strong, with an R^2 of 0.93, reflecting good agreement between calculated and measured VWC values. Results are presented in Figure 1

A similar approach was taken for the oil sands tailings, where key material properties were calculated through Dean Stark method for the mass fractions. The materials saturation ratios varied between 13 and 102%. Following testing two Coarse Sand Tailings (CST) samples were saturated and retested. The correlation between the calculated VWC and the MR derived VWC, was reduced, R^2 dropped to 0.81. This was hypothesized to be attributed the to the potential influence of magnetic minerals and hydrocarbons in the tailings. Further work aims to identify the impact of these inclusions and work to remove it through further calibration of the tool and interpretation methods.

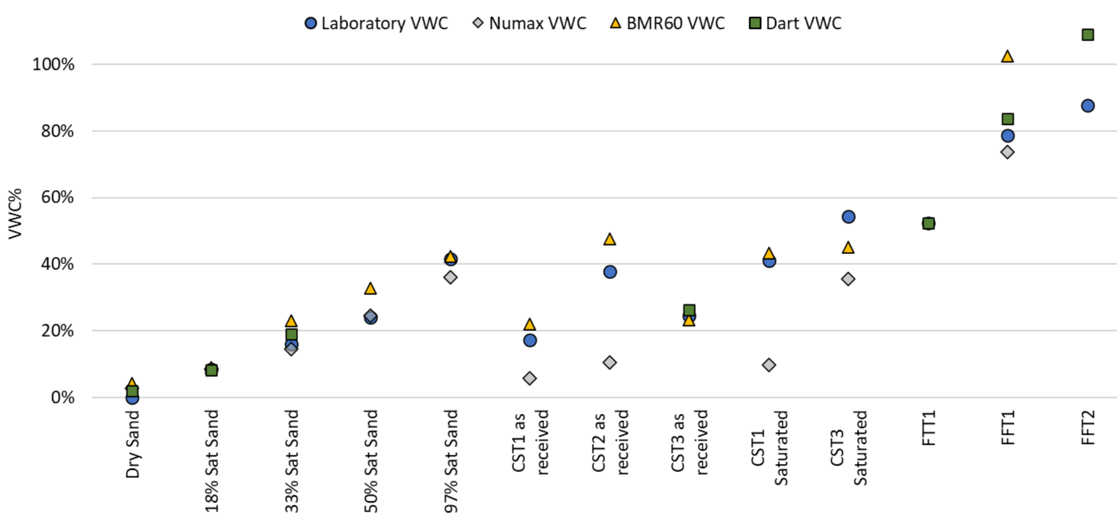

Figure 1- Comparison VWC obtained for differing saturations and sample materials using three MR probes.

Field measurements

Canadian Tailings Beach

Shallow MR tests in a partially saturated treated tailings deposit were conducted in on an oil sand mine site near Fort McMurray. Direct push MR equipment [4] was utilized. During direct push deployment of the MR tool, casing is pushed to depth with hydraulic force from a CPT rig with the end blinded using a sacrificial drop-off tip, once at depth the MR tool is inserted to the bottom of the casing. The casing is then pulled back to expose the tool to the soil, allowing continuous or semi-continuous in-situ MR logging on retraction without a drilled borehole. The MR logged soundings were paired with sonic coring to obtain disturbed samples of the tailings materials which were sent for laboratory analysis of bitumen, mineral, and water content. High noise (low signal to noise ratio) and a manufacturing defect in the MR tool resulted in low data confidence, however the resultant VWC, Sr and e provided valuable insights and plausible measurements of tailings saturation.

Canadian Peat Wetland

Shallow MR tests in a fully saturated peat (muskeg) deposit in northern Alberta were completed using a direct push method [4]. Due to the remote location, EM noise was minimal, reducing common data quality issues encountered in industrial settings. While results appeared reasonable given the deposit conditions, no confirmatory samples were collected.

Canadian Tailings Dams

Wireline MR logging was completed in cased mud rotary boreholes at two separate tailings dams in Fort McMurray, Alberta. At both sites, after drilling reached target depths (62 m and 96 m respectively), PVC casing was installed, and the MR tool was deployed via manual wireline from the drill floor. Logging was conducted in a bottom-up, stepwise manner at 0.25 m intervals, creating a continuous stepped log. Despite sampling not being undertaken, nearby CPTs and historic construction logs are available to support data assessment.

At the first location, historic construction logs indicated minimal potential for residual hydrocarbons. However, the MR data were affected by significant EM noise from nearby plant activity, power transmission lines, and industrial operations. This noisy data set required filtering through frequency stacking and the use of a noise reference box. Of the four frequencies recorded, three were stacked to improve signal to noise ratio. Following filtering and stacking, the results were as expected, showing both mobile and free water, but without samples, the saturation ratio could not be calculated.

At the second site, the MR data compared favourably with nearby CPT data. Several logging runs were completed with varying echo spacings and logging speeds at a rate ranging from 0.5 to 1 meter per minute to capture a high level of detail and observe subtle variation in T2 distributions. Even without stratigraphic information, stratigraphic layers of heightened fines, peat, and natural sands are visible in the log which align with observations from the drill cuttings.

Canadian Aquifer

MR logging was completed just outside a small municipality in British Columbia to determine the presence of, and assess the hydraulic conductivity of an aquifer during a site remediation project. Six PVC cased boreholes were logged using a small-bore MR probe at a 0.25m resolution. Drilling logs indicated silty sand with an interbedded clay layer varying between 0.5 and 2 meters in thickness. MR logging results detected this clay layer, showing decreased T2 decay times which corresponds to lower hydraulic conductivity of the clay lens. Hydraulic conductivity estimates using the Schlumberger-Doll equation (sandstone calibration) ranged from 10^-8 m/s in clays, to 10^-5 m/s in sands.

Peruvian Tailings

To explore the relationship between the VWC obtained from MR and the measurements obtained from seismic piezocone penetration testing (SCPTu), a co-located in situ study was conducted on a coarse tailings embankment in Peru. The objective was to compare both methods to assess the behavior of coarse tailings and through combination of both methods, could an enhanced understanding of the soil properties be obtained.

[4] estimated water content using CPT output and soil phase relationships. Unlike the gravimetric water content equation used by [4], this study estimates VWC through modification of equation 1, under the assumption of an average saturation ratio of 0.20 across the profile. Therefore:

$$VWC = S_r \left(1 - \frac{\gamma}{G_s \gamma_w}\right) \tag{3}$$

where, γ is the unit weight and γ_w is the water unit weight.

The results comparing the VWC obtained from SCPTu and NMR are presented in Figure 1. The average SCPTu calculated VWC estimation (6%) compares well with the average NMR measured VWC (6%).

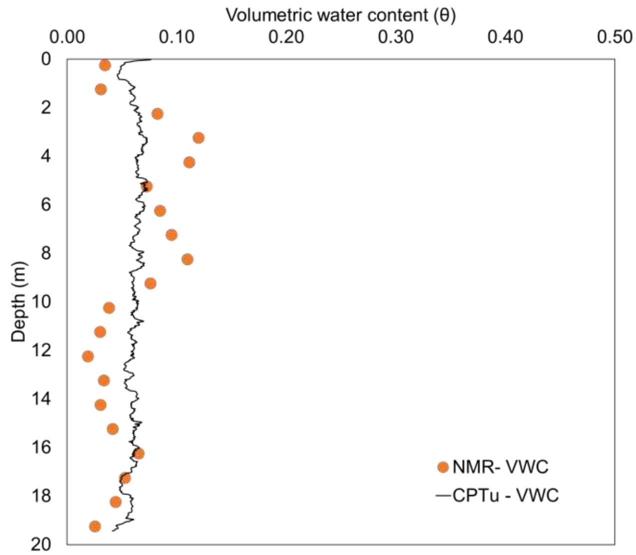

Figure 1: Plot comparing volumetric water content by NMR and inferred from CPTu assuming Sr of 0.20.

USA Tailings

Direct push MR was conducted in partially saturated tailings at a mine in the Western USA. Refusal of the direct push system was reached prior to penetrating below the phreatic surface. MR soundings were complimented with SCPTu data including pore pressure dissipation tests, shear wave velocity (Vs), and compression wave velocity (Vp).

Limitations and outlook

Through testing completed in these case studies, and the collection of other MR data not discussed here, the accuracy of the technique as it related to measuring S_r and e in unsaturated soils can be limited by the presence of external noise, or by low signal amplitude. The influence of EM interference is particularly prominent in unsaturated soils, where the signal amplitude of the T2 decay curve is low. Several noise mitigation measures have been developed to improve the signal to noise ratio, and internal improvements to certain MR tooling have been observed to make remarkable improvements to signal quality.

Further study of MR is necessary to understand how measurements of geo-materials containing hydrocarbons, those with complex mineralogy such as those that contain crystalline water (ie. Gypsum), or that exhibit magnetic properties (ie. magnetite) are impacted by these complexities. Detailed analysis of these materials in the context of unsaturated soils with low T2 signal strength will help to quantify how these mineralogical complexities may impact observations.

Uncertainty in the values of Sr estimated from MR measurements depend on the level of uncertainty in the VWC estimate, as well as the value of Sr and the GWC present in the sample and can be calculated using the following relationship (Dr Jorge Macedo, personal communication):

$$dS_r = \left(\frac{S_r}{GWC}\right)^2 dVWC \tag{4}$$

Where dSr represents the uncertainty in estimated Sr, and dVWC represents the uncertainty in VWC estimate from MR testing. From equation 4, it is apparent that the uncertainty level in estimated Sr depends on the ratio between Sr and GWC, which is a material specific property. This relationship also shows that the dSr term increases more rapidly at higher values of Sr for any given material.

Conclusions

This combination of studies demonstrates MR has the potential to accurately measure VWC in a wide range of geo-materials and estimate the degree of saturation of partially saturated soils and tailings. For geotechnical applications in simple materials such as clean sands, there appears to be a suitable level of accuracy to obtain *Sr* in situ, when combined with the gravimetric moisture content and specific gravity of solids from laboratory testing. Through a combination of laboratory testing, MR, and CPTu, it is possible to enhance the understanding of the geotechnical properties, hydrogeological properties, and volumetric composition of soils.

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