

THE CASE OF AN MRS-ELUSIVE SECOND AQUIFER

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Introduction - At ITC, interest on the MRS (Magnetic Resonance Sounding) technique is ongoing since its commercial introduction in Europe in 1996. Soundings have been done at selected sites in the Netherlands from 1997 onward with both the NUMIS and the NUMIS^{PLUS} instruments. The country is densely populated and industrialized so that at numerous locations, cultural noise does not allow the acquisition of reliable MRS data sets. As part of the countrywide space utilization planning, however, a number of parks have been set aside. These are less or not electrified so that, from an MRS perspective, even if the level of urbanization and industrialization is high, it was possible to find sites with low level of cultural noise (e.g. 50 Hz harmonics due to electrical power grid). Under such conditions, in South-West of the country, because of low artificial noise, shallow groundwater table and high porosity of the near-surface aquifer, MRS data sets were acquired with high signal to noise ratio (S/N) (e.g. S/N = 96 for the second data set presented here). These data sets show a monotonous single peak anomaly corresponding to single aquifer data inversion. However, in the first 200 m below surface, two or even three extensively documented aquifers (Dutch state agency NITG-TNO) are present.



Figure 1: Sites location

1: Delft, 2: Waalwijk

Near surface aquifers - According to the specific locations, the first (top) aquifer is either unconfined or confined by a clay-rich aquitard. In both cases it is characterized by a specific yield and/or specific drainage reaching ~ 20 %. Because of a reduced exposure to contaminants, the characterization of the second aquifer is of interest even if its storage and flow properties may be less than the top aquifer. For this presentation, we will examine the MRS responses from two sites (see Figure 1): one with upper confined aquifer near Delft [1] and the other one with upper unconfined aquifer near Waalwijk [2]. The aquifers in the South West of the country are composed of unconsolidated sands and gravels interchanged with clay layers – aquitards. Even if aquifers are often characterized down to ~ 250 m, in this study, only the first 100 m below surface is of concern because of the range of the MRS investigation.

In Western Netherlands, the depth of the fresh/brackish water interface increases inward from the sea. This interface is reaching a depth of 100 m at a distance of 30 to 60 km from the sea with local irregularities (NHV, 1998). At the Waalwijk location (~ 75 km from the sea), the MRS response is due to fresh water while at Delft (~ 15 km from the sea), the salinity pattern is locally more complex: the town is located over a fresh water aquifer but to the east where MRS data sets were acquired the top aquifer has brackish water.

At the Delft site (Lubczynski and Roy, 2004), the top layer is a clay aquitard [0-15 m, vertical hydraulic conductivity (K_v) = 0.0036 m/d]. Below, there is a confined aquifer [15-39 m, horizontal hydraulic conductivity (K_h) = 32 m/d], followed by a clay aquitard (39-45 m, K_v = 0.0072 m/d) and then a second aquifer (45-128 m, K_h = 12 m/d), which contains clay horizons. Due to the salinity of the water, the formations have lower resistivity (between 4 and 11 Ω -m

according to results of VES done at the MRS site) than at the Waalwijk-2 site, described below, and the attenuation of the MRS signal with larger values of Q (excitation moment) is noticeable (see Figure 2).

At the site Waalwijk-2 (Lubczynski and Roy, 2003), two aquifer layers are observed in the depth range of interest, the layers being separated with a clay aquitard. Downward leakage occurs in the aquitard as evidenced by the reported head decline with depth. The 0-6 m depth interval is unsaturated. The upper aquifer layer (6-52 m) is unconfined and is highly permeable, K_h is estimated at 24 m/d. The underlying clay aquitard (52-85 m) is intercalated by sandy horizons and its K_v is 0.004 m/d. The next aquifer layer (>85 m), with a K_h of 5 m/d, has at least 3 thin less permeable horizons unlikely to be resolved with MRS so the whole sequence from 85 to 180 m is considered here as a single aquifer layer. Except in the aquitard, with a $\sim 20 \Omega\text{-m}$ resistivity, the water bearing layers have an estimated resistivity of $\sim 60 \Omega\text{-m}$. The unsaturated zone has $\sim 120 \Omega\text{-m}$ resistivity.

An examination of the observed MRS responses (MRS & geoelectric sections) and of subsequent modeling exercises allows distinguishing two different cases represented respectively by the Delft and the Waalwijk sites.

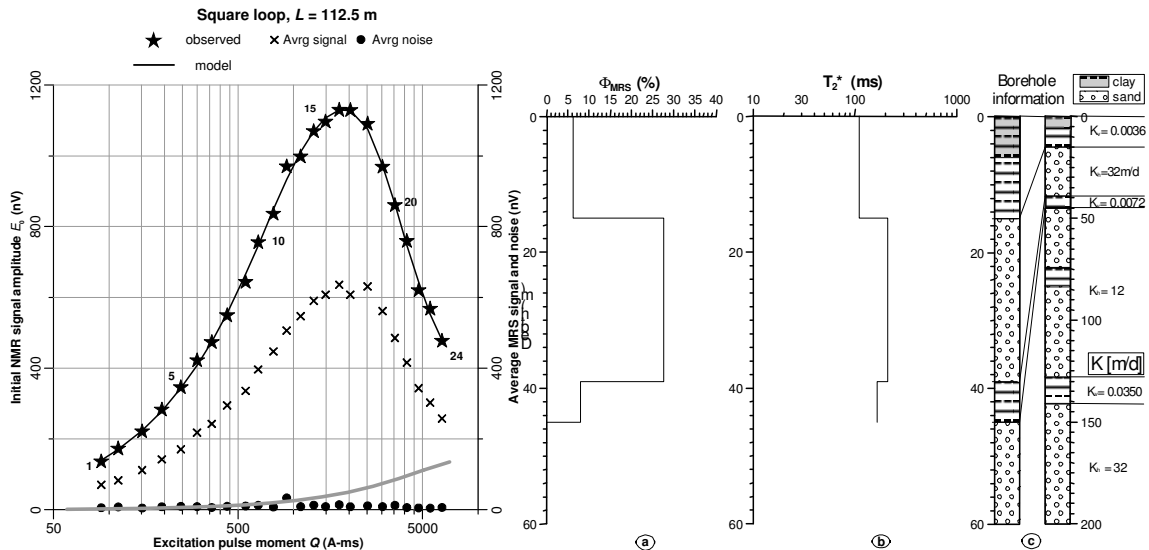


Figure 2: MRS response at the Delft site; left: data set, center: inversion results, right: well data

Delft case - In the first case, at the Delft site see Figure 2, we observe on the E_0 vs Q response (initial value of the NMR signal versus excitation moment), a properly developed peak followed by a rapid decrease of the signal amplitude as the Q is increased past the peak response. Modeling results suggest that this rapid decrease is due to the skin depth attenuation caused by the low resistivity of the formations; this corresponds to a brackish/saline environment. Because of the reduced K_h for the second aquifer (12 vs 32 m/d) and the presence of clay horizons, the 2nd aquifer is modeled with 10% water and 75 ms decay time. The expected response is shown in gray in figure 2. Even at the maximum Q value of 7000 A-ms, the MRS signal expected from the 2nd aquifer is still less than one third of the observed signal: we expect that current inversion tools will not reliably extract the characteristics of the 2nd aquifer under such conditions. Therefore under such conductive environment, we currently detect only the top aquifer; such conclusion may change in the future according to the development of the inversion scheme described in the next section.

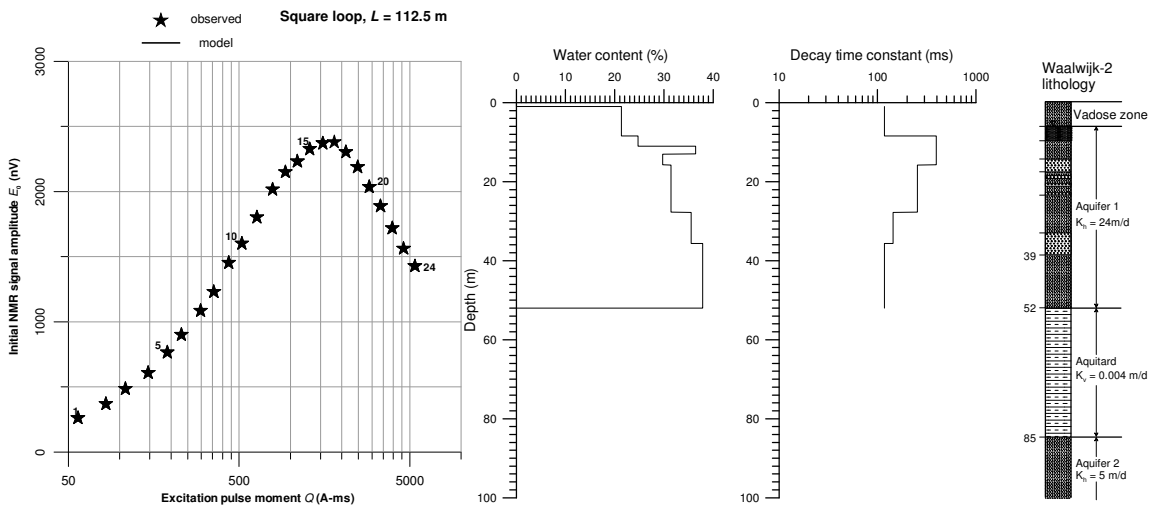


Figure 3: Waalwijk-2 site; left: MRS data set, center: inversion results, right: well data

Waalwijk-2 case - In the second case, at Waalwijk-2, we observe on the E_0 vs Q response, that following the peak response, a normal 'tail' is observed resulting in the above-mentioned inversion of a single aquifer. In order to investigate the case of such un-detected 2nd aquifer, the following modeling was done: (1) the resistivity of the subsurface was estimated from nearby borehole resistivity logs (an in-situ VES or TDEM sounding is not yet available for this site) (2) the MRS response, shown in Figure 3, was modeled with both resistive and conductive [as estimated in (1)] media, the modeling was done in 3 steps: top aquifer only, 2nd aquifer only and both aquifers. A display of such modeling exercise is shown in Figure 4.

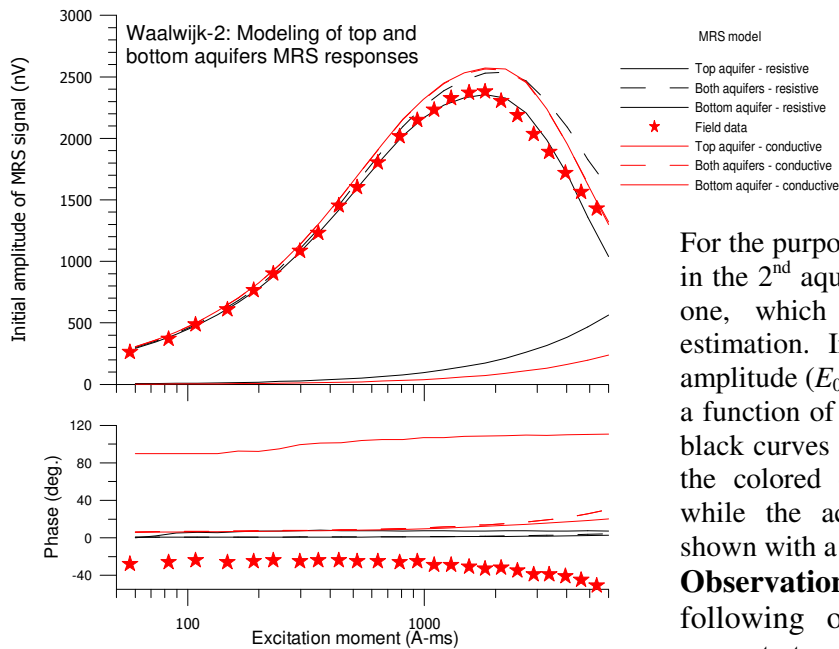


Figure 4: MRS numerical modeling for Waalwijk-2 top and 2nd aquifers

For the purpose of Figure 4, the water content in the 2nd aquifer was set the same as the top one, which is most probably an over-estimation. In the display both the initial amplitude (E_0) and the phase (ϕ) are shown as a function of the excitation moment (Q). The black curves correspond to the resistive case, the colored curves to the conductive case while the actual field measured data are shown with a star.

Observations related to Figure 4 - The following observations are made with respect to this modeling exercise: (1) clearly the water content is underestimated when the media are considered

as resistive; this is generally expected when the aquifer is within or under a conductive medium, (2) in the resistive case, the response from both aquifers is larger than the response from the top aquifer alone while in the conductive case, the response from both aquifers cannot be distinguished amplitude-wise from the response of the top aquifer alone, (3) the phase of the 2nd aquifer is very different from the phase of the top aquifer in the conductive case but not in the resistive case, (4) the actual field data shows a small but significant phase excursion toward the high excitation moment (Q) values, (5) the phase difference between the top and 2nd aquifer response is sufficient (over 110°) to explain that the resultant from the top and the 2nd aquifer responses is the same as the response from the top aquifer alone amplitude wise.

About item (5), let's recall that, contrary to EM induction at high induction numbers, NMR responses are summed directly with due regards to phase and orientation of the magnetic vectors. For example, two collinear vectors of amplitude A will have a resultant amplitude of $2A$ when their phase difference ($\Delta\phi$) is 0° , A with a $\Delta\phi$ of 120° , and 0 with a $\Delta\phi$ of 180° .

Conclusions with respect to standard data inversion and modeling exercise - Thus, while we know that we have a second aquifer with high porosity within the depth range of the MRS implementation (NUMIS) at both the Delft and the Waalwijk-2 sites, we cannot detect them with the standard inversion scheme. With knowledge of the geoelectric section, normally available from a VES or TDEM sounding, it is possible, at least for the Waalwijk-2 case, to understand how the 2nd aquifer is masked and how it can be detected and its upper section characterized. Due to the loop size and Q instrumental limitations at the time of the field data acquisition, the bottom of the 2nd aquifer will remain undetermined. In fact, the signal from the second aquifer is skin-depth attenuated due to the electrical conductivity of the aquitard but it is still well within the dynamic range of the MRS instrument. However it is phase shifted so that the phase vector sum of the signals due to the upper and the second aquifer result in an amplitude very nearly the same as if the top aquifer was alone.

The current conclusion from such exercise on the Waalwijk-2 site, is that, by proper discrimination of the phase, in this case around 111° for the 2nd aquifer and around 6° for the top aquifer, two separate inversions can be carried-out: one for the top and one for the bottom aquifer. The results would then be merged for the site interpretation. All the above assumes that no other factors than formation conductivity is responsible for the observed phase shifts. As previously observed by Legchenko et al. (2003) and by Weichman et al. (2000) other sources of phase shift are observed such as the difference in frequency between the MRS instrument excitation frequency and the in-situ Larmor precession frequency which will have to be taken into account. Braun and Yaramanci (2003) have also stressed the information content of the phase in MRS data sets. The contributions from ITC, NITG-TNO and IRIS Instruments at various stages of these investigations are gratefully acknowledged.

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