MRS CONTRIBUTION TO HYDROGEOLOGICAL PARAMETERIZATION

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Hydrogeological system parameterization is a critical issue in modern regional, water resources management and planing but also in small-scale water resources projects. In such activities the standard hydrogeological investigations are required, which normally include drilling of investigation boreholes providing hydrostratigraphy of the system and pumping tests providing storage and flow parameters. The new hydrogeophysical method called Magnetic Resonance Sounding (MRS) provide such data as complementary (not alternative yet), valuable and cost effective tool next to the standard hydrogeological methods. The MRS as the only geophysical method is water selective and is capable to provide depth dependent information contributing to hydrogeological system parameterization. The two types of MRS output parameters, free MRS water content (Φ_{MRS}) and decay time constant (T_{d}) provide the two types of hydrogeological parameters, storage related parameters and flow related parameters respectively. The nature, complexity and applicability of the two MRS output parameters and their relations with hydrogeological parameters are the main scope of this paper.

Hydrogeological parameterization with Φ_{MRS}

Regarding a soil-rock-water relationship, there are substantial differences in terminology between disciplines of hydrology, soil science and geophysics, particularly with respect to the terminology of the least defined microscopic processes at the pore-water contact. Therefore in order to "translate" Φ_{MRS} into storage related terms the issue of the subsurface MRS water storage concept is discussed and presented in Figure 1.

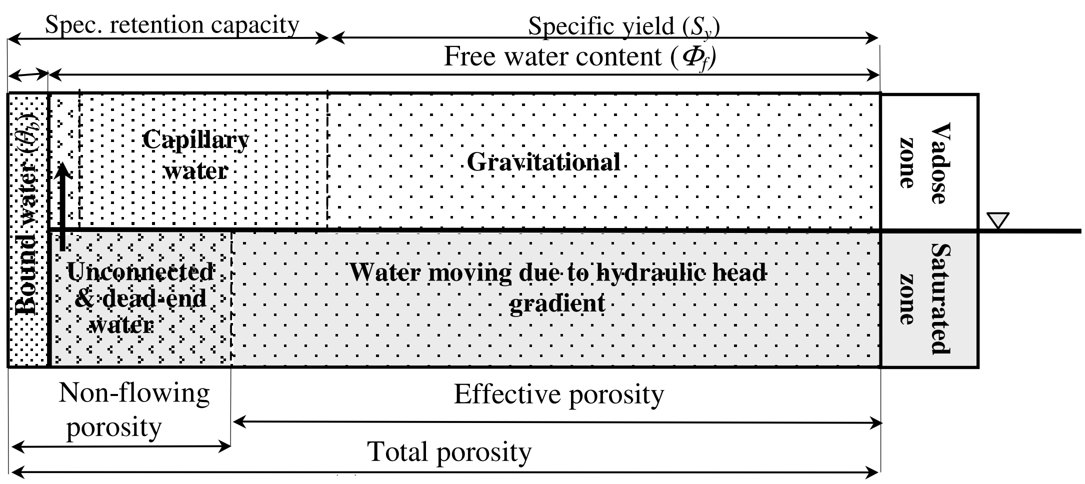

Figure 1. Aquifer storage concept – modified after Lubczynski and Roy (2003).

Free water content *(Φ_f)* is the percentage of water that is outside field of molecular forces of attraction of the solid particles that can be displaced by gravity or pressure gradients, with respect to the total rock volume. Bound water (θ_b) in contrast to free water is the amount of water attached to the solids by molecular forces of attraction, non-removable by gravity and/or hydraulic head gradient forces but removable by centrifugal action at acceleration 70 thousand times exceeding the acceleration of gravity. The thickness of bound water film surrounding a solid (~0.5 μm) varying with size, area and types of the mineral grains, depends on the strength of molecular forces of attraction and therefore is correlated with T_d. The exact relation is not known yet because the very short signals <30 ms are not measured yet with the current MRS instrumentation. It is however widely accepted that the measured signals after the 30 ms dead-time (current instrumental characteristic), have a decay rate corresponding to free water ($\Phi_{MRS} \cong \Phi_f$).

The hydrogeological system introduced schematically in Figure 1 consists of saturated part (aquifer) showed in the lower part of the graph and of the unsaturated part (vadose zone) showed in the upper part of the graph. In the saturated zone the free water content (Φ_f) consists of the effective porosity (n_e) part occupying fraction of the rock with water free to flow and of the part related to unconnected and dead-end porosity. The free water porosity flow in microscopic processes refers to the continual exchange of molecules from one phase to the other through molecular Brownian motion. For example, a circulating molecule may become immobilized in the course of its progress, while another one that was originally immobile may be set in motion (Marsilly, 1986). Dead-end porosity (fractures and micro-joints but also non-flowing karstic cavities etc.) often plays an important role in karstic and hard rocks while unconnected pores are abundant in volcanic and karstic rocks. In unconsolidated sediments the role of unconnected and dead-end porosity is negligible or can even be disregarded. If the MRS sounding is performed over the rocks where the dead-end and unconnected porosity can be neglected, Φ_f and therefore Φ_{MRS} as well, can be directly interpreted as n_e.

The saturated part of the aquifer can be de-saturated by natural lowering of groundwater table or by well abstraction. In such cases the gravitational water (water that can be released by gravity forces) is released from the system either by natural drainage or by well pumps. The amount of water released from the aquifer storage due to the gravity forces is characterized by specific yield (S_y). The amount of water remained immediately after de-saturation is described by specific retention capacity (S_r), in soil science also known as moisture at field capacity (θ_{FC}). The S_r consists of bound water (θ_b) and a portion of free water retained against gravity forces (θ_f). The θ_f is composed of free capillary water and unconnected and dead-end pore water. The capillary water represents the main part of the free water resistant to gravity release and sensitive to hydraulic head difference, which "wets" the solids (air stays in the middle of the voids) due to the surface tension forces. The quantity of unconnected and dead-end water in overall θ_f is usually negligible although in some secondary porosity rocks it can be important.

Under the assumption of $\Phi_{MRS} \cong \Phi_f$, S_y can be calculated from $S_y = \Phi_{MRS} - \theta_f$ (Figure 1). Practical definition of θ_f is cumbersome (unless determined by MRS on the de-saturated part of the aquifer – see below), so instead the use of S_r defined by hydrogeological methods seems to be convenient although only with regard to rocks where θ_b can be neglected. By applying S_r instead of θ_f it is expected that the Φ_{MRS} measurements provide the entire spectrum of water content including bound water. In practice this is not the case yet because current instrumental limitations do not allow for measurements of signals <30 ms covering the main spectrum of θ_b. In most of the water resources application focusing on coarse and permeable rocks, this is however not a big problem because such rocks usually have negligible θ_b permitting the assumption of $\theta_f \cong S_r$ and therefore determination of only slightly underestimated S_y (by amount of θ_b) according to the formula $S_y = \Phi_{MRS} - S_r$.

In many hydrological applications such as e.g. groundwater recharge assessment, not only S_y but also S_r is critical. As mentioned S_r can be defined by standard hydrological methods but also with MRS. This can be done in situ, by analyzing Φ_{MRS} immediately after de-watering of an aquifer at the scale comparable with the volume investigated by MRS. In such case $S_r \cong \Phi_{MRS}$

In confined aquifers, water storage consists of the elastic component called elastic storativity (S_e) and the gravitational component named by Lubczynski and Roy (2004) as specific drainage (S_d). The elastic water release is related to the water expansion and aquifer compaction attributed to aquifer pressure changes and is not directly detectable by MRS. It can however be calculated indirectly by applying MRS originated porosity (n – slightly underestimated with MRS by disregarding θ_b) to standard hydrogeological formula $S_e = S_s \cdot D = \rho_w g(\alpha + n\beta)D$, where not only n but also D (aquifer thickness) can be estimated by MRS. The other parameters such as ρ_w - density of water; g – acceleration of gravity; α - compressibility of the aquifer skeleton; β - compressibility of the water can be estimated by other data sources. The specific drainage (S_d) is the volume of water that could be potentially released from the confined aquifer by gravity forces if piezometric surface fell below the bottom of the confining layer creating unconfined conditions. That storage term is detectable by MRS and can be estimated from the formula $S_d = \Phi_{MRS} - S_r$ applying the same assumptions as used in S_y determination.

In the geophysical inversion Φ_{MRS} is determined at certain depth intervals; the larger the *h*/*L* ratio (*h*: investigation depth, *L*: loop size), the larger the influence of equivalence error in the inversion results. The most reliable quantitative interpretation of water content at the certain analyzed depth intervals can be done by integrating the product of $\Phi_{MRS} \cdot D = H_w \cong \Phi_f \cdot D$ with depth, where H_w is a free hydrostatic column of water. H_w can be estimated for single layers of interest like aquifers but also for the arbitrary depth intervals including the entire investigation depth.

Hydrogeological parameterization with T_d

The second important MRS output parameter decay time constant (T_d) provides the information on how mobile (extractable) is ground water and therefore it is used for parameterization of hydraulic conductivity (K) and aquifer transmissivity (T). In contrast to - storage parameterization with Φ_{MRS}, determination of hydraulic conductivity and aquifer transmissivity is only possible after establishing site (rock) specific regression functions with parameters obtained from hydraulic tests i.e. pumping tests.

In general there are three schemas of T_d measurements: T_1 (longitudinal relaxation), T_2 (transversal relaxation) and T_2^* (free induction decay time constant) schemas. In MRS so far only T_2^* and T_1 schemas are available and both can be used for K and T parameterization. According to Legchenko et al. (2002) however, T_1 schema is more accurate because it is less influenced by magnetic field inhomogenity.

The field MRS experiments indicates a good relationship between T_d and rock pore size (ratio of the pore volume to surface area) correlated with K. T_d increases proportionally with the pore size from about 30 ms in clays to 400-600 ms in coarse materials (e.g. gravels). This dependence is described by the empirical formula $K = C\, \Phi_{MRS}^{a}\, T_d^{b}$ where C, a and b are the empirical parameters to be calibrated in the field by comparison with K values obtained from pumping tests. Parameters C, a, b are site specific.

Since both MRS and pumping test experiments provide information volumetrically with depth (z), the integration of K with depth seems to be the most suitable procedure for transmissivity evaluation. In this particular way various types of rocks such as limestones with sands and clays, fractured diorites and fractured gneisses were investigated by Legchenko et al., (2002) by comparing MRS related T calculated as $T = C_1\int_{\Delta z} \Phi_{MRS}\, T_d^2 dz$ (a = 1; b = 2) and $T = C_2\int_{\Delta z} \Phi_{MRS}^4\, T_d^2 dz$ (a = 4; b = 2) according to T_2^* and T_1 schemas with corresponding pumping test transmissivities. The best correlation was obtained with T_1 schema while using the formula with coefficients a = 1 and b = 2. However, for double porosity sandstones, a number of NMR logging and laboratory experiments showed a = 4 and b = 2 to be the most accurate coefficients (Sen et al., 1990) whereas for unconsolidated glacial rocks in Germany, Yaramanci et al., (2002) found b = 4 to be the most accurate coefficient. In this regard, recently, also Vouillamoz (2003) have made significant contribution making substantial amount of MRS and pumping test experiments with series of empirical correlations between MRS field responses and the corresponding pump test results. However, still more of such experiments in various hydrogeological conditions are needed to establish generic guidelines for appropriate use of parameters a, b and C for K and T determination in various rock types with various hydraulic porosity models.

Conclusions

Φ_{MRS} can contribute to the definition of the following hydrogeological porosity/storage related parameters: effective porosity, porosity, specific yield, elastic storage, specific storage, specific drainage, specific retention capacity and hydrostatic water column.

Only one empirical, site specific relation applying combination of T_d and Φ_{MRS} is available so far to calculate K. T is best calculated by integration of K with layer depths, which is also provided by MRS.

The advantage of MRS system parameterization over the standard hydrogeological parameterization methods relates to the MRS data integration from larger volume than in most of hydrological methods. The comparable in volume pumping test experiments are substantially more costly than MRS experiments.

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