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Classification of Formations by Degree of Saturation in the Electrical Resistivity – Hydraulic Conductivity Relationship

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Abstract

The relationship between aquifer hydraulic conductivity and aquifer resistivity, either measured on the ground surface by vertical electrical sounding (VES) or from resistivity logs, or measured in core samples have been published for different types of aquifers in different locations. Generally, these relationships are empirical and semi-empirical, and confined in few locations. This relation has a positive correlation in some studies and negative in others. So far, there is no potentially physical law controlling this relation, which is not completely understood. Electric current follows the path of least resistance, as water does. Within and around pores, the model of conduction of electricity is ionic and thus the resistivity of the medium is controlled more by porosity and water conductivity than by the resistivity of the rock matrix. Thus, at the pore level, the electrical path is similar to the hydraulic path and the resistivity should reflect hydraulic conductivity. We tried in this paper to study the effect of degree of groundwater saturation in the relation between hydraulic conductivity and bulk resistivity via a simple numerical analysis of Archie's second law and a simplified Kozeny-Carmen equation.

The study reached three characteristic non-linear relations between hydraulic conductivity and resistivity depending on the degree of saturation. These relations are: (1) An inverse power relation in fully saturated aquifers and when porosity equals water saturation, (2) An inverse polynomial relation in unsaturated aquifers, when water saturation is higher than 50%, higher than porosity, and (3) A direct polynomial relation in poorly saturated aquifers, when water saturation is lower than 50%, lower than porosity. These results are supported by some field scale relationships.

Key words: *geophysics, saturation, sensitivity, hydraulic conductivity.*

Introduction

Virtually every hydrogeologic investigation requires an estimate of hydraulic conductivity *(K),* the parameter used to characterize the ease with which water flows in the subsurface [6]. Hydraulic conductivity differs significantly from permeability, where hydraulic conductivity of an aquifer depends on the permeability of the hosting rock and viscosity and specific weight of the fluid, whereas permeability is a function of pore space only.

Hydraulic conductivity has been measured by traditional hydrogeologic approaches. Such approaches are: pumping test, slug test, laboratory analysis of core samples, and geophysical well logging.

Pumping tests do produce reliable *(K)* estimates, but the estimates are large volumetric averages. Laboratory analysis can provide information at a very fine scale, but there are many questions about the reliability of the *(K)* estimates obtained with those analyses. Although the slug test has the most potential of the traditional approaches for detailed characterization of *(K)* variations, most sites do not have the extensive well network required for effective application of this approach [6]. However, these traditional methods are time-consuming and invasive.

Another group of hydrogeological methods is used to measure vertical hydraulic conductivity such as: dipole-flow test (DFT), multilevel slug test (MLST), and borehole flow meter test (BFT). These techniques can only be used in wells, which often must be screened across a relatively large portion of the aquifer and provide information about conditions in the immediate vicinity of the well in which they are used.

The ability to reliably predict the hydraulic properties of subsurface formations is one of the most important and challenging goals in hydrogeophysics, since, in water-saturated environments, estimation of subsurface porosity and hydraulic conductivity is often the primary objective [21].

Many hydrogeophysical approaches have been used to study the relationship between hydraulic conductivity from surface resistivity measurements; these approaches are classified as follows:

a) Combined interpretation of hydrogeologic and geophysical data.
b) Empirical and semi-empirical hydrogeological and geophysical relationship.
c) Theoretically petrophysical based models.

Theoretical Backgrounds

Since the electrical resistivity of most minerals is high (exception: saturated clay, metal ores, and graphite), the electrical current flows mainly through the pore water. According to the famous Archie law, the resistivity of water saturated clay-free material can be described as

$$\rho_{Rt} = \rho_{ai} \cdot F_i \tag{1}$$

where ρ_{Rt} = specific resistivity of water saturated sand, ρ_{ai} = specific resistivity of pore water, F_i = intrinsic formation factor.

The intrinsic formation factor (F_i) combines all properties of the material influencing electrical current flow like porosity φ, pore shape, and digenetic cementation:

$$F_i = a \cdot P^{-m} \tag{2}$$

Different definitions for the material constant (m) are used like porosity exponent, shape factor, and cementation degree. Factors influencing (m) are, e.g., the geometry of pores, the compaction, the mineral composition, and the insolating properties of cementation. The constant (a) is associated with the medium and its value in many cases departs from the commonly assumed value of one. The quantities (a) and (m) have been reported to vary widely for different formations. The reported ranges are exemplified in Table 1, which is based upon separate compilations of different investigators.

Equation (2) is called Archie's first law, where it is valid only in fully saturated clean formations (the grains are perfect insulators).

When the medium is not fully saturated, water saturation plays an important role, where the changing in degree of saturation changes the effective porosity (accessible pore space). It became Archie's second law:

$$F_i = \frac{\rho_{Ri}}{\rho_{ai}} = aP^{-m}S_w^{-n} \tag{3}$$

where ρ_{Ri} is the formation resistivity, ρ_{ai} is the pore water resistivity, P is the porosity, S_w is the water saturation, a and m are constants related to the rock type, and n is the saturation index (usually equals 2).

Table 1. Reported ranges of the Archie constants *(a* and *m*)

Litology	*a*	*m*	Author
Sand	0,47~1.8	1.64~2.23	Hill and Minburn (1956)
	0.62~1.65	1.3~2.15	Carothers (1968)
	1.0~4.0	0.57~1.85	Porter and Carothers (1970)
	0.48~4.31	1.2~2.21	Timur et al. (1972)
	0.004~17.7	0.02~5.67	Gomez-Rivero [14]
Rocks carbonate	0.73~2.3	1.64~2.1	Hill and Minburn (1956)
	0.45~1.25	1.78~2.38	Carothers (1968)
	0.33~78.0	0.38~2.63	Gomez-Rivero [14]
	0.35~0.8	1.7~2.3	Schon (1983)

Many studies concluded that Archie's law breaks down in three cases: (1) clay contaminated aquifer [29; 28; 25], (2) partially saturated aquifer [3; 22], and (3) fresh water aquifer [16].

Archie's first and second laws show the relation between bulk resistivity and formation factor. Formation factor could be linked to hydraulic conductivity by Kozeny-Carmen equation. One of the most recent modifications of this equation is made by Borner and Schon [2]. They obtained the following expression for the estimation of hydraulic conductivity of unconsolidated sediments (sand, gravel, silt) [21]:

$$K_s = \frac{a}{F S_{p[el]}^{c}} = \frac{a}{F(10^{5}\sigma''_{1Hz})^{c}} \tag{4}$$

where K_s is the hydraulic conductivity in m/s, F is the apparent formation factor, $S_{p[el]}$ is the electrically estimated specific surface area per unit volume (μm^{-1}), σ'' is the imaginary conductivity component measured at 1 Hz (S/m), a is a constant equal to 10^{-5}, C is a constant which ranges between 2.8 and 4.6 depending on the material type and the method used to measure K_s.

Accordingly, the modified Kozeny-Carmen equation (4) and Archie's first and second laws (eqs. 2 and 3) should control the relationship between hydraulic conductivity (K) and formation resistivity (R_0) in both saturated and non-saturated sediments.

Analytical Approaches

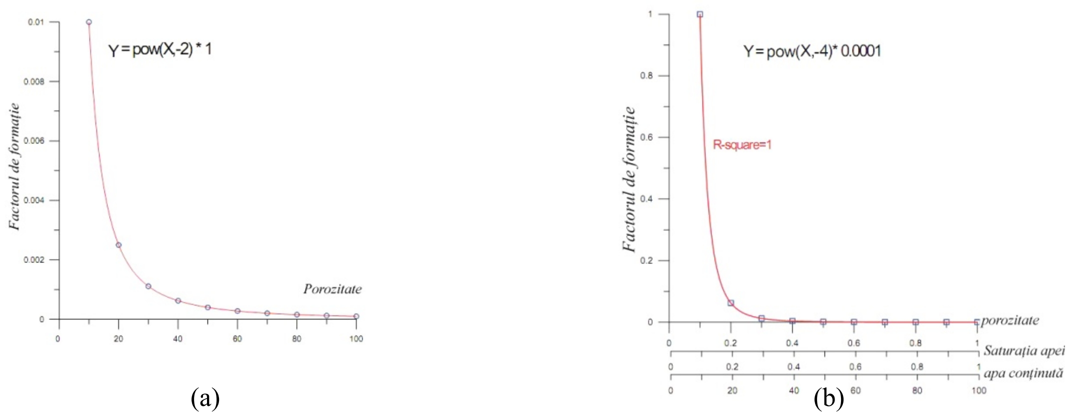
Two important relations have been numerically analyzed: Archie's second (which control the relation between porosity, water saturation, and formation factor) and Kozeny-Carmen model (which control the relation between formation factor and hydraulic conductivity). Beginning with the generalized Archie's second law (eq. 3), using $a = 1$, $m = n = 2$, and proposed values of porosity and water saturation ranging from 0.2 to 1 with an increment of 0.2, we calculated the net product of porosity (P) and water saturation (S_w), which is the volumetric water content (Θ).

$$\theta = P \cdot S_w \tag{5}$$

Figure l,a shows the relation between intrinsic formation factor and porosity when water saturation equals one. Figure 1,b shows the same relation when porosity equals water saturation. The two cases (fig. l, a, b) resulted in an inverse power relationship with a correlation coefficient equals one.

In the case where water saturation and porosity changes inversely to each other, we get the following relation (fig. 2).

Archie's law in this case has deviated from its traditional power law to a polynomial correlation of sixth order. In the right half of the curve, where porosity is lower than water saturation, and lower than 50%, a considerable inverse polynomial relation is achieved. In the left half of the curve, where porosity is higher than water saturation, and higher than 50% (poorly saturated sediments) a direct polynomial relation exists. In this part of the curve Archie's second law does not deviated from its power law to a polynomial correlation only but it breaks down also, where formation factor has a direct correlation with porosity and water saturation. However, for practical purposes, a direct correlation between (F) and (φ) is in common usage [3]. Martys [22] used Lattice Boltzmann method to numerically simulate the diffusive transport of ions in two classes of partially-saturated porous media as a function of saturation and wetting properties. At high saturations, good agreement is found between his estimates of diffusivity and that predicted by the semi-empirical Archie's second law. At lower saturations, it is found that Archie's second law breaks down as percolation effects become important. His study resulted in an empirical polynomial function between relative diffusivity (σ_{bi}/σ_b) and water saturation (S_w),where σ_{bi} is the electrical conductivity of fluid and σ_b the electrical conductivity of wetted (partially saturated) porous material.



(a) (b)

Fig. 1. Analytical relation between formation factor, porosity, water saturation, and water content when (a) water saturation = 1, and (b) porosity = water saturation

Since, Figure 2 describes two different hydrogeological media, they are separated and presented in Figure 3,a and b.

Figure 3 describes the relation when water saturation > 50% > porosity (fig. 3a) and when water saturation < 50% < porosity (fig. 3b). The best fit to the analytical data (correlation coefficient equal 1) is the polynomial regression fourth order (blue line), where power correlation shows a lower fitting (red line) in the two cases. Figure 3,a still reflect the inverse relation between intrinsic formation factor and both porosity and water saturation.

However, Figure 3,b reflects a direct correlation between intrinsic formation factor and both porosity and water saturation, which is in agreement with Martys [22] and Borner et al. [3]. Applying these direct and inverse relations in the modified Kozeny-Carmen model (eq. 4), we can get an inverse correlation between hydraulic conductivity and formation factor in the first case (fig. 3a) and a direct correlation in the second case (fig. 3b). Comparing these results with some published empirical relations concluded between aquifer hydraulic conductivity from pumping test and formation factor, shows an agreement.

Another group of case studies reported the opposite behavior i.e., the direct relation between aquifer hydraulic conductivity and formation factor [1; 20].

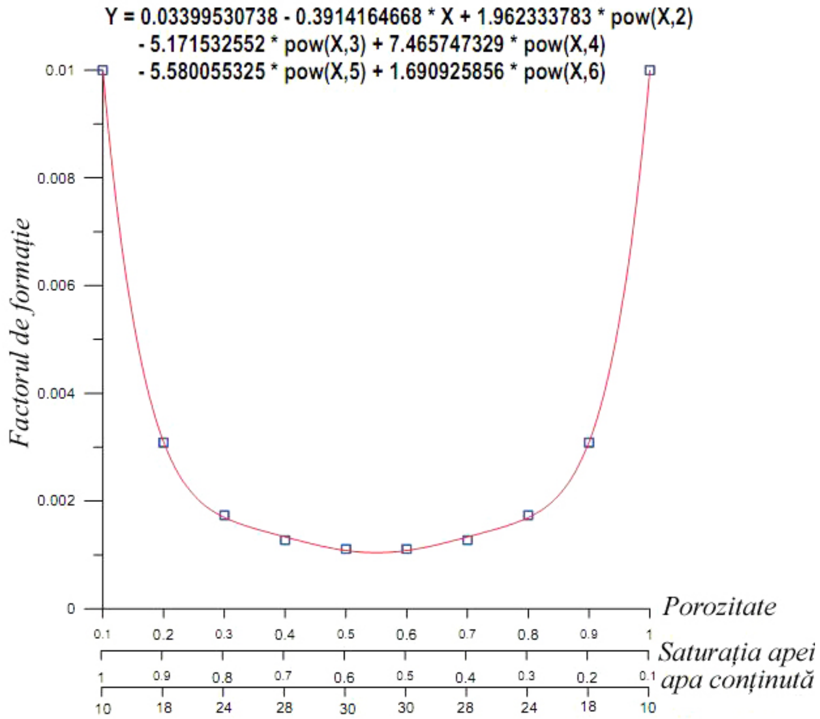
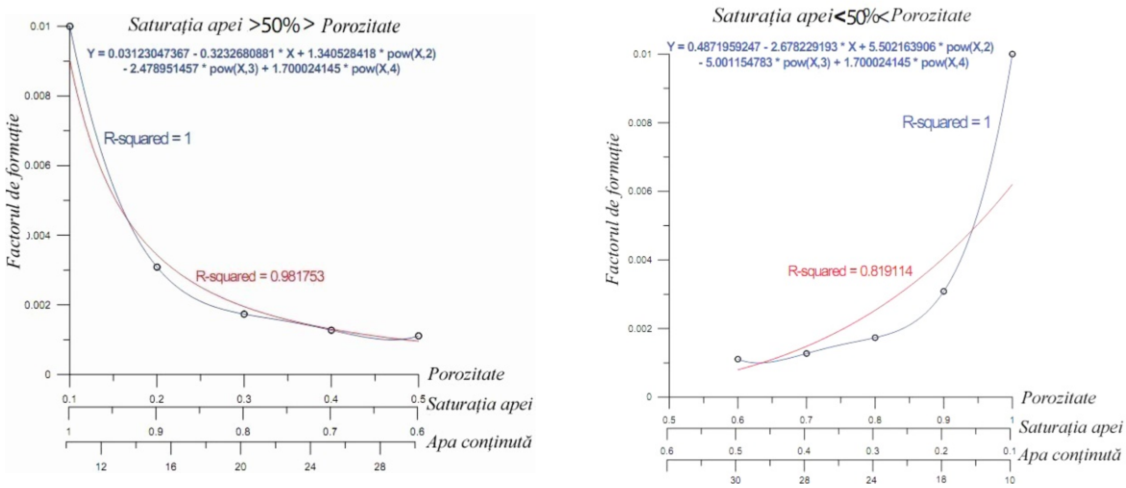


Fig. 2. Analytical relation between formation factor, porosity, water saturation, and water content when porosity ≠ water saturation



(a) (b)

Fig. 3. Analytical relation between formation factor, porosity, water saturation, and water content in the two different cases

In the view of present analysis (figs. 1, 2, and 3), we can expect a group of relations between hydraulic conductivity (K) and formation resistivity (R_0), differ in mathematical expressions and hence in curve form. These relations could be classified into 3 characteristic cases.

In the next section, we will try to compare the present results with some previously published empirical relations between aquifer resistivity and hydraulic conductivity in different geographic locations and hydrogeologic conditions with a comparison between expected porosity and saturation from our models with that measured, as possible as the data is available.

First Category (Fully Saturated Aquifer or Water Saturation Equals Porosity)

Two case studies (fig. 4a, b) are collected: (a) fractured crystalline bedrock, central landfill, Rhode Island, USA [13], (b) Granitic host rock, (OUC), Hyderabad, AP, India [26].

A considerable inverse power correlation between hydraulic conductivity and aquifer resistivity exist in the two case studies. The correlation coefficient of the power relation is higher than that of polynomial in the two cases. Geologically, all cases are from fractured hard rock aquifers. The fractured crystalline bedrock, central landfill, Rhode Island, USA (fig. 4a) is characterized by high fractured granite, high hydraulic conductivity, no primary permeability and hydraulic flow is restricted to fractures, and no clay, where weathering product of granite decomposition, have been washed out by glacial melt waters [13]. Water resistivity ranges from 41 to 125 Ohm.m [13].

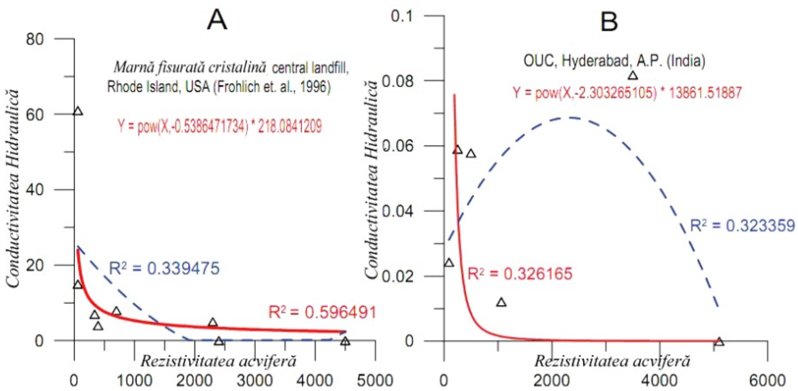


Fig. 4. Empirical relationship between hydraulic conductivity and aquifer resistivity in different location (red sold line is the power relation; blue line is the polynomial relation)

Estimated porosity from the published data of formation resistivity (R_0), water resistivity (R_w), and formation factor (F) ranges from 19 to 82%, assuming that $a = 1$ and $m = 2$, in Archie's first law.

Data published by Singh [26] were measured in Osmania University Campus (OUC), Hyderabad AP (India) for the fractured Granitic aquifer of Archaean age.

The available information of the two fractured hard rock aquifers and the empirical inverse power correlation indicate that they are in a good agreement with our first analytical model (fig. 1).

Second Category (Water Saturation > 50% > Porosity)

Three case studies have non-linear inverse correlation between hydraulic conductivity and formation resistivity: Glacial outwash aquifer in central Illinois, USA [15], Banda area UP, India, and Mount Tsukuba, Central Japan, intact rock aquifer [27].

From Figure 5, the data are correlated as inverse polynomial with more correlation coefficient than that of power correlation, which in agreement with Figure 3,a.

As for Glacial outwash aquifer in central Illinois, USA [15], the explanation of this inverse relation was problematic. Because Kelly [17] found a direct linear relationship between hydraulic conductivity and resistivity of the water bearing deposits in two New England aquifers composed of the same glacial deposits of sand and gravel and one case study of direct relation in glacial deposits is discovered later by Frohlich and Kelly [12]. The inverse correlation was reasoned due to more poorly sorted sediments near the head of the Niantic-Illiopolis aquifer, which are responsible not only for reduced porosity and thus less hydraulic conductivity, but also for an increase in the volume of low conductivity solids which increase the resistivity of the aquifer [15]. Kelly and Reiter [18] explained the inverse relation due to the presence of clay, although the clay fraction of the aquifer was quite small (<4%) [15]. Frohlich [11] explained this inverse relation due to only three data points.

Heigold et al. [15] measured the porosity of these three samples; they are 26, 32, and 39%. Sieve analysis made on each sample indicates that the clay fraction of the aquifer was quite small (< 4%). Water resistivity is 1.818 ohm.cm, and total dissolved solids are 490 ppm. All mentioned parameters of this aquifer are in agreement with our approach in particular the porosity values. The Mount Tsukuba, Central Japan, intact rock aquifer is covered by homogeneous and fine-grained granite of late Cretaceous to early Palaeogene age.

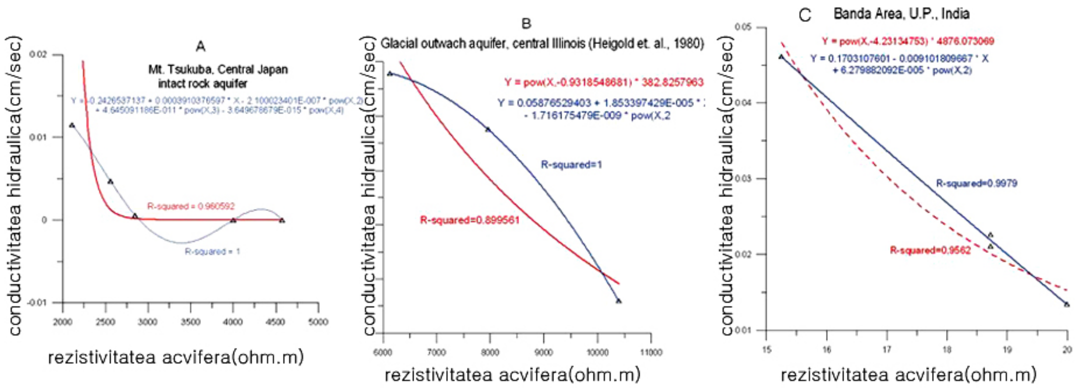


Fig. 5. Empirical relationship between hydraulic conductivity and aquifer resistivity in different locations (red dashed line is the power relation; blue line is the polynomial relation)

The relation between resistivity and hydraulic conductivity is based on electrical logging and in situ permeability data from boreholes [27].

Concerning Banda area UP, India, the presence of hard rock lithologies in the area may be the cause the negative correlation of the variation in permeability with resistivity [26]. This type of inverse correlation typically is found in saturated fractured hard rock aquifer, as previously discussed, but the polynomial correlation is attributed to dissimilarity between porosity and water saturation.

Third Category (Water Saturation < 50% < Porosity)

This category contains one case study for weathered hard rock aquifer is in Mt. Tsukuba, Central Japan [27].

Hydraulic conductivity of this aquifer has an ideal fourth order polynomial direct correlation with the aquifer resistivity. The correlation coefficient of polynomial relation (in blue) is higher than power relation (in red).

The mathematical characteristics of this sample classify it in the third category of our analytical models (fig. 3b), where porosity is higher than 50%, higher than water saturation. The category highlights the effect of low saturation on the relation between hydraulic conductivity and resistivity of porous media, where in low saturation conductivity of the electrical double layer increases, and surface conductance becomes the main transport mechanism [25; 4] (fig. 6).

Data of Mt. Tsukuba, central Japan weathered rock aquifer are sampled from fine grained Granitic rocks with cracks. The cracks have approximately 2-mm-thick fillings [27]. It is worth mentioning that the resistivity and hydraulic conductivity data of Mount Tsukuba, Central Japan, in both intact and weathered rock aquifer reflect perfectly the analytical relation in the form of polynomial forth orders. This is may reasoned to the nature of the data, where resistivity data are extracted from resistivity log, and permeability data are from in situ permeability measurements [27]. It is important to mention that such direct relation between hydraulic conductivity and aquifer resistivity could be resulted also in case of high clay content and/or high groundwater resistivity aquifers, where surface conductance effect resulted on the surface of clay mineral or sand imbedded in fresh water became the main transport mechanism, and Archie's low in these cases breaks down [16; 29; 28; 25].

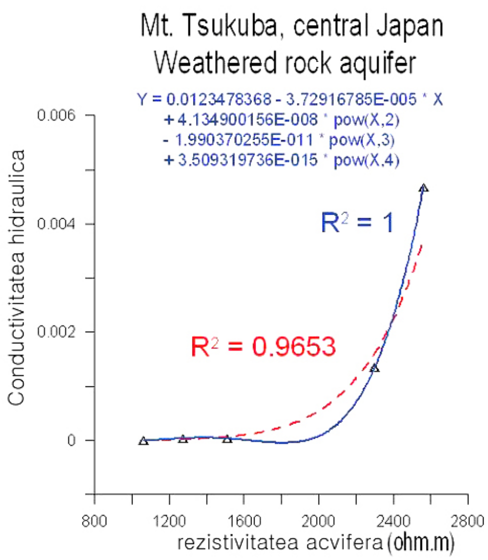


Fig. 7. Empirical relationship between hydraulic conductivity and aquifer resistivity in Mt.Tsukuba, central Japan (red dashed line is the power relation; blue solid line is the polynomial relation)

Conclusion

The present study resembles analytically the relationship between hydraulic conductivity and formation resistivity in different saturation conditions.

The controlling laws of this relation are Archie's second law, which relates formation resistivity to formation factor, and Kozeny-Carmen relation, that relates formation factor to hydraulic conductivity. According to the present study, the relation between hydraulic conductivity and formation resistivity is generally non-linear relation and could be summarized in three characteristic types according to saturation condition:

1. An inverse power relation in fully saturated aquifers and when porosity equals water saturation.
2. An inverse polynomial relation in unsaturated aquifers, when water saturation higher than 50%, higher than porosity.
3. A direct polynomial relation in poorly saturated aquifers, when water saturation lower than 50%, lower than porosity.

Some case studies are collected from different geographic location, geologic conditions, and saturation levels. Matching between case studies and analytical models shows good results, depending on the quality of data and techniques of measurements. The available petrophysical parameters of some cases are compared with the analytical models, indicating a complete matching. The present classification could be used also to predict a general idea about the petrophysical parameters of the aquifer from the type of correlation between aquifer hydraulic conductivity and formation resistivity.

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Clasificarea formaţiunilor după gradul de saturaţie în corelaţia rezistivitate electrică - conductivitate hidraulică

Rezumat

Relaţiile dintre conductivitatea hidraulică a acviferului şi rezistivitatea acviferului, măsurată la suprafaţa solului prin sondaj electric vertical (VES) din carotajul de rezistivitate sau măsurată pe probe de rocă, au fost publicate pentru diferite tipuri de acvifere şi pentru diferite locaţii. În general, aceste relaţii sunt empirice şi semi-empirice şi sunt valabile pentru un număr redus de situaţii. Această relaţie are o corelaţie pozitivă în unele studii şi negativă în altele. Până în prezent, nu există nici o lege fizică cu potenţial de control pentru aceasta relaţie, care nu este complet înţeleasă. Curentul electric curge pe căile de rezistenţă redusă, date de apă. În şi în jurul porilor, conductivitatea electrică este ionică şi astfel, rezistivitatea mediului este controlată mai mult de porozitate şi conductivitatea apei decât de rezistivitatea matricii rocii. Astfel, la nivelul porilor, curgerea electrică este similară cu cea hidraulică şi rezistivitatea trebuie să reflecte conductivitea hidraulică.

Am încercat, în această lucrare, să studiem efectul reducerii saturaţiei în apă asupra relaţiei dintre conductivitatea hidraulică şi rezistivitate prin intermediul unei analize numerice simple, pe baza celei de-a doua legi a lui Archie şi a ecuaţiei Kozeny-Carmen simplificată.

Studiul a condus la trei relaţii caracteristice non-liniare între conductivitatea hidraulică şi rezistivitate în funcţie de gradul de saturaţie. Aceste relaţii sunt: (1) o relaţie inversă în acvifere complet saturate şi când porozitatea este egală cu saturaţia în apă; (2) o relaţie polinomială inversă în acvifere nesaturate, atunci când saturaţia în apă este mai mare de 50% şi mai mare decât porozitatea; şi (3) o relaţie polinomială directă în acvifere slab saturate, atunci când saturaţia în apă este mai mică decât 50% şi mai mică decât porozitatea. Aceste rezultate sunt susţinute de unele rezultate de şantier.