ESTIMATION OF SOIL HYDRAULIC CONDUCTIVITY ON CLAY CONTENT, DETERMINED FROM RESISTIVITY DATA

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Abstract

We considered clay content in loose soil as the factor mostly influencing on hydraulic conductivity (filtration coefficient). We collected and analyzed some published experimental data about hydraulic conductivity relation with soil lithology and clay content in the form of grain size. Also we performed some theoretical modeling modifying well-known formulas to include clay content in them. Experimental and calculated data showed quite good coincidence. Correlation between hydraulic conductivity and clay content seemed better, than correlation between hydraulic conductivity and resistivity. We created some approximation formulas relating filtration coefficient with clay content. Clay content in soil can be estimated on soil resistivity obtained from VES data interpretation and from groundwater salinity found from its resistivity. Then filtration coefficient is determined on clay content. Some examples of this method practical application at clean and oil contaminated areas are presented. We considered anomalies of decreasing filtration coefficient in contaminated zones not as a real effect, but as a good indicator of contamination, though in several publications there were some indications of hydro geological changes in soil properties due to oil contamination.

Introduction

Hydraulic conductivity is an important parameter in hydrogeology. This parameter is useful for groundwater management, groundwater protection and prediction of contaminants transport.

Standard techniques to determine hydraulic conductivity, such as pump tests, tracer tests or grain size analysis require boreholes, which turn to be relatively expensive, with local results and low resolution of resulting maps. The application of superficial geophysical methods (for example, resistivity method) does not need any perforation, obtaining information faster and with higher resolution.

There are different schemes of hydraulic conductivity estimation on geoelectrical parameters, correlating hydraulic conductivity with electric resistivity. This correlation is directly proportional at regional scale (higher resistivity corresponds to higher hydraulic conductivity), but at local scale sometimes the correlation is inversely proportional (Mazac et al., 1990). In this scheme the influence of groundwater salinity and clay content on soil resistivity is not taken into account. But clay content evidently influences on hydraulic conductivity value (Mazac et al., 1990).

In some publications the idea to use transversal resistance ($T=\rho*h$, where h is the thickness of the subject layer) for hydraulic conductivity estimating was discussed. This parameter can be found with higher accuracy than resistivity, because equivalence principle does not influence on it (Melkanovitsky, 1984, Geophysical methods …, 1985). In this scheme the influence of groundwater salinity and clay content is not taken into account as well.

Salem (2001) published the formula relating hydraulic conductivity with formation factor F that leads to finding hydraulic conductivity from resistivity data obtained through VES method:

$$K_f = 7.7 \cdot 10^{-6} \cdot F^{2.09}\ m/s = 0.66528 \cdot F^{2.09}\ \text{m/day, where } F = \rho_{soil}/\rho_{water} \qquad (1)$$

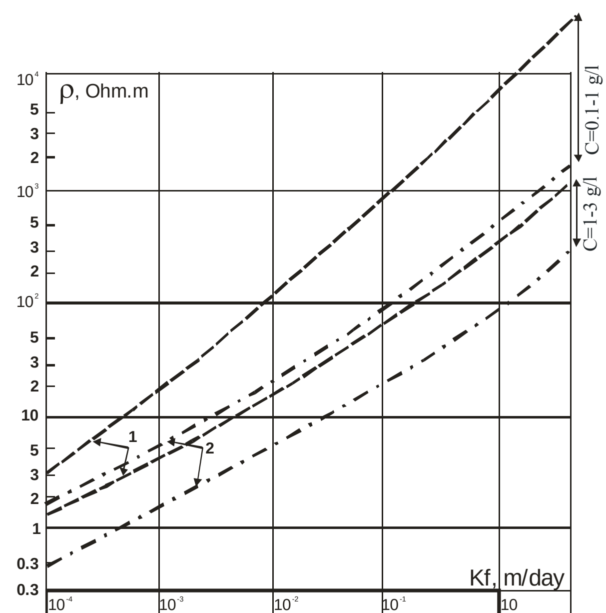
This formula takes into account groundwater salinity influence (through F) but does not consider clay content. When the formation factor is estimating for clay-rich soils this formula is only valid for narrow salinity interval.

Berg (1970) revealed, that in some heterogeneous mixture of different grains, its hydraulic conductivity is controlled by the component with the finest pore system, in other words by clay content.

Clay content influence on filtration coefficient was described in some publications (Marion, 1990; Knoll et al., 1995) as an important factor of the relation between geophysical parameters and hydraulic conductivity for unconsolidated sediments.

Ogilvy (1990) showed results of filtration coefficient studies in the following figure 1.

The dependencies obtained by Ogilvy (1990) between electric resistivity and filtration coefficient for different conditions of humidity and groundwater salinity are presented in Figure 1. At the same time this figure shows relation between soil lithology (sand, sandy loam, loam, clay, with subdivisions for each lithological group), grains size (14 gradations) (inside black frame), and filtration coefficient. The last row with clay content estimated on soil lithology and grains size was added to the table by us. By using this modified table (now with clay content) it was possible to create our formula (10) for filtration coefficient calculation.



Lithology	Clay			Loam			Sandy-Loam			Sand			Pebbles	Boulders
	H	M	L	H	M	L	H	M	L	FG	MG	CG		
d, mm	10^{-5}	10^{-4}	10^{-3}	$2\text{-}5 \cdot 10^{-3}$	$5\text{-}10 \cdot 10^{-3}$	$1\text{-}2 \cdot 10^{-2}$	$2\text{-}5 \cdot 10^{-2}$	$5\text{-}10 \cdot 10^{-2}$	$1\text{-}2 \cdot 10^{-1}$	$2\text{-}5 \cdot 10^{-1}$	0.5-1	1-2	2-10	10-80
Clay, %	100	70	50	40	35	30	20	15	10	4	2	1		

Figure 1.: Dependence between soil resistivity and filtration coefficient for different groundwater salinities (0.1-1 and 1-3 g/l) for natural humidity (1) and at full saturation (2). Legend: d – diameter of soil grains; H, M, L: heavy, medium and light soil subgroups; FG, MG, CG – fine, medium y coarse grained subgroups (from Ogilvy, 1990).

The main relation shown in Figure 1 is disadvantageous: there is no tight relation between filtration coefficient and resistivity because resistivity depends on groundwater salinity and humidity. This figure indeed has an important advantage showing relation between filtration coefficient and soil lithology, grain size and clay content (in the table below the graphs).

Some empirical and theoretical interrelations between the Spectral Induced Polarization (SIP) parameters and hydraulic conductivity were studied both in theory and in laboratory by Börner et al. (1996), Slater and Lesmes (2002). Other researchers (Hördt et al., 2005) performed field measurements through SIP method for hydraulic conductivity estimation. But SIP method is rather complex for fieldworks and needs measurements in wide frequency interval (at least 4 frequency orders). This is the reason why this method seems more useful in the laboratory than in the fieldwork up to now.

According to Börner et al. (1996) hydraulic conductivity can be calculated with the help of Kozeny – Carman equation on values of formation factor F and the specific inner surface area Spor (estimated on the imaging part of complex conductivity measured through the SIP method):

$$k_f = \frac{1}{F(S_{por})^c} \qquad (2)$$

where k_f is in m/s and S_{por} is in 1/μm, $S_{por} = 8.6 \cdot \mathrm{Im}(\sigma)$, σ in S/m, and coefficient ***c*** is a constant in the interval 2.8 - 4.6.

According to Slater and Lesmes (2002), S_{por} is related to the imaginary part of superficial conductivity σ'' which depends on the Cation Exchange Capacity - CEC (in other words - depend on clay content) and depends (in less extent) on electrolytic conductivity (of pore water). Slater and Lesmes demonstrated that σ'' has correlation with d_{10} (granulometric parameter) being nothing else but the fine part of soil component (in other words it is clay).

With the help of superficial electrical methods (like VES) a great volume of non destructive, fast and low cost electrical measurements is feasible performing, contrasting with direct measurements of hydraulic conductivity.

Based on the similarity existing between electric and water current distribution in soils and rocks (using the same pore system) it is possible to establish and use correlation between hydraulic conductivity and electrical parameters.

Calculation Expressions

According to Kozeny theory (Gavich et al., 1983), porous media is considered as a group of fine tubes with the same longitude. Hydraulic conductivity of such system is equal to:

$$K_f = A*\phi^3 d^2 / (36 (1 - \phi)^2 \tau_h^{2}), \qquad (3)$$

where: θ - is porosity for Kozeny model; d – is a tube diameter; mm; τ_h – is a tortuosity; A - is some constant of units: $A=0.92*10^8$ for d in mm and Kf in m/d.

There are some formulas of Kf calculations based on grains diameter (Salem, 2000; Kobranova, 1986).

The formulas of Kobranova (1986) are based on equal diameter spheres, packed on different geometrical systems. For example, for hexagonal packing the expression is the following:

$$K_f = A \cdot \frac{\pi d^2}{32\mu}, \qquad (4)$$

and for cubic packing:

$$K_f = A \cdot \frac{\pi d^2}{128\mu}, \qquad (5)$$

where: d - is diameter of sphere, mm; μ - is viscosity of fluid; $A=0.75*10^6$ (when d is in mm and Kf in m/d).

Expressions (4-5) present the same disadvantage: they do not consider clay content directly. Clay is presented in **d** values, in soil grain size, but can be expressed directly, taking into account clay content by using the next formula, published by Konishi y Kobayashi (2005):

$$d = \left(\frac{C}{d_C} + \frac{1-C}{d_S} \right)^{-1}, \qquad (6)$$

where C is clay content, d_c is clay grains diameter, d_s - is sand grains diameter, d - is the mean value of grains diameter in the soil mixture, with variable clay content.

We can calculate Kf in formulas 4 and 5, taking into account clay content, put in ***d*** value with the help of formula (6). To use formula (3) for Kf calculation, we need to calculate tortuosity with the help of Salem and Chilingarian (2000) formula:

$$\tau = \sqrt{F \cdot \phi}, \qquad (7)$$

where F means formation factor and ϕ is porosity.

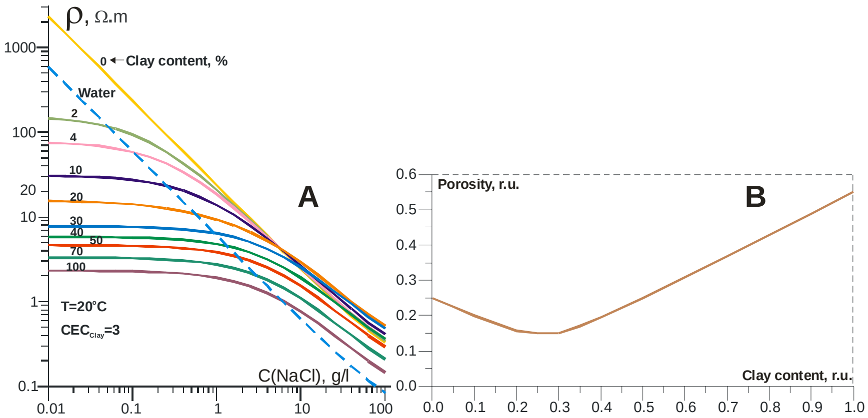


Figure 2.: Theoretical graphs of soil resistivity versus groundwater salinity for different clay content (for clay-sandy soils). B - Relation between soil porosity of clay-sandy soil and clay content.

Theoretical graphs - resistivity versus salinity for different clay content values are displayed in figure 2, A, calculated with Ryjov's algorithm Petrofiz (Ryjov y Sudoplatov, 1990). This algorithm also calculates soil porosity, taking into account porosities of sand and clay components and their concentrations (figure 2, B).

For clay-sand mixture Ryjov and Sudoplatov (1990) used the next empirical formulas of soil porosity dependence from volumetric clay content C:

$$\phi = (\phi_S - C) + \phi_{Cl} \cdot C \quad \text{when } C < \phi_S \qquad (8)$$

and

$$\phi = C \cdot \phi_{Cl}, \quad \text{when } C > \phi_S, \qquad (9)$$

where ϕ_S is sand porosity and ϕ_{Cl} is clay porosity.

We now have all parameters for hydraulic conductivity calculation using formula 3. Results of calculation on formulas 3 and 4 are in Table 1 and Figure 3.

Table 1.: Calculation of hydraulic conductivity using formulas 3 and 4 (for model C en fig. 3).

Clay content, r.u.	**Porosity, r.u.**	**d, mm**	**Tortuosity**	**Kf_Kozeny Carman (m/d)**	**Kf_Kobranova (m/d)**
0.001	0.2455	0.0910	1.224	390.37	608.614
0.002	0.2491	0.0476	1.223	106.59	166.991
0.005	0.2478	0.0196	1.219	17.814	28.3135
0.01	0.2455	0.0099	1.214	4.433	7.21924
0.02	0.2410	0.00498	1.202	1.066	1.82281
0.05	0.2275	0.00199	1.168	0.1476	0.29340
0.1	0.2050	0.00099	1.046	0.0288	0.07350
0.15	0.1825	0.00067	0.980	0.00945	0.03269
0.2	0.1600	0.00050	0.910	0.00387	0.01839
0.25	0.1375	0.00040	0.995	0.00174	0.01177
0.3	0.1650	0.00033	1.075	0.00185	0.00818
0.35	0.1925	0.00029	1.075	0.00198	0.00601
0.4	0.2200	0.00025	1.149	0.00212	0.00460
0.5	0.275	0.0002	1.284	0.00246	0.00294
0.7	0.385	0.00014	1.520	0.00342	0.00150
0.9	0.495	0.00011	1.723	0.00507	0.00091
1.0	0.550	0.0001	1.817	0.00638	0.00074

The main conclusion from figure 3 is: Kozeny-Carman and Kobranova formulas give similar results at low clay content and results slightly different at high clay content. Change of grain size in one order (for clay or sand component in their mixture) changes filtration coefficient in one order. Model A is not typical on clay grains diameter, but models B-E show real parameters of sand and clay grains and the difference between B and E models is four orders in Kf. Models: A: ds=10^{-4} m, dc=10^{-8} m; B:

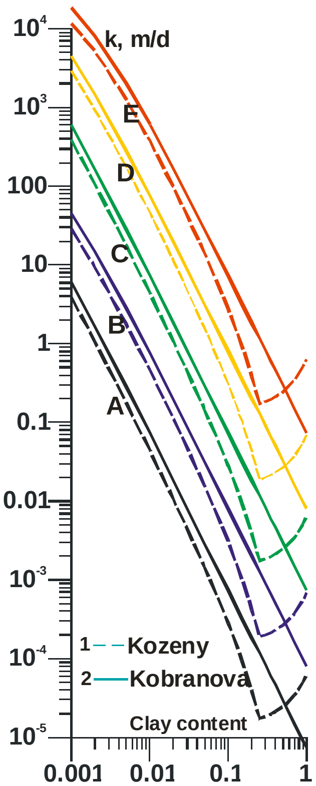


Figure 3.: Hydraulic conductivity versus clay content calculated on formulas (3-4).

Formula 11 was obtained by using experimental data as clay content and hydraulic conductivity estimated in the laboratory and presented in publication of Slater and Lesmes (2002). This information led us to calculate correlation between filtration coefficients measured directly and estimated from clay content (Fig. 5) for different types of formations (sand, till, silt, loam, mixture of sand and clay, kaolinite and bentonite) with correlation coefficient

ds=10^{-4}, dc=$3.3*10^{-8}$; C: ds=10^{-3}, dc=10^{-7}; D: ds=10^{-3}, dc=$3.3*10^{-7}$; E: ds=10^{-3} m, dc=10^{-6} m, (ds - diameter of sand grains; dc - diameter of clay grains).

In coordinate system of clay content and filtration coefficient (in Figure 4) different data are presented: experimental data from several publications (Ogilvy, 1990; Mazac et al., 1990, Slater & Lesmes, 2002; etc.), theoretical calculations using formulas Kozeny-Carman (3) and Kobranova (4) for models B-D from fig.3, empirical formula of Salem (1) and approximation formulas (as straight lines in logarithmic coordinates) for data of Ogilvy (10), Slater & Lesmes (11) including our approximation formula (12) for all data in this figure.

These approximation formulas can be used for recalculation of practical clay content values into filtration coefficient values. These formulas are the following:

$K_f = Clay^{-2.5} \cdot 1.5 \cdot 10^{-4}$ (approximation for Ogilvy (1990) data) (10)

$K_f = Clay^{-2.33} \cdot 4.39 \cdot 10^{-4}$ (approximation for Slater & Lesmes data) (11)

$K_f = Clay^{-2} \cdot 7.2 \cdot 10^{-4}$ (approximation for all data in this paper) (12)

where Clay is clay content in relative units between 0.01 and 1.

These expressions have some restrictions such as: clay content shouldn't be zero, and are only valid for clay-sand soils.

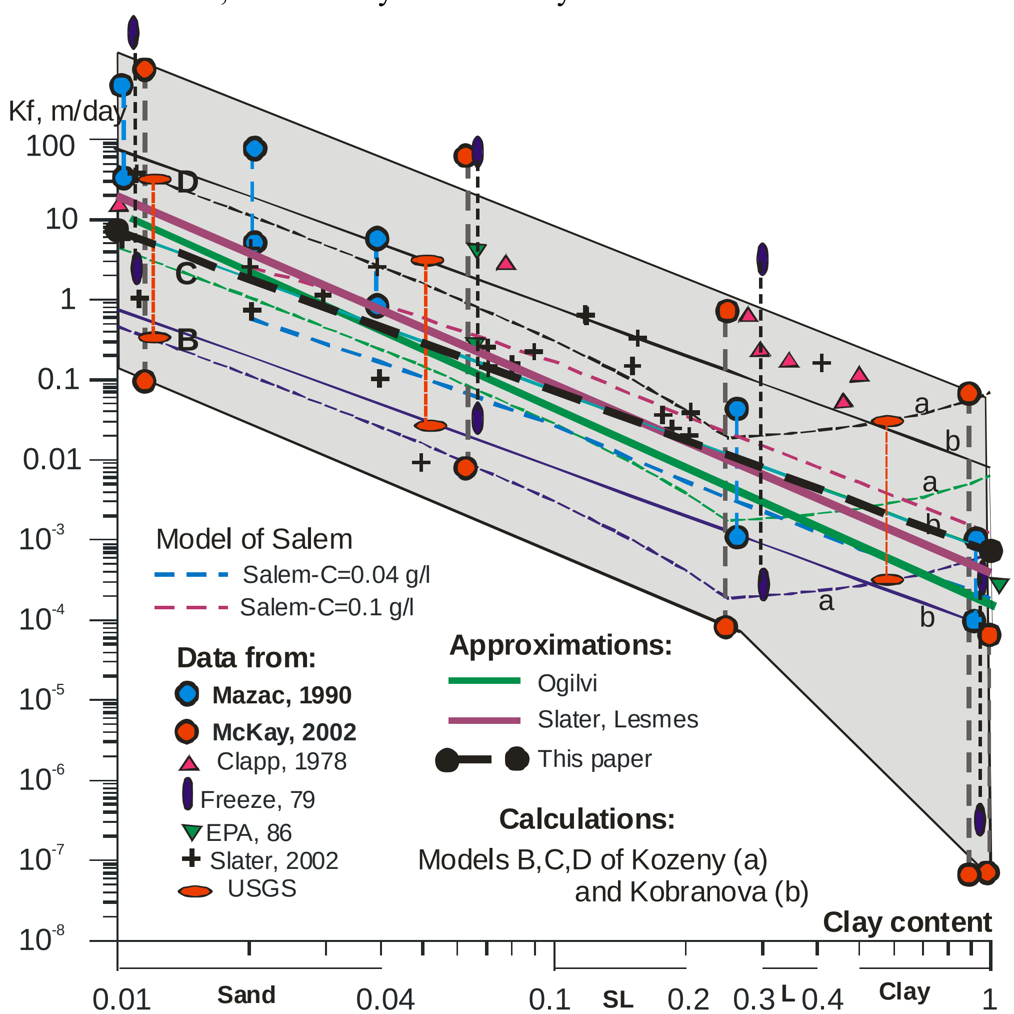


Figure 4.: Dependencies between clay content and filtration coefficient.

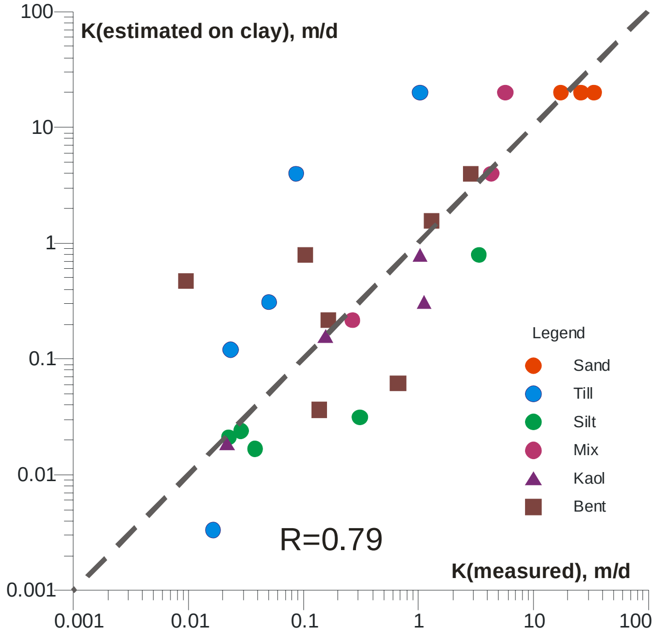


Figure 5.: Correlation between values of hydraulic conductivity measured and estimated on clay content. Correlation coefficient is 0.79. Legend of points is based on classification of Slater & Lesmes (2002).

0.79, helping us to create formula (11).

By means of the VES method application it is possible to estimate filtration coefficient on base of clay content, calculated on soil resistivity and groundwater salinity (Shevnin et al., 2004). Finally, it is possible to calculate the hydraulic conductivity with the following steps:

Geoelectrical measurements along profiles with VES method (in 2D Resistivity Imaging modification) in the studied site.

2D VES data interpretation in order to find true resistivity distribution.

Recalculation of true resistivity values (along with groundwater salinity of the studied site) into clay content.

Recalculation of clay content values into filtration coefficient (hydraulic conductivity values).

Clay Content Estimation on Geophysical Data

Hydraulic conductivity estimation on clay content can only be practical when geophysics can give us clay content. Two technologies for clay content estimation on resistivity measurements were developed. The first technology is based on soil sampling and the measurements of soil resistivity versus pore water salinity in the laboratory (Shevnin et al., 2004). In this case, maximal error of clay content estimation is in the limits 0.7 - 1.4 of the true clay content value (Figure 6). Such error level leads to reliable estimation of main lithological types of sand-clay soils, such as: sand, sandy loam, loam, clay.

The other technology was developed for recalculation of values of soil resistivity and pore water salinity into values of clay content, with the help of the program IzoPlan developed by Ryjov (Shevnin et al., 2005). It is not necessary for this technology to collect soil samples and measure them in the laboratory, but to use only electric resistivity values obtained from VES data interpretation and groundwater salinity, determined in situ with some resistivimeter. Probably, an error of clay content estimation by using this technology should be higher, than in the case of soil sample measurements in laboratory. Taking into account our two years of experience, we concluded that maximal errors of clay content estimation do not exceed 0.5 - 2 times the true clay content value. For example, for clay content value

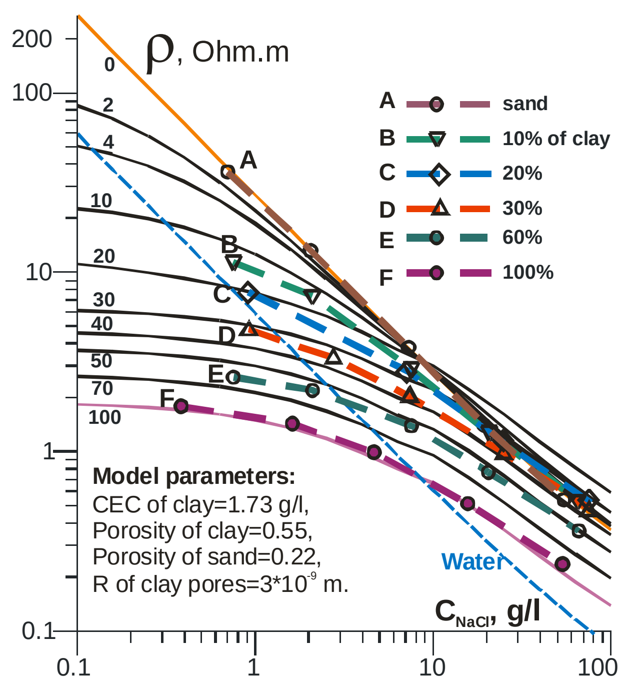


Figure 6.: Theoretical graphs of soil resistivity versus pore water salinity for different values of clay content, and practical graphs (A - F), received on soil resistivity measurements in the laboratory.

0.02 (2%) there will be error limits between 0.01 - 0.04 (1% - 4%). An error in clay content calculation will produce an error in hydraulic conductivity estimation. After using formulas (10 - 12), an error in Kf calculation shouldn't be over 0.5-5 of true Kf value (at the local level), but according to figure 4 the regional dispersion has 4 orders of magnitude for some clay content value. Such error can only be diminished with the help of Kf calibration at the studied site.

Clay content variation between 0.01 and 1 (1 - 100%) produces 50,000-fold variation in Kf value. In this case the 5-fold error in Kf calculation constitutes only 1/1000 part of the total Kf range. With this level of errors we count on the needed resolution in Kf calculation ensuring real Kf value estimation within one order or decade of logarithmic scale, in all range of Kf values. So we shall receive an acceptable Kf estimation in the intervals 0.01-0.1; 0.1-1; 1 -10 m/d, etc., this accuracy is sufficient enough to resolve the majority of hydrogeological problems.

All experimental Kf data in Figure 4 have noticeable dispersion (up to 4 orders of magnitude!) for any clay content. There are different factors that cause this dispersion: General variation of Kf values is in limits from 5 to 9 orders of magnitude. When these values were obtained directly (with hydrogeological methods), they were very dispersed and insufficient in quantity (low resolution). There are also different types of clay with different Kf values, for example, exchange of clay montmorillonite to kaolinite changes Kf in two orders of magnitude (De Wiest, 1965). Change of sand and clay grains diameter can change hydraulic conductivity as shown in fig. 3 and 4. Superficial soil frequently has horizontal layering (with anisotropy in its properties). As a result values of hydraulic conductivity in horizontal and vertical directions differ up to 4 orders of magnitude (Gavich et al., 1983). Kulchitsky et al., (2000) found in different types of clay two types of capillaries with diameters 10 angstrom (typical for clay) and 400 angstrom. Difference 40 times in diameters corresponds to 3 orders of magnitude in Kf.

Practical Examples

We developed a technique of hydraulic conductivity calculation based on clay content values found on VES resistivity and groundwater salinity. Similar to VES data results, hydraulic conductivity values can be presented as cross-sections (for VES profiles, Fig. 8), maps (Fig. 9) or tables of parameters (Table 2).

As an example of this technique application we demonstrate the site Km42, Tabasco, where cross-section includes four layers, such as superficial covering (layer 1), loam (layer 2), sandy aquifer (layer 3), and clay-rich basement (layer 4) (Fig. 7). This site was studied after some oil contamination event, contamination level was low that is why mean values of layers parameters in Table 2 can be considered as non-contaminated soil values.

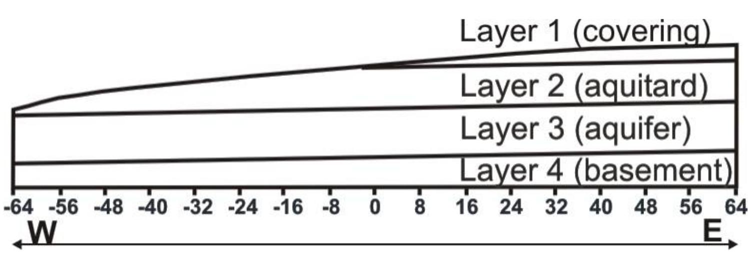


Figure 7.: Geological cross-section for the site Km42.

Table 2.: Properties of the layers in the cross-section of the site Km42.

Layer	**Rho, Ohm.m**	**Clay, %**	**Porosity, %**	**CEC, g/l**	**Kf, m/d**
Covering (Layer 1)	54	14	19	8	0.02
Aquitard (Layer 2)	30	23	14.6	14	0.005-0.01
Aquifer (Layer 3)	280	2	24.5	1.2	1-2.65
Basement (Layer 4)	10	59	32	34	0.0006

We calculated petrophysical parameters (Table 2) by using mean values of electrical resistivity for each layer and mean groundwater salinity (0.05 g/l) estimated for this site.

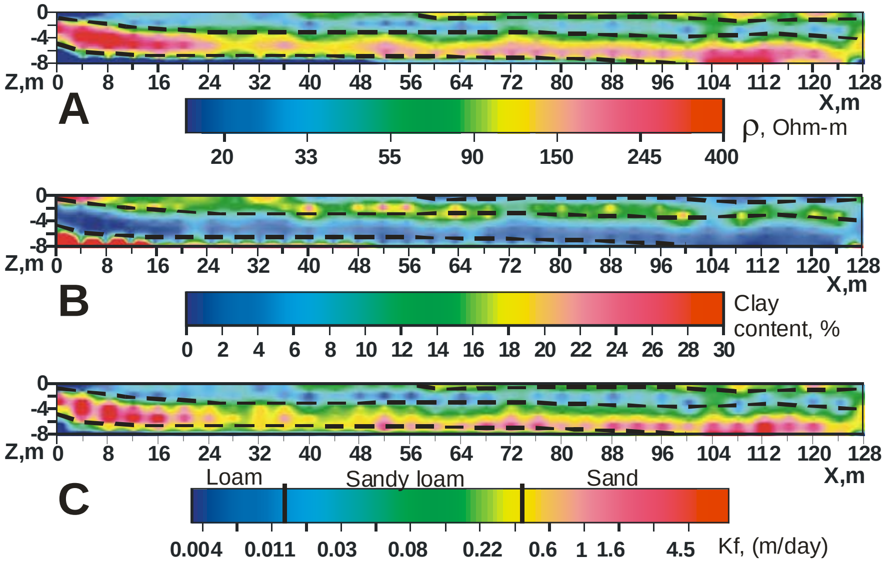


Figure 8.: Vertical cross- sections on VES data interpretation for profile 1 of the site Km42: A - resistivity; B - clay content; C - hydraulic conductivity. Dotted lines mean approximated geological boundaries.

There are three cross-sections for the same profile of the site in Figure 8: resistivity cross-section obtained after 2D VES data interpretation, cross-sections of clay content and filtration coefficient. At these cross-sections it is possible to separate four layers on values of resistivity, clay content and filtration coefficient. The main sandy aquifer is clear visible on its maximum resistivity, minimum clay content and high values of filtration coefficient.

In Figure 9 three maps: electric resistivity, clay content and filtration coefficient are presented for oil contamination site named Mecatepec, Ver. In resistivity map there is a low resistivity anomaly corresponding to petroleum contaminated zone. This contaminated zone is shown in two other maps by anomalous values of clay content and filtration coefficient. These anomalies also allow contaminated zone mapping. Probably clay content and filtration coefficient values are not true within contaminated zone, but these apparent anomalous values allow mapping contaminated zone both in plan and with depth, sometimes with higher accuracy than with resistivity data. We think that petrophysical parameters (in this case clay content and filtration coefficient, estimated on VES data are very useful and practical for contamination mapping.

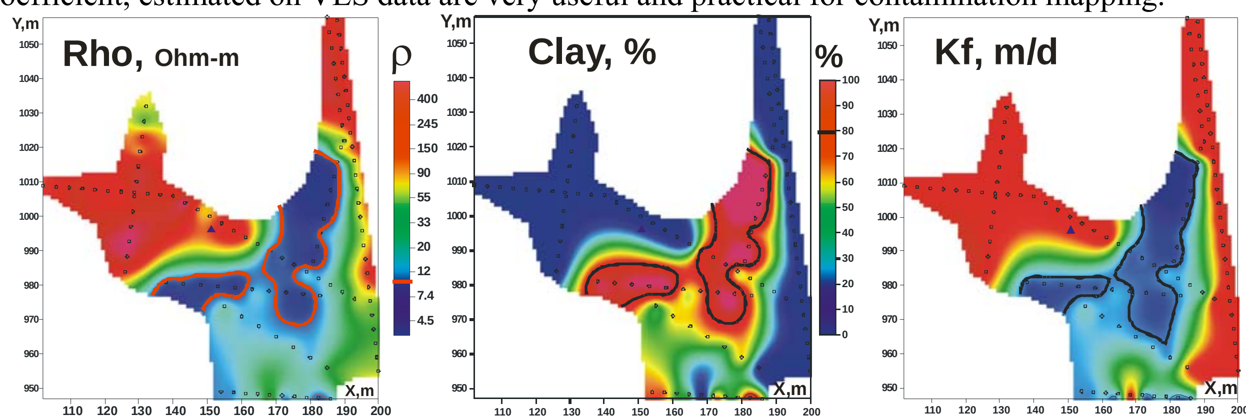


Figure 9.: Maps for layer 3 of the site Mecatepec obtained on 2D VES data interpretation: resistivity; clay content and filtration coefficient. Bold lines on the maps marked contamination zones estimated on VES.

Conclusions

1. - Estimation of filtration coefficient values with the help of superficial geophysical methods has an advantage in comparison with direct estimations of this parameter due to their quickness, high resolution and low cost.
2. - Filtration coefficient is related to different soil parameters, and among these, in our opinion, clay content has the best correlation with filtration coefficient.

3. - The technology here described allows clay content estimating on true resistivity (obtained from VES interpretation) and groundwater salinity values (determined in situ with groundwater resistivimeter).
4. - The steps for estimation of filtration coefficient are the following:
a) VES field measurements in the area of study with Resistivity Tomography (2D Resistivity Imaging) technology.
b) 2D interpretation of VES data (with the program Res2DInv).
c) Measurements of groundwater resistivity in all possible points of the site to estimate its salinity.
d) Recalculation of two parameters (soil electrical resistivity and groundwater salinity) into clay content (with the help of IzoPlan program). In this step we can use soil resistivity received from different electrical and EM methods.
e) Recalculation of clay content into filtration coefficient with the help of formulas (10 - 12).
f) Visualization of calculation results as sections and maps.

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