# SOIL RESISTIVITY MEASUREMENTS FOR CLAY CONTENT ESTIMATION AND ITS APPLICATION FOR PETROLEUM CONTAMINATION STUDY

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## Abstract

Information about clay content is useful at contamination study because clay influences on position and movements of contaminants by means of soil permeability and adsorption. Technology for clay content estimation is based on soil resistivity measurements as function of water salinity at full saturation of soil samples and data interpretation (or inversion) to find clay content and porosity of the sample. Together with water resistivity estimation for an investigated site this information permits characterizing uncontaminated soil and estimating boundary conditions for separating uncontaminated and contaminated zones. This information helps in geological interpretation of vertical electrical sounding data. Soil resistivity is determined by pore water resistivity, porosity, clay content and humidity. To reduce number of unknown factors influencing on resistivity, we measure both soil and water resistivity in the survey area. Soils below a groundwater level have humidity 100 % of pore space that allows not taking this factor into account. Measurements of water and soil resistivity can be performed with different types of resistivimeters and field resistivity meter. Estimating soil parameters is performed with the help of forward and inverse petrophysical calculation.

Measurements of petrophysical parameters on calibrated sand and clay samples and on their mixtures showed good accuracy of clay content estimation.

We studied sensitivity of petrophysical algorithm to principal soil parameters and estimated errors of interpretation depending on input error.

Practical examples from different contaminated sites are presented. These demonstrate good correspondence between vertical electrical sounding data, water and soil resistivity measurements, and petrophysical estimations.

## Introduction

The application of resistivity method is based on apparent resistivity determination with the help of some four-electrode array. As a result of interpretation true layers resistivity is estimated. The resistivity technique (like vertical electrical sounding - VES) is usually applied to analysis of shallow geological structures (frequently up to depth 20 m). In many cases the upper part of a section is composed of unconsolidated sediments, for example of sand and clay mixture. When groundwater salinity is low, the clay content in soil influences greatly on geoelectrical soil properties. Measurements of soil and water resistivity together with superficial resistivity survey make the process of interpretation more definite in geological conclusions. For hard rocks the technology of electrical properties measurements is sufficiently developed (for example, Taylor and Barker, 2002; Waxman and Smits, 1968). Samples of unconsolidated sediments should be packed into some containers. Resistivity can be measured at different water saturation (Taylor and Barker, 2002), different salinity (Waxman and Smits, 1968) or at different frequencies (Seabrook and Boadu, 2002; Wildenschild, Roberts and Carlberg, 1999).

Petrophysical model is essential part of technique allowing estimate some model parameters. There are many petrophysical models proposed by G. Archie, V. Dakhnov, M. Waxman and L. Smits, A. Ryjov. This list is really very long.

The technology described in this paper is based on soil resistivity measurements at full saturation as a function of pore water mineralization and estimating soil porosity, clay content and cation exchange capacity. These parameters together with water resistivity are helpful for geological characterization of a study area and for separating uncontaminated and contaminated zones.

## The forward problem of water and soil conductivity calculation

A.Ryjov developed the method of water and soil conductivity calculation in 1984 – 1990 (Ryjov, 1987; Ryjov, Sudoplatov, 1990). It includes analysis of soil components mixture with estimation of this mixture properties and electrochemical calculation of free water resistivity and water in porous space of soil. As a result soil resistivity is calculated (Ryjov and Shevnin, 2002).

The soil model includes the next components: a component with wide pores (sand), a component with narrow pores (clay), fluid in sand and fluid in clay. The words wide and narrow pores are used to emphasize their dimensions in comparison with double electric layer (DEL) thickness. DEL thickness depends on water salinity, but in near surface conditions fresh water salinity changes in limits of two orders (0.05 - 2 g/l), while difference in pore size between sand and clay consists 3-4 orders. We consider capillaries as cylindrical paths of definite radius (radii are different for sand and clay) with the same longitude and neglect their tortuosity. The total pore volume in sand and clay is expressed through a porosity value, separately for sand and clay. Thus the mix model consists of two types of capillaries having different radii. In general the model includes: sand and clay skeleton, non-conducting electrical current; elements with parallel connection of sand and clay capillaries; elements with series connection of sand and clay capillaries.

The conductivity in a double electric layer is higher, than in a free solution, and the less is salt content in solution, the more this difference is. At approach to a capillary wall the cations concentration grows (on 1-1.5 order), and the anions concentration decreases that breaks an electroneutrality of a solution near to skeleton - fluid interface. The significant concentration of free charges near to the interface essentially raises DEL electrical conductivity. As a result the electrical conductivity of a fluid with decreasing of capillaries' radius grows and essentially differs from electrical conductivity of an electroneutral solution. The DEL thickness decreases with concentration growth. In solutions with concentration more then 100 mol/m$^3$ it is possible to neglect the DEL influence (Ryjov, 1987; Ryjov, Sudoplatov, 1990).

Water and soil resistivity depends on temperature. For correction of resistivity measurements to 293°K (20°C) the next simple formula is used (for both water and soil):
$$\rho_{293} = \rho(T)\,[1 + \alpha\,(T - T_0)], \tag{1}$$
where $\alpha$ is a temperature coefficient equal to 0.0177, 1/°K, $T_0 = 293$°K (20°C).

To calculate conductivity of capillary ($\sigma_C$) we take into account a double electric layer and calculate $\sigma_C$ as the integral along the radius r perpendicular a capillary wall. This formula is applied to "active" and "passive" capillaries (in clay and sand), with the influence of cation exchange capacity and without it:
$$\sigma_C = \frac{2zFK_p}{r_C^2} \int_0^{r_C} r\left[ U_c \cdot (C_c(r) + C_{co}) \cdot \exp\left(\frac{C_c(r) + C_{co}}{1000zn}\right) + U_a \cdot (C_a(r) + C_{ao}) \cdot \exp\left(\frac{C_a(r) + C_{ao}}{1000zn}\right)\right] dr, \tag{2}$$
where $C_c(r)$, $C_a(r)$ - concentration of cations and anions, dependent from a distance r from the capillary wall (mol/m$^3$) (these parameters depend on the type of salt in solution); $C_{co}$ ($C_{ao}$) - concentration of ions

in cation (anion) exchange capacity (these parameters depend on soil properties); $K_p$ - soil porosity, $U_a$, $U_c$ - ions mobility; n - hydration number; $r_C$ – capillary radius. Such approach allows taking into account different solutions (NaCl, KCl, $Ca(HCO_3)_2$, $CaCl_2$, $MgCl_2$, $CaSO_4$, $NaHCO_3$, $Na_2SO_4$, etc). In formula (2) values $C_{co}$ and $C_{ao}$ are different, but to simplify calculations we shall consider these equal. To calculate sand or clay conductivity we multiply conductivity of capillary on sand or clay porosity.

Some examples of this approach application were published in Ryjov, 1987; Ryjov, Sudoplatov, 1990; Ryjov and Shevnin, 2002.

Fig. 1 shows an example of theoretical dependence of sandy-clayish mixture resistivity from groundwater salinity, calculated for the following parameters: NaCl solution and full soil saturation, temperature 20°C, sand porosity 25%, clay porosity 55%, CEC (Cation Exchange Capacity) of clay is 3 g/l. (Values on curves – clay content in % from 0 (sand) until 100 (clay) and soil porosity in %). Inclined dash line is for water resistivity. If groundwater resistivity is 20 Ohm.m, we can estimate on fig.1 water mineralization (0.3 g/l) and lithological legend, where each type of soil (sand, sandy loam, loam, light (C3), medium (C2) and heavy (C1) clay) has its own resistivity interval. Knowing groundwater and soil resistivity (at full saturation), we can estimate with the help of fig.1 the soil lithology, clay content and porosity. Looking at fig.1 we can see that soil porosity changes with growing of clay content from porosity of sand (25%) to porosity of clay (55%) passing through minimum (16%) for 20% of clay. Pure sand with 100% humidity has resistivity 4 times more, than water. Resistivity of sandy-clayish mixture is more, than that of water and sometimes sand (at high water salinity) due to mixture porosity lower then for sand. Resistivity is lower, than that of water and sand (at low water salinity). The cause of that effect is in the influence of double electric layer in clay. For the first time such figure was published in Russia in Sharapanov et al, 1974 (on experimental data); and then in Ryjov, 1987; Ryjov, Sudoplatov 1990 (as theoretical calculation).
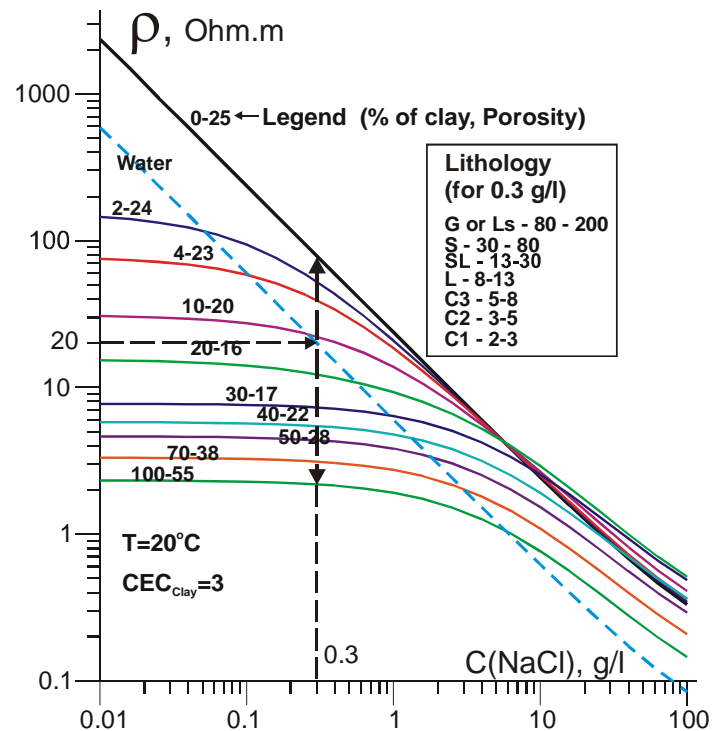


**Figure 1.:** Theoretical dependence of sandy - clayish mixture resistivity from groundwater salinity

## Information analysis

The principles of information analysis (or sensitivity analysis) of geophysical problems were developed in different countries, in Russia in works of F.M.Goltsman, 1971, L.N.Porohova (Statistical..., 1981), in France in works of A. Tarantola (1994).

If we describe a forward geophysical problem in symbolical form as f=A p (3), where f is geophysical field (in our case f=ρ(C)), p - vector of model parameters, A - a forward problem operator, then it is possible to describe an inverse problem as p = A$^{-1}$ f (4), where A$^{-1}$ is an operator inverse to A. By virtue of inverse problem non-linearity it is inconvenient to realize transformation (4) practically, but it is possible to linearize an inverse problem. For linearization lets decompose formula (3) in Taylor series, taking into account only the first derivatives:

$$f = A\vec{p}_0 + F \cdot \Delta\vec{p} + \vec{\varepsilon}. \qquad (5)$$

where F is a matrix of the first partial derivatives $F_{ji} = \partial f_j^t / \partial p_i + \varepsilon$, $\varepsilon$ − vector of residuals, which we turn down later. $f^t$ denotes $A\vec{p}_0$, $j$ − index of C, $i$ − index of parameters. From (5) we obtain:

$$\frac{f - f^t}{f^t} = \frac{p}{f^t} F \frac{\Delta p}{p} \qquad (6)$$

By using the next notations $Y = \dfrac{f - f^t}{f^t}$, where Y is a vector of the relative differences between theoretical and experimental curves, $X = \dfrac{\Delta p}{p}$, where X is a vector of the relative corrections in parameters $\Phi = \dfrac{p}{f^t} F$ - $\Phi$ is a matrix of the logarithmic partial derivatives of the field f on model parameters p:

$$\frac{\partial \ln f}{\partial \ln p} \approx \frac{p \cdot \Delta f}{f \cdot \Delta p}. \qquad (7)$$

Now we shall rewrite (6) as: $\Phi X = Y$ . (8)

Expression (8) is a system of linear algebraic equations for the corrections in parameters $\Delta p / p$. To find these we can inverse the system (8). $X = \Phi^{-1} Y$ (9).

In statistical definition of an inverse geophysical problem the matrix $\Phi$ is called an information matrix of Fisher (its diagonal terms show a relative information quantity introduced by each model parameter), and $\Phi^{-1}$ is called a covariance matrix or the matrix of errors. On its diagonal terms it is possible to determine errors of parameter estimation, while the off-diagonal terms determine correlation between jointly estimated parameters.

The information analysis (Statistical..., 1981) is the analysis of the matrix $\Phi$ components (partial derivatives of the field f on model parameters), diagonal terms, and the matrix $\Phi^{-1}$ (errors and correlations between jointly estimated parameters).

We have applied the information analysis to the algorithm of soil resistivity calculation considering such parameters as porosity, clay content, humidity, cation exchange capacity (CEC), clay capillary radii and temperature.

The figure 2 has been calculated for sand porosity 25%, clay porosity 55%, radius of sand capillaries is $10^{-4}$ m, of clay capillaries - $10^{-8}$ m, CEC of clay=3, CEC of sand is 0, humidity is complete (100% of pores volume), temperature 20°C. The numerical method (calculation of the function increments through increments of each argument) was applied for calculation of partial derivatives. It is possible to make the following conclusions from fig. 2.

Most strongly the soil resistivity depends on porosity, then humidity, clay capillary radii, clay content and then CEC (for small salinity). Temperature influence is equal for all salinities. The minimum on informant curve for clay content
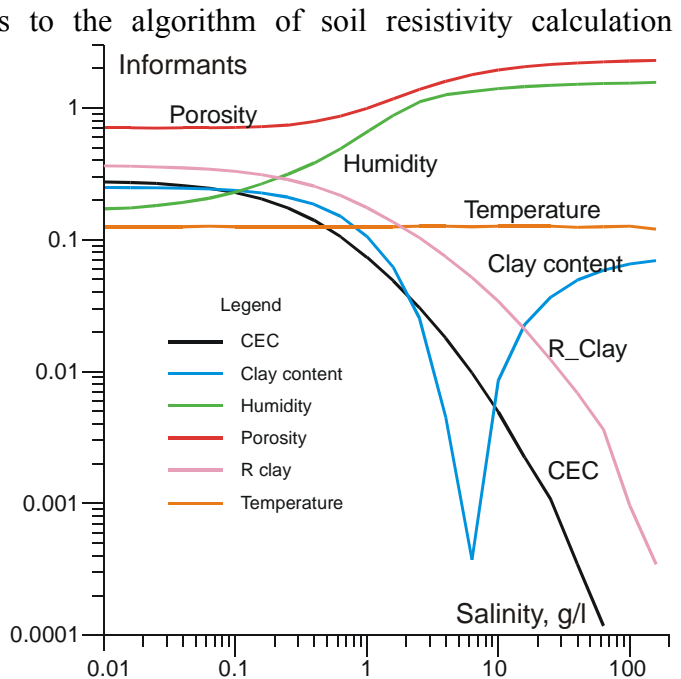


**Figure 2.:** Informants for six model parameters.

resulted in the sign change of the first derivative, for fresh waters the clay content growth decreases resistivity, and for salted waters - the clay content growth increases resistivity with decreasing porosity (see Fig.1). Nonlinear reaction of resistivity on clay content helps to estimate this parameter.

The clay capillary radii and CEC informants descend similarly and sharply with salt content growth, since the DEL (double electric layer) influence is decreasing. The influence of clay capillary radii is more than CEC.

The information matrix of Fisher contains on its main diagonal a relative information quantity introduced by each parameter:

**Table 1.:** Relative quantity of information about each parameter in information matrix

| CEC | Clay content | Humidity | Porosity | R clay |
|-----|-------------|----------|----------|--------|
| 2.353 | 2.746 | 19.172 | 29.37 | 3.791 |

The greatest information quantity in the curve $\rho(C)$ resulted from porosity (29.37), then humidity (19.172), clay capillary radii (3.791), clay content (2.746) and CEC (2.353). We have eliminated temperature effect from further analysis, since temperature can be measured and taken into account easily. Similarly we can eliminate humidity working with fully saturation samples.

Inversed from the information matrix is a covariance matrix, and correlation matrix after its normalization. Before the inversion the regularization should be made. We have used a regularization of the diagonal terms of a matrix $\Phi$ according to the next formula:

$$\Phi_{ii} = (\Phi_{ii} + \alpha) + \Phi_{ii} \cdot \beta, \qquad (10)$$

where $\alpha$ and $\beta$ are some constant coefficients (Statistical..., 1981).

The diagonal terms of a covariance matrix allow estimating an error of interpretation and confident limits of joint parameters estimation.

The off-diagonal terms of a correlation matrix contain some information about a correlation between jointly estimated parameters.

**Table 2.:** Correlation matrix

|  | CEC | Clay content | Humidity | Porosity | R clay |
|--|-----|-------------|----------|----------|--------|
| **CEC** | 1 | -0.347 | 0.396 | -0.391 | 0.494 |
| **Clay content** | -0.347 | 1 | -0.061 | 0.507 | 0.621 |
| **Humidity** | 0.396 | -0.061 | 1 | -0.859 | 0.176 |
| **Porosity** | -0.391 | 0.507 | -0.859 | 1 | 0.245 |
| **R clay** | 0.494 | 0.621 | 0.176 | 0.245 | 1 |

The maximal correlation between porosity and humidity is -0.859, sign minus shows, that when one parameter is growing the other is descending. When we work with 100% humidity, this parameter is fixed and doesn't influence. The next high correlation 0.621 is between clay radii and clay content.

On the diagonal terms of the covariance matrix we find errors of parameters estimation. Below they are displayed as confident limits (minimal and maximal). Two methods of these limits estimation were used (by the standard deviation of an error ($\gamma$) and by the standard deviation factor of an error – STDF ($\varepsilon$)).

$$\gamma = \sigma \cdot \sqrt{\Phi_{ii}^{-1}} \cdot p_i, \quad \varepsilon = \sigma \cdot \sqrt{\Phi_{ii}^{-1}} \qquad (11)$$

Here $\sigma$ is an error of input data (estimated on control measurements or on fitting error between theoretical and experimental data).

**Table 3.:** Parameters values and intervals of their estimation at input error 5%.

| Parameter | Value | Min (on ε) | Max (on ε) | Min (on γ) | Max (on γ) |
|---|---|---|---|---|---|
| CEC, g/l | 3 | 2.517 | 3.575 | 2.474 | 3.526 |
| Clay content | 0.1 | 0.088 | 0.114 | 0.087 | 0.113 |
| Humidity, % | 1 | 0.939 | 1.065 | 0.937 | 1.063 |
| Porosity, r.e. | 0.205 | 0.193 | 0.218 | 0.192 | 0.218 |
| R clay $*10^{-6}$ m | 0.01 | 0.008 | 0.012 | 0.008 | 0.012 |

As it is visible from the table 3 at an error of input data 0.05 (5 %) both methods give similar estimations of limits.

More evident presentation of dependencies between errors in input data (in an interval 1-14%) and errors of parameters estimation is given in Fig.3. Porosity and humidity have minimal errors of parameters estimation, as earlier was indicated in an information matrix, because data contains more information about them. CEC has a maximal estimation error.



**Figure 3.:** Errors in parameters estimation as function of fitting error.

Possibility of forward calculation of soil resistivity allows passing to inverse problem by using the dependence of soil resistivity from water salinity ρ(C). At the interpretation of ρ(C) curve an estimation of clay content and porosity is performed automatically, while the CEC and R clay values are fixed. As CEC, clay and sand porosity and sometimes R clay also require estimation, their variation is performed manually. The main criterion is the fitting error minimum and reasonable coincidence with additional geological information.

Practical estimation of porosity $K_p$ demonstrated that this value in reality was $K_p{}^m$, where m is cementation exponent that slightly increases with clay content growth. For unconsolidated soils m is 1.2-1.3. All estimations of porosity below are $K_p{}^m$ values.
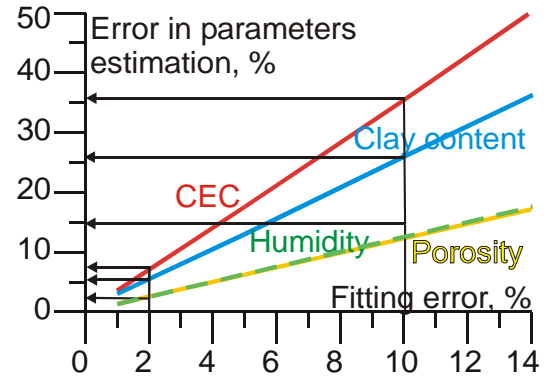
## Resistivity of unconsolidated soils

Resistivity of solid rocks and unconsolidated soils depends on porosity, humidity, temperature, conductivity of pore water, porous space structure (cementation factor, pore tortuosity), etc. Pores are the spaces in soil that are filled with air or liquid and are distributed in a rock volume heterogeneously. Pores interconnected with each other are named effective porous space, whereas pores isolated from each other are named as porous space with a small or zero effective porosity. Clay is usually considered as a soil with small effective porosity, though its general porosity is rather high and sometimes achieves 60 % from the total rock volume. In a hard rock, for example, in a limestone there are some fractures and caverns among regularly distributed micro-pores (named usually as primary pores). In well-sorted fluvial sand the structure of porous space is more homogeneous and is defined by empty space between mineral grains (mainly quarts and feldspar). The elementary model of a porous soil is a system of spherical particles (grains) of rather small radius and identical size. In the case of spherical particles the porosity does not depend on their radius, but depends on a type of stacking. Porosity at cubic stacking is equal to 47.64%, and at hexagonal stacking - 25.95%. In practice, the sand porosity is increased at reduction of the grains size. It is explained that pores in sand frequently have not identical radii and are formed by not spherical particles.

Structure of granular porous medium is characterized by a curve of particles' size distribution or grading curve. The particles distribution often submits normal or lognormal statistical laws. If porous medium is determined only by a single distribution curve, it is named homogeneous; if medium is characterized by at least two distribution functions F(r), such medium is named heterogeneous. We are considering loose porous media consisted of two principal components - sand and clay. This is a heterogeneous model. We shall consider a soil as a model of several components. The 1-st component (sand) contains wide pores; the second component (clay) contains narrow pores, fluid in sand and clay pores is the next component. The model of a multicomponent mix (sand and clay) can include both parallel and series connection of sand and clay capillaries. At parallel connection the clay is distributed as films on the walls of capillaries in sand, while at series connection the clay is distributed as corks in capillaries of sand.

## Laboratory Method

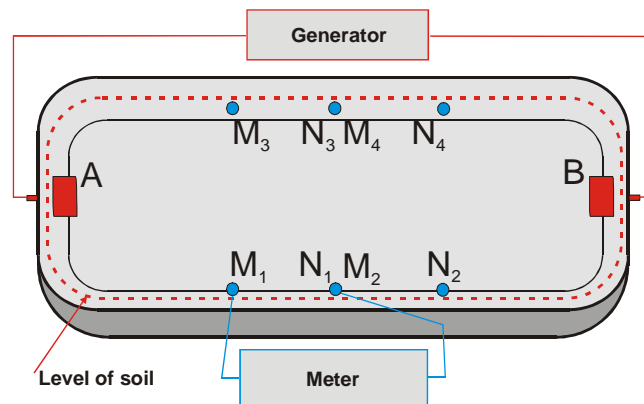***Resistivity measurements of the unconsolidated soils.***



**Figure 4.:** Resistivimeter for unconsolidated soil

We have tried to simplify a resistivimeter construction having the purpose to make accessible similar measurements to any group of geophysicists. As temperature and humidity are not our purpose of study, all measurements were performed at complete water saturation and corrected to temperature 20°C.

For estimating soil resistivity we apply a flat plastic box resistivimeter (fig. 4). In such a box it is faster and easier to load a new sample of a soil and to remove it after measuring. Several MN lines are used to diminish measuring errors. Another source of errors is a soil level in resistivimeter. The deviation from the fixed filling level produces errors. It is necessary to saturate a soil with water and then to check the level once more. The clayish soils can increase its volume as a result of humidifying. We used resistivimeters of different volumes between 200 and 725 cm$^3$ (with the size from 10.5 x 6.5 x 3 until 22 x 11 x 3 cm). Geometrical coefficients of resistivimeters (for each MN line) were found by calibration with water of known resistivity.

For each sample we measured soil resistivity several times after sample preparation. Preparation of sample includes filling the resistivimeter with the soil and with water of known salinity. At the end of preparation the sample level should correspond the volume mark and soil humidity should be 100%. Sample can change its volume in the process of preparation and its resistivity can vary during some time until stabilization. To have a stable resistivity value for sandy samples 10 min is enough. For clayish samples, if take into account their viscoelastic properties and their capacity to expand and contract volume due to salinity variations, the resistivity stabilization requires more time (0.5 – 1.5 h).

## Difficulties at soil resistivity measurements, distorting their results

1. Incomplete water saturation of the sample.
2. Excessive water saturation.
3. No uniform water saturation (there are more dry parts in the sample).
4. Too rapid solution preparation (yet not all salts were dissolved). Resistivity measuring during solution preparation differs from its resistivity a bit later (1 hour).
5. Deviation from a fixed level of soil in resistivimeter.
6. Process of a sample drying – to avoid it we used a protective film or tap.
7. Temperature variations are not taken into account. Change of T at 0.6° gives 1% change in $\rho$.
8. No uniform mixing of sand and clay, when in different soil boxes clay content is different.
9. Solutions with low mineralization (less than 0.6 g/l) sometimes give distorted results because of natural soil salinity.

## Resistivity measurement of calibrated samples

We performed series of measurements with pure fine-grained silica sand, bentonite clay and their mixtures, presented in figure 5. We have tested two methods for soil model preparation - blending fixed volumes of dry sand and clay with the subsequent moistening or separate moistening of each component up to complete water saturation and then blending their fixed volumes. The second method is more laborious, since samples are prepared separately for 5 different water salinities. A volume of sand does not depend on salinity. At clay saturation its volume increases (up to 25 %) and differently depending on water salinity. At usage of the first method (moistening of the mixture) the volume of a mixture increases and it is necessary to remove some part of the mixture. Apparently, that in this case mixture has the heightened content of clay, and the surplus of clay depends on salinity.

Interpretation of soil resistivity graphs (displayed in fig.5) was performed in two stages, at first each curve was interpreted independently, and then all curves together, trying to obtain models with similar sand and clay characteristics. At individual interpretation the main factor was good correspondence of the estimated clay content with the real one, used at mixture preparation. It was
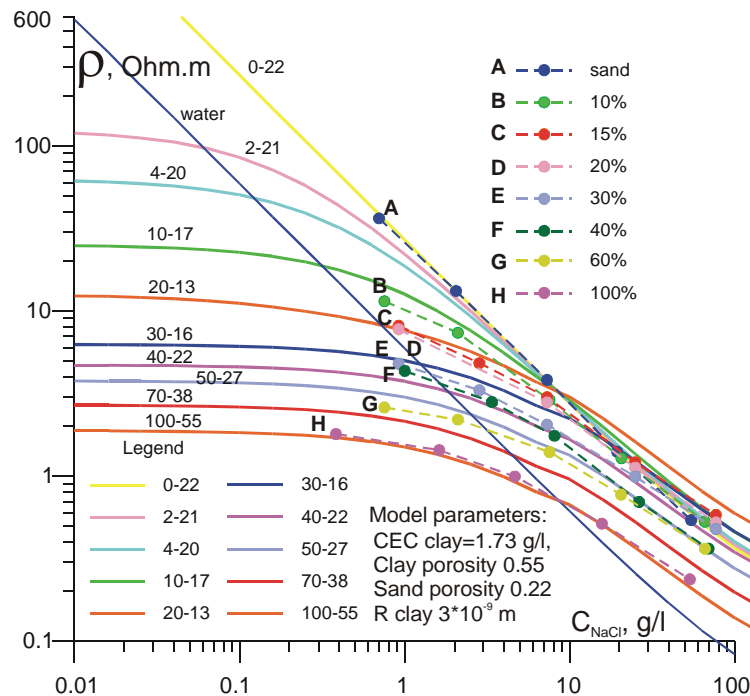


**Figure 5.:** Resistivity measurements for pure sand, clay and their mixtures.

possible, but the other parameters (first of all CEC), were rather different for different mixtures. At the second stage we tried to minimize differences in sand and clay parameters for different mixtures. For this purpose it was necessary to refuse precise coincidence of the clay content in the samples and to change parameters of sand and clay porosity and clay capillary radii that we did not change at the first stage. The results of the second stage of interpretation are presented in table 4.

**Table 4.:** Results of $\rho(C)$ curves interpretation for calibrated samples.

| Sample | CecClay, g/l | CecSoil, g/l | Clay content,% | Soil porosity, % | $R_{clay}*10^{-8}$ m | Clay porosity, % | Sand porosity, % | Fitting error, % |
|--------|-------|-------|------|------|------|------|------|------|
| Sand | ----- | ----- | 0 | 22.5 | ---- | ---- | 22.5 | 3.6 |
| 10% clay | 1.4 | 0.18 | 14 | 21.2 | 0.3 | 55 | 27 | 3.5 |
| 15% | 2.2 | 0.4 | 19 | 16.9 | 0.3 | 55 | 25 | 4.6 |
| 20% | 1.4 | 0.3 | 22 | 18.5 | 0.3 | 55 | 28 | 3.6 |
| 30% | 1.3 | 0.47 | 37 | 19.8 | 0.3 | 55 | 28 | 3.5 |
| 40% | 1.5 | 0.8 | 53 | 28.1 | 0.6 | 55 | 28 | 3.9 |
| 60% | 1.25 | 0.74 | 59 | 30.8 | 0.3 | 55 | 28 | 2.5 |
| 100% | 1.8 | 1.75 | 98 | 50 | 0.3 | 53 | ----- | 3.1 |

It is necessary to make some comments concerning this table. At $\rho(C)$ curve interpretation for clean sand its porosity was found diverse (22.5%), than in a mixture (27-28%). Now we can't explain this fact. We don't estimate clay parameters at interpretation of clean sand sample, just as sand parameters at clean clay interpretation. The clay content was overrated for 10-40 % of clay and was underrated for 60-100 % of clay. In spite of some errors the type of soil (sand, sandy loam, loam, clay) was found correctly.

## Some practical examples of soil resistivity measurements.

We performed several measurements of soil resistivity from different areas in Mexico with resistivimeters like presented at fig.4. For each sample we prepared several solutions of NaCl with concentration between 0.1 and 80 g/l. Each soil sample was separated into 4-5 equal probes for measuring soil resistivity with different water salinities.

Dependencies of soil resistivity of water salinity were interpreted quantitatively to find several soil characteristics: clay content, soil porosity, cation exchange capacity (CEC), capillary radii for clay component and sometimes sand and clay porosity. Usually we assigned sand porosity equal to 25% and clay porosity 55%. Results are presented in Table 5 and in figures 6-9. Each figure shows experimental dependence of soil resistivity from water mineralization in comparison with theoretical curves for different clay content between 0 (pure sand) and 100% (pure clay) and dependence of water resistivity on salinity. Theoretical dependence is a function of many factors: a type of salt (we used NaCl only), temperature (20°C), clay content and type of clay (calculations were made for hydromica), position of clay in pores of sand (parallel position of clay in sand capillaries or in series, we used model with 75% of parallel and 25% of serial connection of clay in pore of sand). Pore radii also influence on soil resistivity because of the double electric layer thickness in capillaries. We used pore radii $10^{-4}$ m for sand and $10^{-8}$ m for clay. Soil porosity depended on clay content. Final fitting error between experimental and theoretical $\rho=f(C)$ curves was between 2 and 6% depending on soil homogeneity. Results of interpretation are in Table 5.

**Table 5.:** Results of parameters estimation for soil samples

| N | Sample | Clay content, % | Porosity, % | CEC of clay | CEC of soil | Fitting error |
|---|--------|-----------------|-------------|-------------|-------------|---------------|
| 1 | MPI - 1 | 9 | 21 | 7.2 | 0.65 | 3.2 |
| 2 | MPI - 2 | 6 | 22 | 7.2 | 0.43 | 5.5 |
| 3 | Campo 10 | 63 | 35 | 0.45 | 0.28 | 2.9 |
| 4 | Gómez Palacio | 41 | 23 | 2.9 | 1.2 | 4.6 |
| 5 | Paredon - 31 | 43 | 24 | 0.12 | 0.05 | 2.1 |

At figure 6 there are theoretical graphs of sandy-clayish soil resistivity (figures on lines – clay content in % and porosity in %) and the graph of water resistivity as function of water salinity together
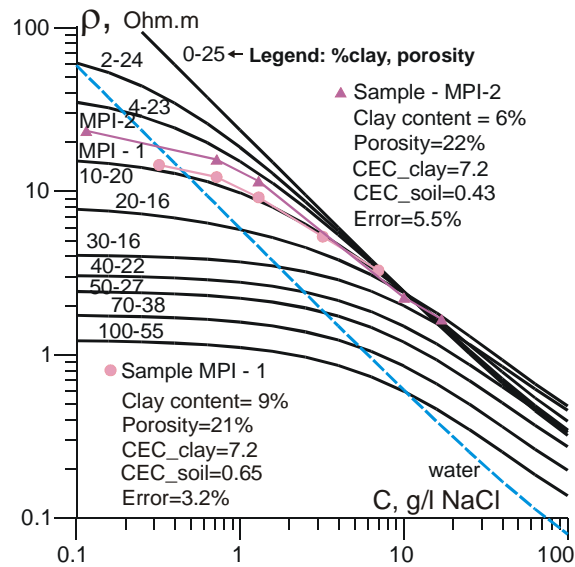


**Figure 6.:** Experimental result and theoretical dependence of soil resistivity versus salinity. Samples MPI – 1 and 2.

with two samples of soil taken in the Mexican Petroleum Institute (MPI). The experimental resistivity measurements are marked with circles and dash lines. Five solutions with salinity from 0.1 up to 20 g/l were used for samples preparation. This soil is light sandy loam. The characteristics of two samples are
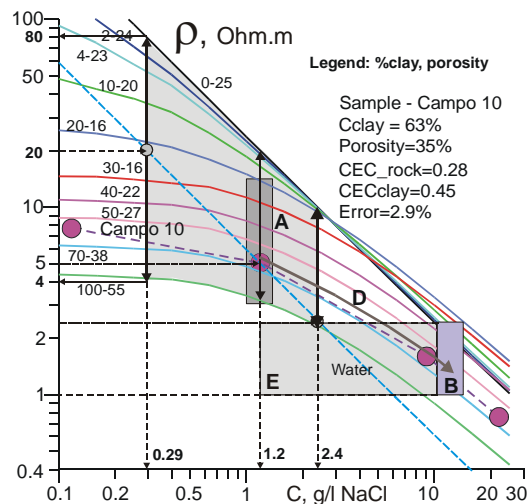


**Figure 7.:** Sample – Campo 10

similar. In this probe we received rather high CEC of clay value (7.2). This sample was the only one for cultivated soil.

Sample from Campo 10, Poza Rica, Veracruz (fig.7) is an example of soil from the site, were oil contamination was studied (Shevnin et al., 2003b). It is heavy lumpy clay with many inclusions of sand and gravel. We had problems with preparation of homogeneous samples for our measurements. After adding water the volume of the sample had grown. We received several measurements of water resistivity in the study area with values 20, 5 and 2.45 Ohm.m and supposed that 5 Ohm.m was more typical value of groundwater resistivity Vertical lines drawn in crossing points of these three values with the line of water resistivity are marked in fig.7 as light gray polygon. On statistical distribution of VES apparent resistivity values for the uncontaminated area these values are in interval 3-15 Ohm.m (gray rectangular A). That is why we are considering the value 5 Ohm.m as typical value of groundwater resistivity. Resistivity distribution for contaminated zone is in interval 1-2.5 Ohm.m (gray rectangular E). Boundary value between uncontaminated and contaminated soil was estimated equal to 2.8 Ohm.m. Rectangular B means that in the process of long-time contamination water resistivity probably should decrease 20 times when soil resistivity decreases 5 times (arrow D). The other possibility is discussing below for the site Paredon.

Sample from site near the city Gómez Palacio, Durango (fig.8). In this site two probes of water and one probe of soil were measured. Water resistivity was 9 and 15.4 Ohm.m (in two probes separated at several km). These values corresponded to water salinity 0.4-0.6 g/l (gray rectangular A in fig.8) with mean value 0.5 g/l. Soil resistivity was measured at three values of water salinity between 0.3-30 g/l (that gave clay content 41% that corresponds to light clay or loam. Some part of this site was contaminated with oil resulted in pipeline accident. According to Ateqwana et al. (2001) oil biodegradation diminishes water resistivity 5 times for a single contamination event (rectangular B in fig.10 for C=2.5 g/l). For clay content 41% it would change soil resistivity until 4.5-5 Ohm.m (arrow D).
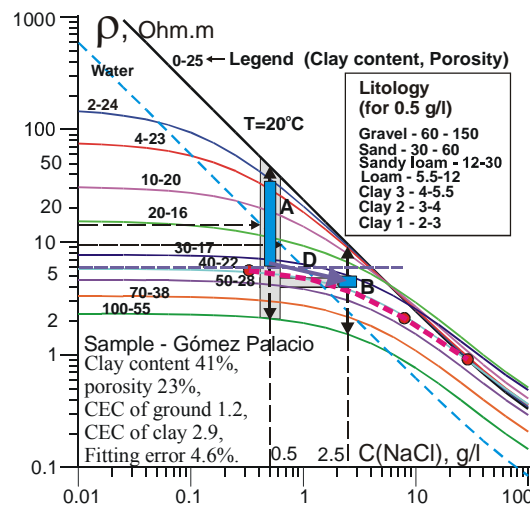


**Figure 8.:** Sample from the site near Gómez Palacio

Such values were estimated on VES data near to pipeline accident zone (rectangular B at C=2.5 g/l). Boundary value between uncontaminated and contaminated soil was estimated equal to 6 Ohm.m.

The next sample (fig.9) was taken at the site Paredon in Tabasco, where we studied oil contamination with resistivity method (Shevnin et al., 2003a). We tried to take the sample in uncontaminated zone and with probably maximal clay content. On a priory information the clay content in this site is no more than 40% and on our estimation the clay content of the sample is 43%. Cation exchange capacity of the clay (0.12) is the lowest among five investigated grounds (see Table 5). At this site the mean value of groundwater resistivity in uncontaminated zones is 27 Ohm.m. Horizontal line
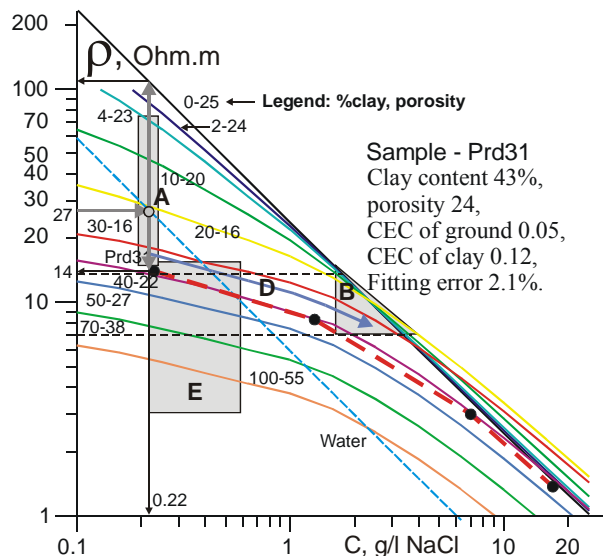
**Figure 9.:** Sample – Paredon.

with the level 27 Ohm.m has crossing point with water line in point C=0.22 g/l. In this case soil resistivity from pure sand until sand with 40% of clay is in interval 14 – 120 Ohm.m. Statistical data processing of apparent resistivity values for the uncontaminated area gives interval 15-75 Ohm.m (grey rectangular A). Statistical distribution of apparent resistivity values for contaminated zone has values 7-14 Ohm.m (polygon B). Boundary value between uncontaminated and contaminated soil was estimated equal to 15 Ohm.m. In the process of long-time contamination water resistivity probably decreased 10 times and soil resistivity decreased 2 times (arrow D).

In this site we measured water resistivity in 44 points and interpreted 260 VES. Rectangular E shows distribution of true soil resistivity in contaminated zone jointly with water resistivity in the same points. Two areas B and E in fig.9 are in some contradiction. According to position of area B water resistivity should be ten times smaller than in uncontaminated area. According to position of area E water resistivity changed until 2.5 times and change of soil resistivity looks like great increase of clay content. For the first time such effect in contaminated site was described by Ateqwana et al., 2003. At the site Paredon oil pumping well was drilled and then used for a long time. But the last 15 years this well is closed. We can suppose the next scheme of resistivity transformation for such type of contamination.

The 1st stage (one month after contamination) – the contaminated soil has higher resistivity and contamination is situated mainly in sandy part of soil.

The 2nd stage - after oil biodegradation water and soil resistivity decrease and contamination is placed in both sand and clay parts of soil. The mechanism of contamination movement in clay pores was discussed in Shevnin et al., 2002a.

The 3rd stage – groundwater movement makes water in sand cleaner and contamination concentrated mainly in clay. The situation in site Paredon and probably in Campo-10 (fig. 9) can correspond to the 3rd stage.

## Conclusions

Measurements of water and soil resistivity can provide additional valuable information for interpretation of resistivity data. For such additional measurements only resistivity instrument and resistivimeters for water and soil measurements are needed.

Technology of clay content estimation was checked on calibrated sandy-clayish mixtures and demonstrated an acceptable accuracy.

To obtain useful parameters of soil such as clay content, porosity and CEC, it is necessary to perform 4-5 soil resistivity measurements for different water salinity (between 0.6 and 80 g/l).

Knowledge of petrophysical parameters of soil makes VES data interpretation more correct at separation of contaminated and uncontaminated zones.

# References

Atekwana, E. A., Cassidy, D. P., Magnuson, C., Endres, A. L., Werkema, D. D., Jr., Sauck, W. A. 2001, Changes in geoelectrical properties accompanying microbial degradation of LNAPL, SAGEEP Proceedings, OCS1, 10 pp.

Atekwana, E. A., Atekwana, E. A., Rowe, R. S., 2003, Relationship Between Total Dissolved Solids and Bulk Conductivity at a Hydrocarbon-Contaminated Aquifer, SAGEEP Proceedings, pp. 228-237.

Goltsman, F.M., 1971, Statistical models of interpretation, Moscow, 328 pp.

Ryjov, A.A., The main IP peculiarities of rocks // In "Application of IP method for mineral deposits' research", Moscow, 1987, pp. 5-23. (In Russian)

Ryjov, A.A., Sudoplatov, A.D., 1990, The calculation of specific electrical conductivity for sandy - clayed rocks and the usage of functional cross-plots for the decision of hydro-geological problems. // In "Scientific and technical achievements and advanced experience in the field of geology and mineral deposits research, Moscow, pp. 27-41. (In Russian).

Ryjov, A. and Shevnin, V., 2002, Theoretical calculation of rocks electrical resistivity and some examples of algorithm's application, SAGEEP Proceedings, 10 pp.

Seabrook, B. C. and Boadu, F. K., 2002, Relating Electrical Response and Petrophysical Properties of Sands Subjected to Stress Changes, Journal of Environmental & Engineering Geophysics, Volume 7, Issue 2, pp. 88 – 99.

Sharapanov, N.N., Cherniak, G.J., Baron, V.A., 1974, Geophysical methods at hydrogeological survey for land improvement, Moscow, Nedra, 176 pp.

Shevnin, V., Ryjov, A., Nakamura E., Sanchez A., Korolev V., Mousatov A., 2002, Study of oil pollution in Mexico with resistivity sounding, SAGEEP Proceedings, 10 pp.

Shevnin, V., Delgado-Rodríguez, O., Fernández-Linares, L., Zegarra-Martínez, H., Mousatov, A., and Ryjov, A., 2003a, Geoelectrical and geochemical characterization of an oil-contaminated site in Tabasco, Mexico, Near surface geophysics. In print.

Shevnin, V., Delgado-Rodríguez, O., Mousatov, A., Nakamura-Labastida, E. and Mejía-Aguilar, A., 2003b, Oil pollution detection with resistivity sounding. Geofísica Internacional, Vol. 42, N 4, pp. 613-622.

Statistical interpretation of geophysical data, 1981, Goltsman, F.M. ed., LGU edition, 255 pp.

Tarantola, A., 1994, Inverse problem theory. Method for data fitting and model parameter estimation, Elsevier Science, Amsterdam, 600 pp.

Taylor, S. and Barker, R., 2002, Resistivity of partially saturated Triassic Sandstone, Geophysical Prospecting, **50**, pp. 603-613

Waxman, M.H. and Smits, L.J.M., 1968, Electrical conductivities in oil-bearing shaly sands, Journal of the Society of Petroleum Engineering, 8, pp. 107-122.

Wildenschild, D., Roberts, J.J. and Carlberg, E.D., 1999, Influence of microstructural properties on geophysical measurements in sand-clay mixtures, SEG Expanded Abstracts.