



## **METHOD OF THE CONTROLLED CURRENT REGULATION – THE SURFACE RECORDS**

## **METODA KONTROLOVANÉ REGULACE PROUDU – POVRCHOVÁ MĚŘENÍ**

*Ryšavý František<sup>1</sup>*

### **Abstract**

Method of the controlled current regulation can be used too for the surface geophysical registering if there is made focusing of the electric field. It can be the resistivity registering, registering of SP-potentials as static/selective ones or the chargeability registering like static/selective chargeability. There are again two basic conditions of electric regulation either  $U_N = U_M$  or  $U_N = 0$ . For the surface registering it holds that the mud is here replaced with electrically conductive regolith covering fresh rocks. If you have condition  $U_N = U_M$  the current contours will go downwards perpendicularly to the earth surface and penetrate through regolith into rocks below. In the second case when  $U_N = 0$  the current contours are focused parallelly to the earth surface and are curved very close to the guard electrodes. The last mentioned one is not too convenient because prevails the regolith influence. For registering of SP-potentials does not suit at all. As for the electrode array there are acceptable two variances; 3 and 5-electrode arrays.

### **Abstrakt**

Metoda kontrolované proudové regulace se může také použít pro povrchová geofyzikální měření, jestliže se jedná o měření s fokusací elektrického pole. Může jít o měření měrného elektrického odporu, měření SP-potenciálů buď statických, nebo selektivních nebo o měření polarizovatelnosti hornin, a to ve variantě buď statické polarizovatelnosti, nebo selektivní polarizovatelnosti. Opět se jedná o dvě základní podmínky elektrické regulace pole;  $U_N = U_M$  nebo  $U_N = 0$ . Pro povrchová měření platí, že výplach je zde nahrazen elektricky vodivým regolitem, který pokrývá nezávětralé horniny. Máte-li podmínku, že  $U_N = U_M$ , pak proudnice vstupují směrem dolů do země kolmo k povrchu a procházejí regolitem do hornin pod ním. V druhém případě, kdy platí  $U_N = 0$ , proudnice jsou usměrňovány paralelně se zemským povrchem a zakřivují se v těsné blízkosti stínících elektrod. Tento druhý případ není příliš vhodný, neboť převládá vliv regolitu. Pro měření SP-potenciálů se nehodí vůbec. Z hlediska elektrodového uspořádání jsou možné dvě varianty; 3-elektrodové nebo 5-elektrodové uspořádání.

## Keywords

*focused electric field, the coefficient of focusing, the constant of electrode array, the controlled current regulation, well-logging*

## Klíčová slova

*usměrněné elektrické pole, koeficient fokusace, konstanta elektrodového uspořádání, kontrolovaná regulace proudu, karotáž*

## 1 Introduction

Method of the controlled current regulation uses the focused electric field in the boreholes. Here offers whether or not you can use the focused electric field too on the earth surface for the geoelectric measurements. This theoretical study presents an analysis how to imply the above method too for registering such characteristics as resistivity, the static and selective SP-potentials and chargeability are. The only condition is using of the focused electric field and the surface geophysical methods can be as well as analysable like it was in the borehole. The surface of earth is covered by regolith; it is often enough a thick layer being electrically-conductive. Below there are fresh rocks affected by weathering. It is very similar like in the borehole where highly conductive mud is between electrodes and the borehole wall. Therefore one can apply too two basic condition of regulation of the focused electric field; the first when the current contours go downwards perpendicularly to the earth surface when holds  $U_N = U_M$  and the second when holds  $U_N = 0$  and the current contours are focused parallelly to the earth surface.

As you work with the point electrodes it needs to be the formulas derived for three-dimensional space to adjust to be respected the half-space. And it is topic of the next chapters; the formulas for the surface records will be much simpler than in boreholes.

## 2 Theory of the resistivity measuring

The last mentioned author presents there formula of SCHLUMBERGER (1989). The formula looks in the adjusted form like this:

$$U_M = \frac{R_t \times I_A}{K} \times \left\{ 1 + \frac{R_s}{R_{reg}} + \frac{R_t}{R_{reg}} \right\}^{-1}, \quad (1)$$

The formula adjusted for resistivity has the following form:

$$R = K \times \frac{U_M}{I_A} = R_t \times \left\{ 1 + \frac{R_s}{R_{reg}} + \frac{R_t}{R_{reg}} \right\}^{-1}, \quad (2)$$

where  $R_{reg}$  = the regolith resistivity [ $\Omega\text{m}$ ],

$R_s$  = the resistivity of adjacent beds [ $\Omega\text{m}$ ] and  $R_t$  = the resistivity of the bed [ $\Omega\text{m}$ ].

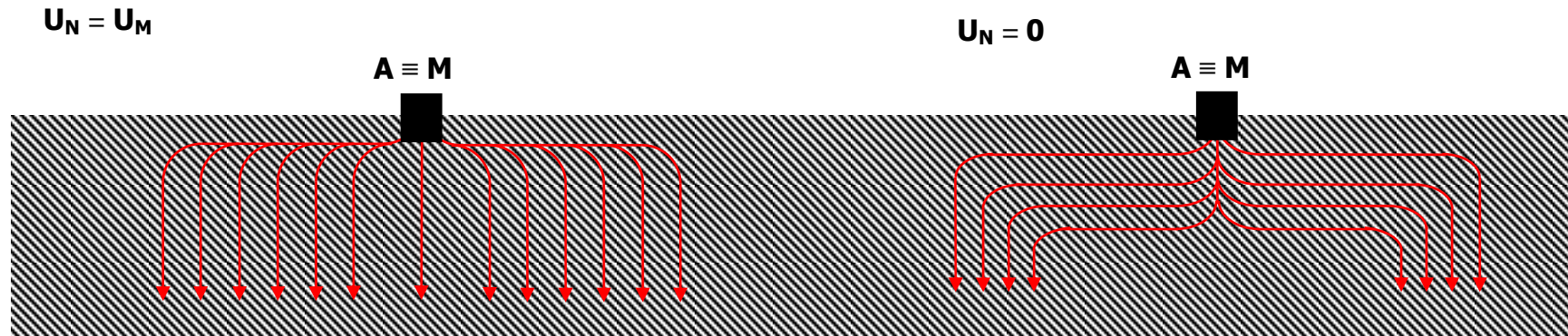
For condition  $U_N = U_M$  what presents that  $R_{reg} \rightarrow \infty$ ; current contours flow perpendicularly to the earth surface.

$$R = K \times \frac{U_M}{I_A} = \lim_{R_{reg} \rightarrow \infty} R_t \times \left\{ 1 + \frac{R_s}{R_{reg}} + \frac{R_t}{R_{reg}} \right\}^{-1} \approx R_t \quad \text{for } U_N = U_M. \quad (3)$$

If it is condition  $U_N = 0$  then holds that  $R_{reg} \rightarrow 0$ ; current contours flow parallelly with the earth surface.

$$R = K \times \frac{U_M}{I_A} = \lim_{R_{reg} \rightarrow 0} R_t \times \left\{ 1 + \frac{R_s}{R_{reg}} + \frac{R_t}{R_{reg}} \right\}^{-1} \approx \lim_{R_{reg} \rightarrow 0} R_t \times \left\{ \frac{R_s}{R_{reg}} + \frac{R_t}{R_{reg}} \right\}^{-1} \approx \lim_{R_{reg} \rightarrow 0} R_{reg} \times \left\{ 1 + \frac{R_s}{R_t} \right\}^{-1} \quad \text{for } U_N = 0. \quad (4)$$

Note, please, what results from formula (4) too: for  $R_s \ll R_t$  holds that  $R = R_{reg}$ ; for  $R_{reg} \rightarrow 0$  always holds that  $R = 0$  – it is highly conductive regolith. In case that holds that  $R_s \gg R_t$ , you receive  $R = 0$  what is all independent on  $R_{reg}$ . An influence of characteristics  $R_s$  and  $R_t$  is well visible in fig.1. It is that area where electric flux contours direct vertically downward. This second case, for  $U_N = 0$ , is unacceptable because we measure, thanks to way of focusing, only the resistivity of conductive regolith. Only if the regolith is not too conductive you will be able to test possible changes in the resistivity of regolith when you use the before focusing; for investigation of the rock resistivity below regolith this way of focusing is not acceptable. See fig.1.



*Fig.1 Two fundamental ways of focusing of the electric field*

### 3 Adjustment of the partial constants for the point surface records

The formulas derived for three-dimensional bodies presenting well-logging tools must be simplified and adjusted for surface electrode arrays. Moreover, observations being made on the surface of earth are the ones studying the half-space. Also here is needed to distinguish whether the current and potential electrodes are identical or are single. On the ground of that you have to select the right formulas for counting of the partial point constants.

### 3.1 The current and potential electrodes are not identical; linear model

In such case solution is very simple. You have to use the following formula:

$$k = 2\pi \times L, \quad (5)$$

where L = the spacing, i.e., the distance being between centres of both point electrodes [m].

The symbol L is abscissa lining centres both electrodes like  $\overline{AM}$ ,  $\overline{EM}$  and the next are. It holds for **linear model**, that has its limitation. It is when the current and potential electrodes are identical. As L = 0 it must be k = 0 too, i.e. (k/a<sub>n</sub>) = 0. However, reciprocal value of characteristic k goes to infinity and it presents problem for counting of characteristics the main constant K and the focusing coefficient η. Therefore you need to use **space model**; there is an electrode defined as a cylindrical surface having two characteristics, the length denoted as **n** and the diameter denoted as **a<sub>n</sub>**. These determine so called slenderness ratio (n/a<sub>n</sub>). This cylindrical surface is transformed into zone of infinitely-small quantities. For the length n holds that is equal to zero, n = 0, what presents geometrically circle. This circle has a final diameter a<sub>n</sub> tending to zero, however, being non-zero. Even if the circle is degenerated cylindrical surface, remains always that diameter a<sub>n</sub> ≠ 0 as it was for non-degenerated cylindrical surface. For the slenderness ratio it results in that (n/a<sub>n</sub>) → 0.

Thus an electrode presents not dimensionless point as before but a circle with infinitely-small diameter in [m]. Just thanks to that, the partial constant is presented as a **final value** having **own non-null dimension**. It holds that k → 0 but **never** that k = 0 as it was for the linear model. So it is (k/a<sub>n</sub>) ≠ 0. The values of partial constant will be quite very small, however, non-zero. The reciprocal value of such constant will be then high.

### 3.2 The current and potential electrodes are identical; space model

This case will be more complicate and you have to use the limit calculus. We start from the derived formulas yet for the three-dimensional space when both electrodes are identical; RYŠAVÝ (2013). Even if the formulas are enough large, they are for calculation well-applicable to. Here they are.

$$\left(\frac{k}{a_n}\right) = \frac{1}{F_1 + F_2}, \quad (6)$$

$$F_1 = \frac{1}{8} \times \left(\frac{n}{a_n}\right)^{-1} \times \left\{ \ln \left[ \left(\frac{\sqrt{2}}{2}\right) \times \sqrt{\left(\frac{n}{a_n}\right)^2 + 1} + \frac{n}{a_n} \right] - \ln \left[ \left(\frac{\sqrt{2}}{2}\right) \times \sqrt{\left(\frac{n}{a_n}\right)^2 + 1} - \frac{n}{a_n} \right] \right\}, \quad (7)$$

$$F_2 = \frac{1}{16} \times \left(\frac{n}{a_n}\right)^{-1} \times \left\{ \operatorname{Argsinh} \left[ \left(\frac{\sqrt{2}}{2}\right) \times \sqrt{\left(\frac{n}{a_n}\right)^2 + 1} + \frac{n}{a_n} \right] - \operatorname{Argsinh} \left[ \left(\frac{\sqrt{2}}{2}\right) \times \sqrt{\left(\frac{n}{a_n}\right)^2 + 1} - \frac{n}{a_n} \right] \right\}. \quad (8)$$

As the slenderness ratio is denoted the ratio being between the length of electrode presented by symbol  $n$  and the diameter of the same electrode that has symbol  $a_n$ . For the line it holds that  $\lim (n/a_n) \rightarrow \infty$ , whereas for the point there is  $\lim (n/a_n) \rightarrow 0$ . This you have to use during calculus formulas from (6) up to (8). For calculus we can use L'Hospital rule. Through such limit process you transfer from three-dimensional space to one-dimensional.

As the first you can calculate characteristic denoted as  $F_1$ , after that the characteristic denoted as  $F_2$ . From their numeric values we can calculate the constant  $k$ .

$$\begin{aligned} \lim_{(n/a_n) \rightarrow 0} F_1 &= \frac{1}{8} \times \lim_{(n/a_n) \rightarrow 0} \ln \left\{ \left[ \left( \frac{\sqrt{2}}{2} \right) \times \sqrt{\left( \frac{n}{a_n} \right)^2 + 1} + \frac{n}{a_n} \right] - \ln \left[ \left( \frac{\sqrt{2}}{2} \right) \times \sqrt{\left( \frac{n}{a_n} \right)^2 + 1} - \frac{n}{a_n} \right] \right\} \times \left( \frac{n}{a_n} \right)^{-1} = \\ &= \frac{1}{8} \times \lim_{(n/a_n) \rightarrow 0} \frac{\left[ \left( \frac{\sqrt{2}}{2} \right) \times \frac{\left( \frac{n}{a_n} \right)}{\sqrt{\left( \frac{n}{a_n} \right)^2 + 1}} + 1 \right]}{\left[ \left( \frac{\sqrt{2}}{2} \right) \times \sqrt{\left( \frac{n}{a_n} \right)^2 + 1} + \left( \frac{n}{a_n} \right) \right]} - \frac{1}{8} \times \lim_{(n/a_n) \rightarrow 0} \frac{\left[ \left( \frac{\sqrt{2}}{2} \right) \times \frac{\left( \frac{n}{a_n} \right)}{\sqrt{\left( \frac{n}{a_n} \right)^2 + 1}} - 1 \right]}{\left[ \left( \frac{\sqrt{2}}{2} \right) \times \sqrt{\left( \frac{n}{a_n} \right)^2 + 1} - \left( \frac{n}{a_n} \right) \right]} = \end{aligned}$$

$$= \frac{1}{8} \times \lim_{(n/a_n) \rightarrow 0} \frac{\left[ \left( \frac{\sqrt{2}}{2} \right) \times \frac{\left( \frac{n}{a_n} \right)}{\sqrt{\left( \frac{n}{a_n} \right)^2 + 1}} + 1 \right]}{\left[ \left( \frac{\sqrt{2}}{2} \right) \times \sqrt{\left( \frac{n}{a_n} \right)^2 + 1} + \left( \frac{n}{a_n} \right) \right]} - \frac{1}{8} \times \lim_{(n/a_n) \rightarrow 0} \frac{\left[ \left( \frac{\sqrt{2}}{2} \right) \times \frac{\left( \frac{n}{a_n} \right)}{\sqrt{\left( \frac{n}{a_n} \right)^2 + 1}} - 1 \right]}{\left[ \left( \frac{\sqrt{2}}{2} \right) \times \sqrt{\left( \frac{n}{a_n} \right)^2 + 1} - \left( \frac{n}{a_n} \right) \right]} =$$

$$= \frac{1}{8} \times \left( \frac{2}{\sqrt{2}} + \frac{2}{\sqrt{2}} \right) = \frac{\sqrt{2}}{4} = \frac{1}{2} \times \frac{\sqrt{2}}{2}.$$

$$\lim_{(n/a_n) \rightarrow 0} F_2 = \frac{1}{16} \times \lim_{(n/a_n) \rightarrow 0} \frac{\operatorname{Argsinh} \left[ \left( \frac{\sqrt{2}}{2} \right) \times \sqrt{\left( \frac{n}{a_n} \right)^2 + 1} + \frac{n}{a_n} \right] - \operatorname{Argsinh} \left[ \left( \frac{\sqrt{2}}{2} \right) \times \sqrt{\left( \frac{n}{a_n} \right)^2 + 1} - \frac{n}{a_n} \right]}{\left( \frac{n}{a_n} \right)} =$$

$$= \frac{1}{16} \times \lim_{(n/a_n) \rightarrow 0} \frac{\left[ \left( \frac{\sqrt{2}}{2} \right) \times \frac{\left( \frac{n}{a_n} \right)}{\sqrt{\left( \frac{n}{a_n} \right)^2 + 1}} + 1 \right]}{\sqrt{\left[ \left( \frac{\sqrt{2}}{2} \right) \times \sqrt{\left( \frac{n}{a_n} \right)^2 + 1} + \left( \frac{n}{a_n} \right) \right]^2 + 1}} - \frac{1}{16} \times \lim_{(n/a_n) \rightarrow 0} \frac{\left[ \left( \frac{\sqrt{2}}{2} \right) \times \frac{\left( \frac{n}{a_n} \right)}{\sqrt{\left( \frac{n}{a_n} \right)^2 + 1}} - 1 \right]}{\sqrt{\left[ \left( \frac{\sqrt{2}}{2} \right) \times \sqrt{\left( \frac{n}{a_n} \right)^2 + 1} - \left( \frac{n}{a_n} \right) \right]^2 + 1}} =$$

$$= \frac{1}{16} \times \left\{ \left( \frac{2}{4} + 1 \right)^{\frac{1}{2}} + \left( \frac{2}{4} + 1 \right)^{\frac{1}{2}} \right\} = \frac{\sqrt{6}}{24} = \frac{1}{6} \times \frac{\sqrt{2}}{2} \times \frac{\sqrt{3}}{2}.$$

$$\left( \frac{k}{a_n} \right) = \lim_{(n/a_n) \rightarrow 0} \left( \frac{1}{F_1 + F_2} \right) = \frac{4}{11} \times (6\sqrt{2} - \sqrt{6}) = 2.195. \quad (9)$$

Thanks to formula (5) you get the final formula for the point electrode that is simultaneously the current and potential.

$$k = 2.195 \times a_n, \quad (10)$$

where  $a_n$  = diameter of the electrode [m]; ratio  $(k/a_n) \neq 0$ , the ratio is non-null value and partial constant  $k$  has dimension in [m].

It is really diameter of the electrode stick not the length of one; we do have a horizontal measurement – parallelly to the earth surface. But, **in the horizontal direction**, too you measure the spacing presenting the distance between the current and potential electrodes. Even if counted values after formula (10) will be low, their reciprocal values needed for calculation constant  $K$ , are high, probably much bigger than those according to formula (5). It is however fully real value, not any error, no handicap.

## 4 Generally about implication knowledge from boreholes on the surface recordings

Let's go to fig.2. In the boreholes one can use various electrode arrays. Here are 9, 7 and 3- electrode arrays; each of them can have different degree of focusing and penetration of electric field can be different too. The focused electric observations in the borehole are profitable when the mud is highly salted what means the mud resistivity is very conductive.

It makes the borehole section is illegible; we register very low and constant resistivity. Focusing allow you to break through the conductive barrier of mud and to reach the jagged profile. The focused electric measurements in the boreholes are for a long time used yet and they are credible.

That is why to use them too for the surface electric recordings. Mainly in such case where a power layer of the conductive regolith exists. Such regolith if highly conductive is can be an equivalent of mud in the borehole. These focused electric systems present very complicated electrode arrays having big number of electrodes than usual arrays, no wonder that their enlargement was not big up to now. It was KAROUS (1989) who pointed that out. Nevertheless MARUŠIAK (1968) and (1969) supposed too possible implement of the focused measurements for the surface electric registrations. The technique of the recent registering devices is revolutionary in comparison to the at that time technique, nevertheless, I think that an analysis of such systems for the surface focusing electric observations is needed. Therefore this paper presents an attempt to do that.

It was said the arrays having a lot of electrodes are difficulty acceptable for the surface recordings. It confirms fig.2 where you see non-adjusted electrode arrays for 9, 7 and 3- electrode Laterolog transferred on the surface of earth. The 9 and 7-electrode variance is all unacceptable but the 3-electrode one can be interesting. This variance is worked up in the next figure, fig.3. The 7-electrode array it cannot

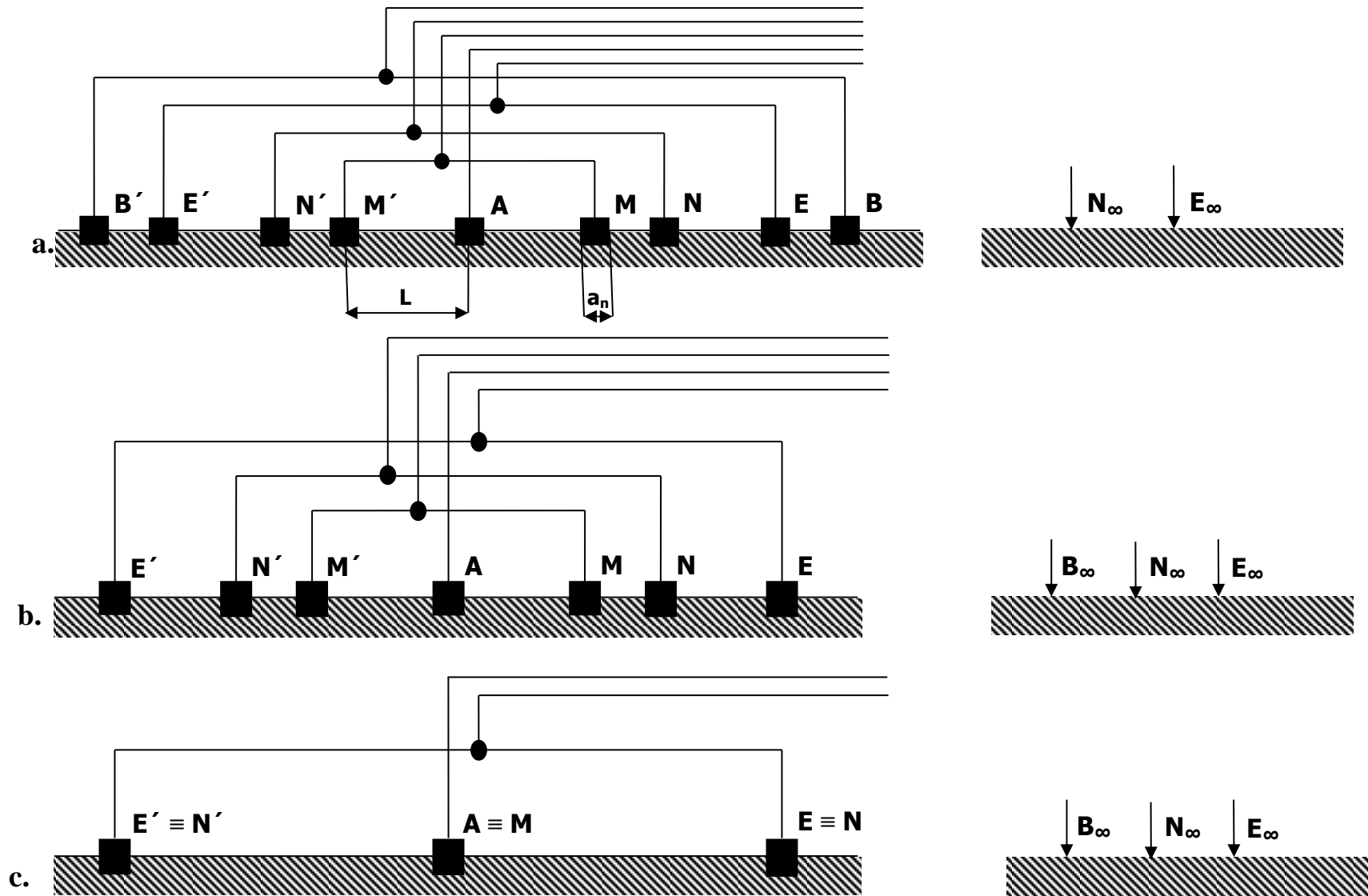
be, there can be only the remaining ones, 5 and 3-electrode arrays. Both variances are acceptable not only for the resistivity recording, but too for the SP-potential and the IP-recordings. All three electric methods can be registered as the focused on the surface of earth. It seems to be interesting and has point in analysing electrode arrays. It is the aim of this paper.

## **5 Registering resistivity with the help of focused electric field**

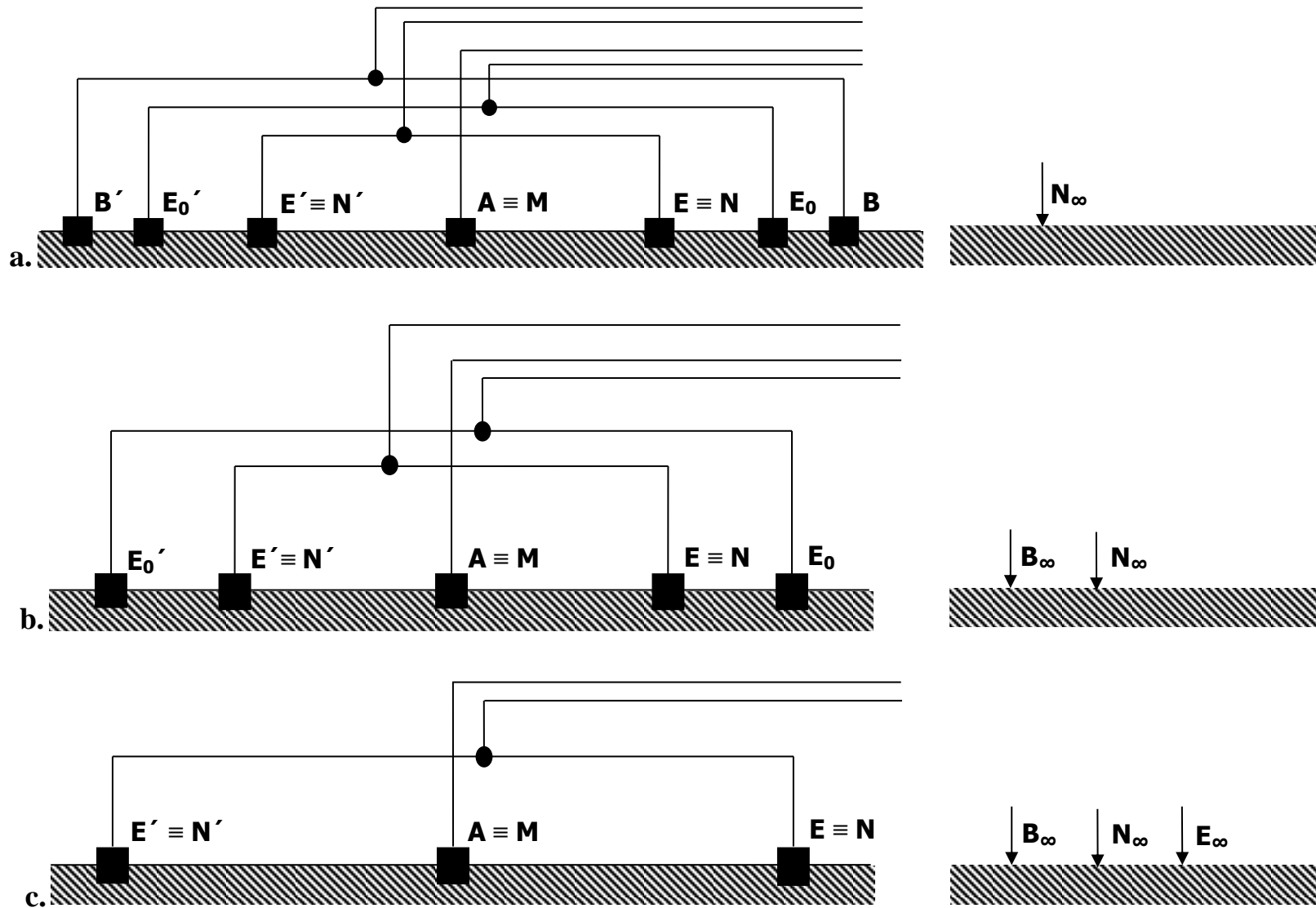
We register changes of voltage when electric currents are stabilized. By that the before changes of voltage are the resistivity ones. The registered curve is calibrated directly in resistivity. The mentioned electric currents are these; the feeding denoted as  $I_A$  and the regulative having symbol  $I_E$ . Between them there is this relation:

$$I_E = \eta \times I_A \quad \text{where } \eta = \text{the coefficient of focusing; it is dimensionless characteristic.} \quad (11)$$

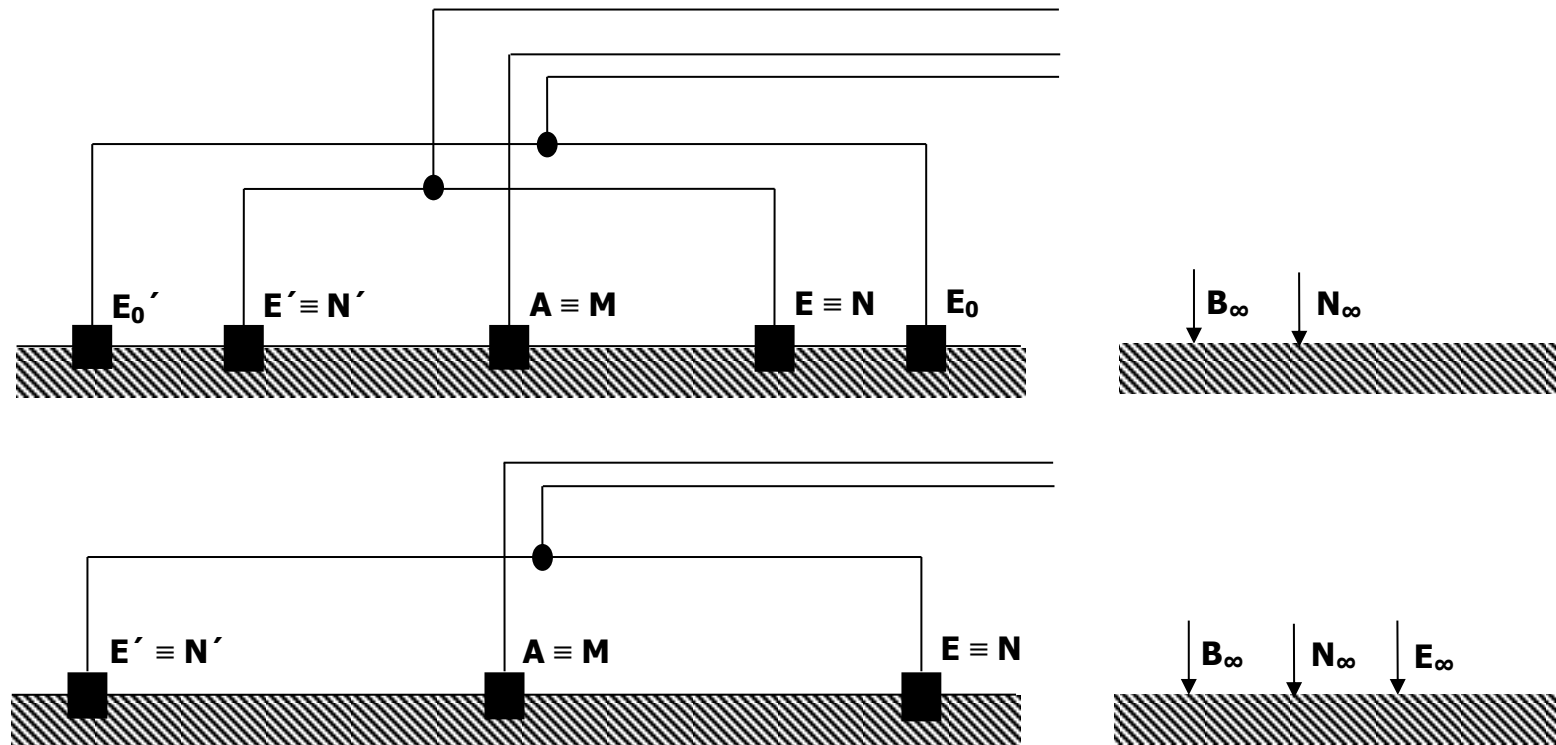




*Fig.2 Various types of the electrode arrays for registering of the surface recordings*



*Fig.3 Basic three variances derived from the variance c of fig.1. The bottom one looks to be the best.*



**Fig.4 Two suggested variances for registering of resistivity of rocks**

The next important formula is one for the curve of resistivity. It looks like that:

$$R = K \times \frac{U_M}{I_A}, \tag{12}$$

where K = the main constant of the electrode array in [m].

Both important characteristics  $\eta$  and K are fully numeric and they depend on numeric values of the partial constants. Both are constants. The current  $I_A$  is stabilized and the regulative current  $I_E$  is too stabilized, because is by numeric multiple of characteristic  $I_A$ . The regulative current can be positive, when the currents contours have the same direction like the contours of the feeding one, or negative when flow in the opposite direction to the feeding current. It determines the sign of the focusing coefficient  $\eta$ .

Further, as the curve of voltage is calibrated in resistivity you need to have the main constant K to be able such calibrating to make. Both characteristic  $\eta$  and K are very important for registering. The basic electrode arrays can be two; 5 and 3-electrode ones. They are in fig.4. It is electrical horizontal profiling, not electrical sounding (VES), because the distances between electrodes are fixed and all electrode array moves alongside profile.

## 5.1 The 5-electrode array with focusing $U_N = U_M$

On condition that  $U_N = U_M$  it means that the current contours enter perpendicularly into earth. As you can see in fig.4 each of electrodes, except guard electrodes, is together current and potential. It holds that  $A \equiv M$ ,  $E \equiv N$  and  $E' \equiv N'$ . Electrodes  $E_0$  and  $E_0'$  are component of the moveable electrode array. The electrodes  $N_\infty$  and  $B_\infty$  are positioned in an infinity distance. We register the potential difference between electrodes  $M$  and  $N_\infty$ .

The basic equations are these:

$$U_M = R \times \frac{I_A}{k_{AM}} + R \times \frac{I_E}{k_{EM}} - R \times \frac{I_E}{k_{E_0M}}, \text{ and} \quad (13)$$

$$U_N = R \times \frac{I_A}{k_{AN}} + R \times \frac{I_E}{k_{EN}} - R \times \frac{I_E}{k_{E_0N}}. \quad (14)$$

For the partial constants hold these relations:

$$k_{AM} = 2.195 \times a_{AM}, \quad (15)$$

$$k_{EN} = 2.195 \times a_{EN}, \quad (16)$$

$$k_{AN} = 2\pi \times \overline{AN}, \quad (17)$$

$$k_{EM} = 2\pi \times \overline{EM}, \quad (18)$$

$$k_{E_0N} = 2\pi \times \overline{E_0N}, \quad (19)$$

$$k_{E_0M} = 2\pi \times \overline{E_0M}. \quad (20)$$

By implication  $U_N = U_M$  into equations (13) and (14) you will be able to count characteristics  $\eta$  and  $K$  which are expressed in this way:

$$\eta = \frac{(k_{AM}^{-1} - k_{AN}^{-1})}{(k_{EN}^{-1} - k_{E_0N}^{-1}) - (k_{EM}^{-1} - k_{E_0M}^{-1})} \cdot \text{ and } K = \left\{ k_{AM}^{-1} + (k_{EM}^{-1} - k_{E_0M}^{-1}) \times \eta \right\}^{-1}. \quad (21), (22)$$

The array is depicted in fig.3 as the upper variance. The currents  $I_A$  and  $I_E$  can flow in the same direction, then the coefficient of focusing is positive, i.e., it holds that  $\eta > 0$ . However they can also flow against one another, then  $\eta < 0$ . It depends on numeric size of partial constants. Counting of resistivity  $R$  is after formula (12) where characteristics  $K$  and  $I_A$  are constant, the only variable is  $U_M$ .

## 5.2 The 5-electrode array with focusing $U_N = 0$

If you have condition  $U_N = 0$  then degree of focusing is weaker than it was in the previous case. The current contours direct parallelly with the earth surface. . However, it holds again for the upper variance in fig.4; the electrode array is identical like before case.

It presents that we can use the basic formulas denoted as (13) and (14) however for condition  $U_N = 0$ . For partial constants hold formulas from (15) up to (20):

$$k_{AM} = 2.195 \times a_{AM}, k_{EN} = 2.195 \times a_{EN}, k_{AN} = 2\pi \times \overline{AN}, k_{EM} = 2\pi \times \overline{EM}, k_{E_0N} = 2\pi \times \overline{E_0N} \text{ and } k_{E_0M} = 2\pi \times \overline{E_0M}.$$

Also the electrodes  $N_\infty$  and  $E_\infty$  are positioned in an infinity distance. But now you register the potential difference between electrodes M and N, not between M and  $N_\infty$ ! Characteristics  $\eta$  and  $K$  are expressed then like this:

$$\eta = - \frac{k_{AN}^{-1}}{\left( k_{EN}^{-1} - k_{E_0N}^{-1} \right)}. \quad (23)$$

$$K = \left\{ \left( k_{AM}^{-1} - k_{E_0M}^{-1} \right) + k_{EM}^{-1} \times \eta \right\}^{-1}. \quad (24)$$

The focusing coefficient is negative; however it depends too on partial constants. Counting of resistivity  $R$  is after formula (12).

### 5.3 The 3-electrode array with focusing $U_N = U_M$

Counting of resistivity  $R$  is after formula (12). On condition that  $U_N = U_M$  it holds that the current contours are oriented perpendicularly to the earth. It is the lower variance in fig.4. Here the electrode  $E_0$  is positioned in an infinity distance and therefore is denoted as  $E_\infty$ . We have only three electrodes:  $A \equiv M$ ,  $E \equiv N$  and  $E' \equiv N'$ . The remaining  $E_\infty$ ,  $B_\infty$  and  $N_\infty$  are infinitely distant. It means that holds:

$$k_{E_0M}^{-1} \rightarrow 0, k_{E_0N}^{-1} \rightarrow 0. \quad (25)$$

It presents that from equations (21) and (22) you receive:

$$\eta = \left( \frac{k_{AN}^{-1} - k_{AM}^{-1}}{k_{EM}^{-1} - k_{EN}^{-1}} \right). \quad (26)$$

$$K = \left\{ k_{AM}^{-1} + k_{EM}^{-1} \times \eta \right\}^{-1}. \quad (27)$$

As the electrode  $E_\infty$  is far we have only four partial constants:

$$k_{AM} = 2.195 \times a_{AM}, k_{EN} = 2.195 \times a_{EN}, k_{AN} = 2\pi \times \overline{AN}, k_{EM} = 2\pi \times \overline{EM}.$$

### 5.4 The 3-electrode array with focusing $U_N = 0$

Counting of resistivity  $R$  is after formula (12). When you have condition  $U_N = 0$  the current contours go parallelly with the earth surface. In fig.4 it is again the lower variance. For partial constants again holds that:

$$k_{AM} = 2.195 \times a_{AM}, k_{EN} = 2.195 \times a_{EN}, k_{AN} = 2\pi \times \overline{AN}, k_{EM} = 2\pi \times \overline{EM}.$$

Electrodes  $B_{\infty}$ ,  $N_{\infty}$  and  $E_{\infty}$  are again in infinity, but you register the voltage difference between electrodes M and N. Characteristics  $\eta$  and  $K$  are defined as follows:

$$\eta = -\frac{k_{AN}^{-1}}{k_{EN}^{-1}} \quad . \quad (28)$$

$$K = \left\{ k_{AM}^{-1} + k_{EM}^{-1} \times \eta \right\}^{-1}.$$

I am sure you noticed that it holds  $\eta < 0$ ; the currents flow against themselves. Formula for  $K$  is formula (27).

## 6 Calibration of resistivity

Calibration of resistivity is very simple. For calibration in the linear scale one standard is enough, however, for the non-linear scale you will need to have all set of standards. Like standards there are used resistors having their values of electrical resistance in  $[\Omega]$ . These are defined with certain error. Such resistor simulates the resistivity of rocks according to formula:

$$R^* = R_0 \times K, \quad (29)$$

where  $R_0$  = the electrical resistance of resistor  $[\Omega]$ ,

$K$  = the main constant of the electrode array [m] and

$R^*$  = the simulated resistivity of rocks  $[\Omega m]$ .

Deflection of record denoted as  $l^*$  answering to  $R^*$  you receive from the next formula:

$$l^* = \frac{R^*}{n}, \quad (30)$$

where  $n$  = the step of linear scale  $[\Omega m / 1 \text{ cm}]$ , and

$l^*$  = deflection for  $R^*$  [cm].

It needs to note that the simulated resistivity  $R^*$  will be for various electrode arrays various, because the main constant  $K$  is just different too. The fact we know error of standards is important when is done estimation of the registered error. Control of standards is made with the help of the gauge having two-times higher accuracy, at least, than well-logging instrument. The made control record presents the controlled document which is archived for some years.

## 7 Relation between SP-potentials and the diffusively-adsorptive electrochemical activity of rocks

Registering of SP-potentials is done simultaneously with the registering of the diffusively-adsorptive electrochemical activity of rocks. Both the above characteristics have the same dimension, milivolts [mV]. However, priority of them has the electrochemical activity. You can see it when you will see over the formula:

$$A_{da}^{(sh)} = A_{da} + U_{SP}, \quad (31)$$

where  $A_{da}$  = the diffusively-adsorptive electrochemical activity of rocks [mV],

$A_{da}^{(sh)}$  = the adsorptive electrochemical activity of shales [mV], and

$U_{SP}$  = pseudo-static SP-potential taken away of the line of shale [mV].

It is clear that the basic is calibration of the electrochemical activity that is the main characteristic, not SP-potentials. The line of shale is simultaneously the continuous line of characteristic  $A_{da}^{(sh)}$ . So, when you want to express SP-potentials, it holds that:

$$-U_{SP} = A_{da} - A_{da}^{(sh)} \quad \text{mostly holds } A_{da} < A_{da}^{(sh)}. \quad (32)$$

Thanks to that the characteristic  $U_{SP}$  presents registering being differential, because registers differences of the shale line. Left of the shale line are negative values, right are positive values.

## 8 Registering static SP-potentials with the help of focused electric field

As the first it needs to say what geologic situation is when you make the surface records. The surface of earth is covered by regolith. It is often very thick layer of the mantle rocks, which had been formed with weathering. Regolith is electrically conductive; in case that its thickness is big it is analogy situation to the borehole having highly conductive mud. Therefore using of the electrode array with focused electric field is the right decision.

In opposite to registering of resistivity where feeding current is stabilized for all time interval of registering, here is other situation. The feeding current  $I_{SP}$  is variable and it means that the regulative current  $I_E$  will be variable too for all interval of registering. Moreover, we register voltage, which changes with the feeding current  $I_{SP}$  and simultaneously with resistivity of rocks. It can be well visible in the following formula:

$$U_{SP} = \frac{R_{reg} \times I_{SP}}{k} = U_{SSP} \times \frac{R_{reg}}{R_{reg} + R_{sh} + R_t} = U_{SSP} \times \frac{1}{1 + \left( \frac{R_{sh} + R_t}{R_{reg}} \right)}. \quad (33)$$

where  $R_{reg}$  = resistivity of the layer of the highly conductive regolith [ $\Omega m$ ],

$R_{sh}$  = resistivity of adjacent rocks, mostly shales [ $\Omega m$ ], and

$R_t$  = resistivity of the fresh rock [ $\Omega m$ ].

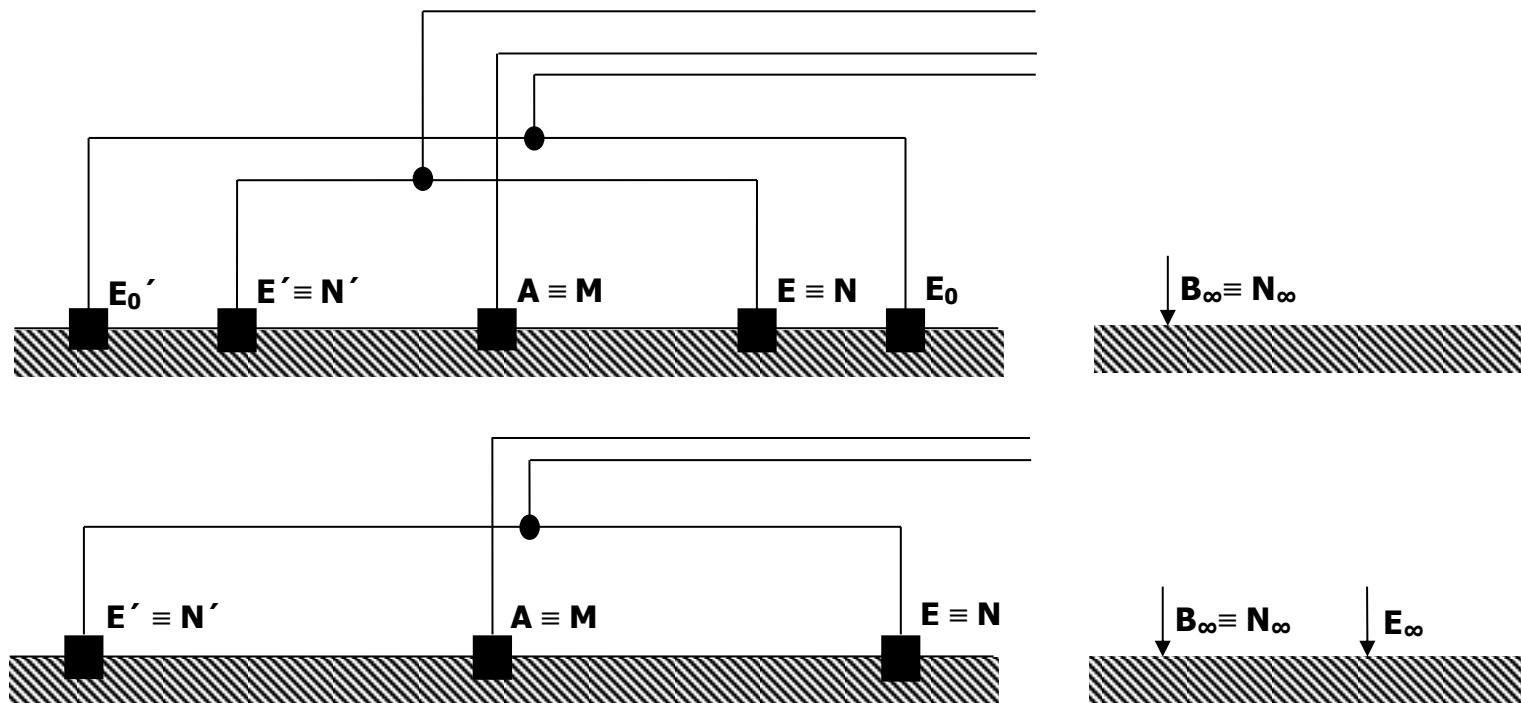
Not to flow electric current predominantly in the regolith one forms focused electric field. There is simulated virtually the layer of regolith having infinite resistivity, i.e.,  $R_{reg} \rightarrow \infty$ , and it is made with the help of the electrode array and focusing electric field. There is simulated virtually the layer of regolith having infinite resistivity, i.e.,  $R_{reg} \rightarrow \infty$ , and it is made with the help of the electrode array and

focusing electric field. From the formula (34) it is well visible. We register the potential difference between electrodes M and  $N_\infty$  on condition that holds:  $U_N = U_M$  !

$$U_{SP} = \frac{R_{reg} \times I_{SP}}{k} = \lim_{R_{reg} \rightarrow \infty} U_{SSP} \times \frac{1}{1 + \left( \frac{R_{sh} + R_t}{R_{reg}} \right)} \approx U_{SSP}, \quad \text{for } U_N = U_M. \quad (34)$$

The current contours direct perpendicularly down into earth. I have also to say that is possible focusing of electric field when the current contours go parallelly to the earth surface. It is on condition that  $U_N = 0$ . In such case is formed virtually the layer of regolith having zero resistivity, i.e.,  $R_{reg} \rightarrow 0$  when SP-potentials are influenced by regolith. You can test that with the help of a bit adjusted equation (34). We should register the potential difference between electrodes M and N!

$$U_{SP} = \frac{R_{reg} \times I_{SP}}{k} = \lim_{R_{reg} \rightarrow 0} U_{SSP} \times \frac{1}{1 + \left( \frac{R_{sh} + R_t}{R_{reg}} \right)} \approx \lim_{R_{reg} \rightarrow 0} U_{SSP} \times \frac{R_{reg}}{R_{sh} + R_t} \approx 0, \quad \text{for } U_N = 0.$$



*Fig.5 Two suggested variances for registering of SP-potentials*



Registering is intensely influenced by ratio! The variance when  $R_{reg} \rightarrow 0$  does not suit! In opposite to variances connected with registering of resistivity I think that this way of focusing is not convenient for the surface records of SP-potentials. Relation between the feeding and the regulative currents is very similar to equation (11); however, both **are not stabilized** but are **variable**!

$$I_E = \eta \times I_{SP}. \quad (35)$$

where  $\eta$  = the coefficient of focusing; it is dimensionless characteristic.

The coefficient of focusing is a numeric constant and is exactly counted thanks to known partial constants; can be positive or negative. For condition  $U_N = U_M$  is positive. We need it for continuous counting of the regulative current. The main constant  $K$  can be counted too, but has marginal significance if you plan to record only SP-potentials. In case you want to register the diffusively-adsorptive electrochemical activity and SP-potentials the main constant is needed for calibration.

### 8.1 The 5-electrode array with focusing $U_N = U_M$ registering of the static SP-potentials $U_{SSP}$

On condition that  $U_N = U_M$  it means that the current contours enter perpendicularly into earth. As you can see in fig.5 the electrodes are together current and potential,  $A \equiv M$ ,  $E \equiv N$  and  $E' \equiv N'$ . The electrodes  $N_\infty \equiv B_\infty$  are positioned in an infinity distance. It holds for the upper variance with electrodes  $E_0$  and  $E_0'$ ; fig.5. It presents the identical array like it was for the resistivity measurement.

We register  $U_{SSP}$  between electrodes  $M$  and  $N_\infty$  and simultaneously too the current of SP-potentials  $I_{SP}$ ! Characteristic  $I_{SP}$  is needed to make the continuous regulating  $I_E$  after formula (35). For the partial constants hold these relations:

$$k_{AM} = 2.195 \times a_{AM}, k_{EN} = 2.195 \times a_{EN}, k_{AN} = 2\pi \times \overline{AN}, k_{EM} = 2\pi \times \overline{EM}, k_{E_0N} = 2\pi \times \overline{E_0N}, \text{ and } k_{E_0M} = 2\pi \times \overline{E_0M}.$$

The fundamental equations are those denoted as (13) and (14), however, designation of indexes is a little changed.

$$U_M = R_m \times \frac{I_{SP}}{k_{AM}} + R_m \times \frac{I_E}{k_{EM}} - R_m \times \frac{I_E}{k_{E_0M}}, \text{ and} \quad (36)$$

$$U_N = R_m \times \frac{I_{SP}}{k_{AN}} + R_m \times \frac{I_E}{k_{EN}} - R_m \times \frac{I_E}{k_{E_0N}}. \quad (37)$$

For characteristics  $\eta$  and  $K_{SSP}$  hold the following formulas. Note, please that  $K_{SSP}$  is in [m]. There are again formulas (21) and (22). The continuous regulation is made after formula (35); as the feeding current  $I_{SP}$  is variable the regulative current  $I_E$  is variable too.

$$\eta = \frac{(k_{AM}^{-1} - k_{AN}^{-1})}{(k_{EN}^{-1} - k_{E_0N}^{-1}) - (k_{EM}^{-1} - k_{E_0M}^{-1})}, \quad K_{SSP} = \left\{ k_{AM}^{-1} + (k_{EM}^{-1} - k_{E_0M}^{-1}) \times \eta \right\}^{-1} \quad \text{and} \quad I_E = \eta \times I_{SP}.$$

The coefficient of focusing  $\eta$  can be positive or negative; the currents  $I_{SP}$  and  $I_E$  can flow in the same direction or in opposite direction. Both are variable because the current  $I_{SP}$  is changing with resistivity of rocks. The constant  $K_{SSP}$  is needed for calibration if you calibrate in the electric power flux of the static SP-potentials.

## 8.2 The 3-electrode array with focusing $U_N = U_M$ registering of the static SP-potentials $U_{SSP}$

This is the lower variance being in fig.5. The electrodes  $E_0$  and  $E_0'$  are in an infinity distance as the only one denoted as  $E_\infty$ . We register again the potential difference between electrodes  $A \equiv M$  and  $N_\infty \equiv B_\infty$ . For the partial constants hold these relations:

$$k_{AM} = 2.195 \times a_{AM}, k_{EN} = 2.195 \times a_{EN}, k_{AN} = 2\pi \times \overline{AN}, k_{EM} = 2\pi \times \overline{EM}.$$

As it holds that  $k_{E_0M}^{-1} \rightarrow 0, k_{E_0N}^{-1} \rightarrow 0$  you obtain formulas (26) and (27) from formulas (21) and (22):

$$\eta = \left( \frac{k_{AN}^{-1} - k_{AM}^{-1}}{k_{EM}^{-1} - k_{EN}^{-1}} \right), \quad K_{SSP} = \{ k_{AM}^{-1} + k_{EM}^{-1} \times \eta \}^{-1} \quad \text{and} \quad I_E = \eta \times I_{SP}.$$

We register again  $U_{SSP}$  between electrodes  $M$  and  $N_\infty$  and simultaneously too the current of SP-potentials  $I_{SP}$ . The last characteristic is needed for continuous regulating  $I_E$ . The coefficient of focusing can be again positive or negative; the currents  $I_{SP}$  and  $I_E$  can flow in the same direction or against one another and are variable. It needs to say that the condition  $U_N = U_M$  being characteristic for registering of the static SP-potentials is preferred over condition  $U_N = 0$  for its deep penetration and mainly for overcoming the influence of regolith.

## 9 Calibration of the diffusively-adsorptive electrochemical activity $A_{da}$ and SP-potentials

For calibration of the diffusively-adsorptive electrochemical activity  $A_{da}$  and SP-potentials in [mV] you need to have a calibrator presenting a voltage source with accurately calibrated values. These present primary standards for calibration. They have certain accuracy determined with an error. For linear scale one standard is enough, whereas, for non-linear scale you have to use all set of primary standards. Voltage of standard denoted as  $U_0$  is reflected on a linear scale like deflection  $l_0$ . The zero level presents a line of shale.

$$l_0 = \frac{U_0}{n} = \frac{U_{SP}}{n} = \frac{U_{SSP}}{n}, \quad (38)$$

where  $U_0$  = the voltage like primary standard of simulated SP-potentials  $U_{SP} \equiv U_{SSP}$  [mV],  $U_0 \equiv U_{SP} \equiv U_{SSP} < 0$ ,

$n$  = the step of linear scale [mV/ 1cm], and

$l_0$  = deflection presenting  $U_0$  [cm].

However, you can calibrate too as  $W_{SSP}$  i.e., the electric power flux of static SP-potentials [mV×m]. Just this way of calibration allows us to imply into calibration an influence of the electrode array. Relative calibration of the static SP-potentials, when you calibrate from zero being on the shale line, do not allow that. It is way how to determine more recording curves for  $W_{SSP}, A_{da}^{SSP}$  and  $U_{SSP}$ .

In such way of calibration you can use formulas:

$$W_{SSP} = U_0 \times K_{SSP}, l_0 = \frac{W_{SSP}}{n}, \quad (39)$$

where  $U_0$  = the calibrated value of voltage from standard [mV],

$K_{SSP}$  = the main constant of the electrode array [m], and

$W_{SSP}$  = the simulated electric power flux of static SP-potentials [mV×m].

So you have record of the characteristic  $W_{SSP}$ . The diffusively-adsorptive electrochemical activity  $A_{da}$  you receive from the formula:

$$W_{SSP} = A_{da}^{SSP} \times K_{SSP} \Rightarrow A_{da}^{SSP} = W_{SSP} / K_{SSP}. \quad (40)$$

Classical record of the static SP-potentials is directed with formula:

$$-U_{SSP} = A_{da}^{SSP} - A_{da}^{(sh)}. \quad (41)$$

Here  $A_{da}^{(sh)}$  presents the continuous trend curve with the borehole depth; you get it if you insert the trend curve through all shale intervals of characteristic  $A_{da}^{(sh)}$ . This way of calibration needs, however, to use the main constant  $K_{SSP}$ . This is then an absolute measurement.

## 10 Registering chargeability of rocks from Induced Polarisation with the help of focused electric field

I am sure you noticed too that favourable condition is when  $U_N = U_M$ , whereas, when holds that  $U_N = 0$  it is less favourable condition. In both cases you have electric field that is focused, however, variants of focusing are different. In the first variant the current contours are perpendicular to the surface of earth and go perpendicularly down into soil. They penetrate deeply inwards, they overcome the layer of regolith and in big distance they are curved and return to electrode B. The second variant offers too focused electric field. The current contours go too into rocks but because are intensively curved at once from start in the direction being parallel to the surface of earth, they flow mainly in regolith and in the upper part of rocks below.

Registration of induced polarization reacts on the current pulse in rocks. The first step is action of the rectangular current pulse on the outer environment. The voltage denoted as  $U_{M0}$  of such pulses is measurable. Feeding electric current denoted as  $I_A \neq 0$  flowing through A, and  $B_\infty$  electrodes must be stabilized. Regulative electric current denoted as  $I_E$  is stabilized permanently, is independent on changes of current  $I_A$  and presents numeric multiple of  $I_A$ . The second step is the feeding current is cut, i.e., it holds that  $I_A = 0$  what does not mean that  $I_E = 0$ , too. This must remain to be non-zero,  $I_E \neq 0$ , because you register the voltage  $U_M$  being between electrode M and electrodes  $N_\infty$  or N on condition that runs regulation for first or second variances. Concurrently it holds that the regulation is made with the help of the regulative current denoted as  $I_E$  flowing through E, E' and  $E_\infty$  electrodes. Its size is directed by either condition that  $U_N = U_M$ , this is first variance of registration for the static chargeability of rocks, or that  $U_N = 0$ , it is the second variance for registration. The regulative current  $I_E$  acts permanently both for measurements of voltage  $U_M$  and  $U_{M0}$ . The regulative current forms the focused electric field and simultaneously keeps conditions of regulation; either  $U_N = U_M$  or  $U_N = 0$ .

We can study both variances more in detail. I utilize from work, SCHLUMBERGER (1989) that formula where the published relation between pseudo-static and static SP-potentials is. It seems you can use very similar formula for the induced polarization.

$$U_M = K_e^{(t)} \times U_{M0} \times \frac{K_e^{(reg)} \times R_{reg}}{K_e^{(reg)} \times R_{reg} + K_e^{(sh)} \times R_{sh} + K_e^{(t)} \times R_i}. \quad (42)$$

This formula can be adjusted in the way like that:

$$\kappa_e^{SIP} = \frac{U_M}{U_{M_0}} = \kappa_e^{(t)} \times \frac{\kappa_e^{(reg)} \times R_{reg}}{\kappa_e^{(reg)} \times R_{reg} + \kappa_e^{(sh)} \times R_{sh} + \kappa_e^{(t)} \times R_t}, \quad (43)$$

where  $R_{reg}$  = resistivity of the layer of the highly conductive regolith [ $\Omega m$ ],

$R_{sh}$  = resistivity of adjacent rocks, mostly shales [ $\Omega m$ ],

$R_t$  = resistivity of the fresh rocks [ $\Omega m$ ],

$\kappa_e^{SIP}$  = the static chargeability of rocks that is dimensionless [ $\kappa$ ],

$\kappa_e^{(t)}$  = the real chargeability of rocks that is dimensionless [ $\kappa$ ],

$U_M$  = voltage response of rocks on the current pulse [mV], and

$U_{M_0}$  = the primary voltage bound by the current pulse [mV].

Now, if we are able to simulate virtually the regolith layer having infinite resistivity, i.e.,  $R_{reg} \rightarrow \infty$ , and it is with the help of the electrode array and focusing electric field always possible, equation (43) will gain the following form:

$$\kappa_e^{SIP} = \frac{U_M}{U_{M_0}} = \lim_{R_{reg} \rightarrow \infty} \kappa_e^{(t)} \times \frac{1}{1 + \left( \frac{\kappa_e^{(sh)} \times R_{sh} + \kappa_e^{(t)} \times R_t}{\kappa_e^{(reg)} \times R_{reg}} \right)} \approx \kappa_e^{(t)}, \quad \text{for } U_N = U_M. \quad (44)$$

In this case we are possible to create non-conductive virtual layer of regolith with the help of electric field focused, even if the real layer of regolith is sometimes highly conductive. The result is that the static chargeability is independent on the rock resistivity and because the current contours go deeply downwards into rocks, the registered static chargeability is close to the chargeability of the fresh rock.

We can analyse too the second variance. If it is possible to simulate virtually the layer of regolith having zero resistivity, i.e.,  $R_{reg} \rightarrow 0$ , and it is the second case, equation will have definition like this:

$$\kappa_e^{SLIP} = \frac{U_M}{U_{M_0}} = \lim_{R_{reg} \rightarrow 0} \kappa_e^{(t)} \times \frac{1}{1 + \left( \frac{\kappa_e^{(sh)} \times R_{sh} + \kappa_e^{(t)} \times R_t}{\kappa_e^{(reg)} \times R_{reg}} \right)} \approx \lim_{R_{reg} \rightarrow 0} \kappa_e^{(t)} \times \left( \frac{\kappa_e^{(sh)} \times R_{sh} + \kappa_e^{(t)} \times R_t}{\kappa_e^{(reg)} \times R_{reg}} \right)^{-1} \approx \lim_{R_{reg} \rightarrow 0} \kappa_e^{(t)} \times \frac{\kappa_e^{(reg)} \times R_{reg}}{\kappa_e^{(sh)} \times R_{sh} + \kappa_e^{(t)} \times R_t} \approx$$

$$\approx \lim_{R_{reg} \rightarrow 0} \kappa_e^{(t)} \times \frac{\left( \frac{\kappa_e^{(reg)} \times R_{reg}}{\kappa_e^{(t)} \times R_t} \right)}{1 + \left( \frac{\kappa_e^{(sh)} \times R_{sh}}{\kappa_e^{(t)} \times R_t} \right)} \approx \lim_{R_{reg} \rightarrow 0} \kappa_e^{(t)} \times \left( \frac{\kappa_e^{(reg)} \times R_{reg}}{\kappa_e^{(t)} \times R_t} \right) \approx \lim_{R_{reg} \rightarrow 0} \kappa_e^{(reg)} \times \left( \frac{R_{reg}}{R_t} \right) \approx 0, \text{ for } U_N = 0. \quad (45)$$

where  $\kappa_e^{SLIP}$  = the selective chargeability of rocks, that is dimensionless [ $\kappa$ ].

This event shows that when the current contours are focused parallelly to the surface of earth, the registered chargeability is mainly influenced by resistivities of rocks and regolith. The recorded chargeability tends to chargeability of regolith. Fresh rocks have minimal influence; regolith, in particular, affects strongly the recorded chargeability, because penetration of electric field downwards into rocks is small. It is evident that the static chargeability is much more important than the selective chargeability which is fully unsuitable.

The used electric currents are these; the feeding denoted as  $I_A$  and the regulative having symbol  $I_E$ ; both are stabilized. Between them there is relation:

$$I_E = \eta \times I_A. \quad (46)$$

where  $\eta$  = the coefficient of focusing; it is dimensionless characteristic.

The next important formula is one for the curve of chargeability. For the static chargeability holds formula:

$$\kappa_e^{SIP} = K \times \kappa_e [\kappa] \dots \text{for condition } U_N = U_M. \text{ Main constant } K \text{ is dimensionless too.} \quad (47)$$

### 10.1 The 5-electrode array with focusing $U_N = U_M$ registering of the static chargeability $\kappa_e^{SIP}$

On condition that  $U_N = U_M$  it means that the current contours enter perpendicularly downwards into rocks. As you can see in fig.6 the electrodes  $N_\infty$  and B are positioned in an infinity distance whereas electrodes  $E_0$  and  $E_0'$  are components of the electrode array. It is possible too to imply condition that  $N_\infty \equiv B_\infty$ . It is again about 5-electrode and 3-electrode arrays. The best is to register the ratio of voltages  $U_M$  and  $U_{M0}$ , what presents the curve of the real chargeability of rocks, formula (54). Voltage  $U_M$  is on electrode M between M and  $N_\infty$  on condition that holds  $U_N = U_M$ ; is directed by formula (53). Voltage  $U_{M0}$  is the primary voltage bound by the current pulse; is directed by formula (52). Both voltages we register and count ratio between  $U_M$  and  $U_{M0}$ . So you get the continuous curve of the characteristic  $\kappa_e^{SIP}$  for each of depth points.

The fundamental equations of 5-electrode array are these:

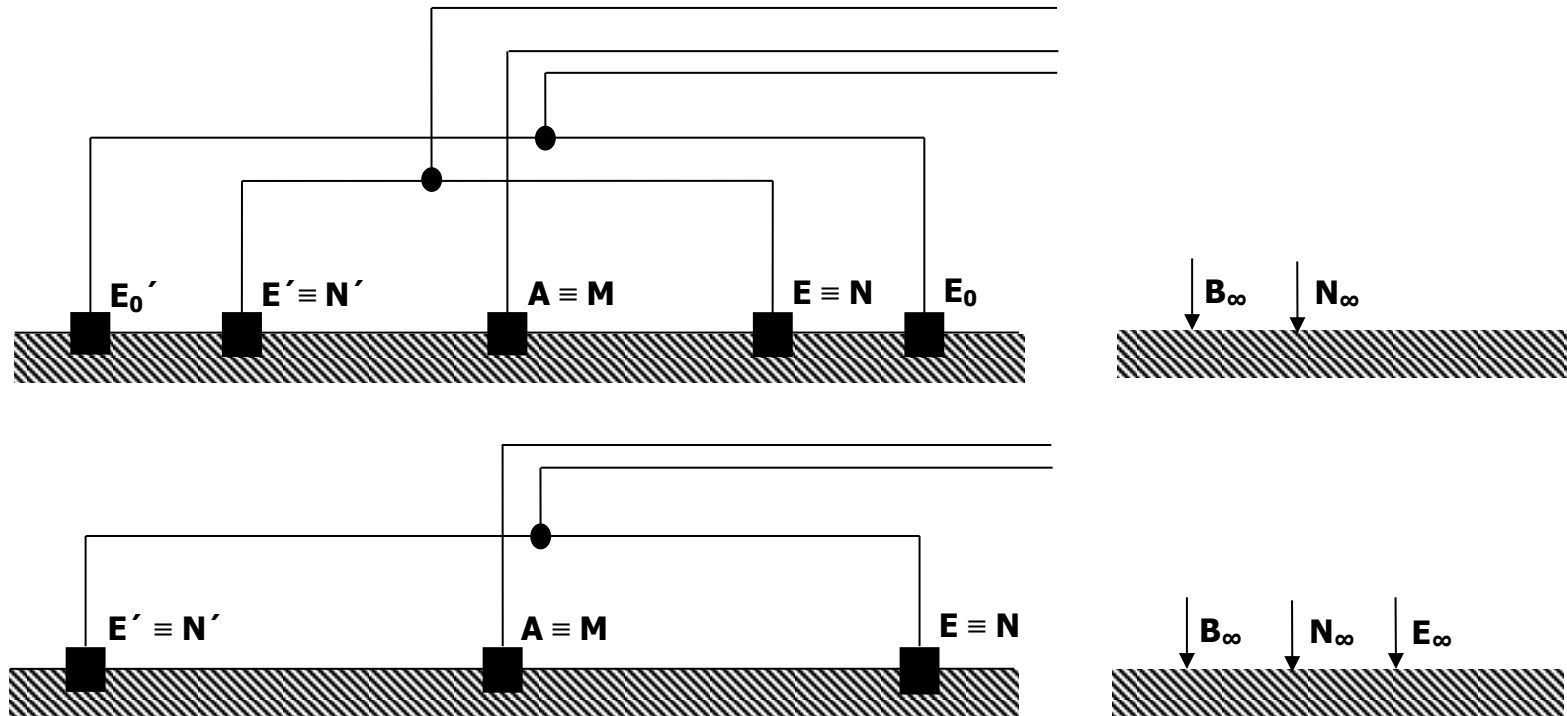
$$U_M = \kappa_e^{(t)} \times \frac{R \times I_A}{k_{AM}} + \kappa_e^{(t)} \times \frac{R \times I_E}{k_{EM}} - \kappa_e^{(t)} \times \frac{R \times I_E}{k_{E_0'M}}, \text{ and} \quad (48)$$

$$U_N = \kappa_e^{(t)} \times \frac{R \times I_A}{k_{AN}} + \kappa_e^{(t)} \times \frac{R \times I_E}{k_{EN}} - \kappa_e^{(t)} \times \frac{R \times I_E}{k_{E_0N}}. \quad (49)$$

Next adjustment is following:

$$U_M = \kappa_e^{(t)} \times \frac{R \times I_A}{k_{AM}} \times \left[ 1 + \left( \frac{k_{AM}}{k_{EM}} - \frac{k_{AM}}{k_{E_0M}} \right) \times \left( \frac{I_E}{I_A} \right) \right], \text{ and} \quad (50)$$

$$U_N = \kappa_e^{(t)} \times \frac{R \times I_A}{k_{AN}} \times \left[ 1 + \left( \frac{k_{AN}}{k_{EN}} - \frac{k_{AN}}{k_{E_0N}} \right) \times \left( \frac{I_E}{I_A} \right) \right]. \quad (51)$$



*Fig.6 Two suggested variances for registering of chargeability of rocks*

Formula (50) is further adjusted

$$U_{M_0} = \left( \frac{R \times I_A}{k_{AM}} \right) \text{ and } \eta = \left( \frac{I_E}{I_A} \right), \quad (52)$$

$$U_M = \kappa_e^{(t)} \times U_{M_0} \times \left[ 1 + \left( \frac{k_{AM}}{k_{EM}} - \frac{k_{AM}}{k_{E_0M}} \right) \times \eta \right]. \quad (53)$$

The last adjustment is like that:

$$\kappa_e^{SIP} = \left( \frac{U_M}{U_{M_0}} \right) = \kappa_e^{(t)} \times \left[ 1 + \left( \frac{k_{AM}}{k_{EM}} - \frac{k_{AM}}{k_{E_0M}} \right) \times \eta \right] = \kappa_e^{(t)} \times K_{SIP}, \quad (54)$$

$$K_{SIP} = \left[ 1 + \left( \frac{k_{AM}}{k_{EM}} - \frac{k_{AM}}{k_{E_0M}} \right) \times \eta \right]. \quad (55)$$

Note, please, formula (54) is dimensionless. From equations (50) and (51) if you implicate condition that  $U_N = U_M$  you will attain coefficient of focusing. It is formula (21).

$$\eta = \frac{\left( k_{AM}^{-1} - k_{AN}^{-1} \right)}{\left( k_{EN}^{-1} - k_{E_0N}^{-1} \right) - \left( k_{EM}^{-1} - k_{E_0M}^{-1} \right)}.$$

We register the voltage  $U_M$  being between electrodes M and  $N_\infty$  and voltage  $U_{M_0}$ . Both voltages are needed for making the ratio denoted as  $(U_M / U_{M_0})$ .

For the partial constants hold these relations:

$$k_{AM} = 2.195 \times a_{AM}, k_{EN} = 2.195 \times a_{EN}, k_{AN} = 2\pi \times \overline{AN}, k_{EM} = 2\pi \times \overline{EM}, k_{E_0N} = 2\pi \times \overline{E_0N} \text{ and } k_{E_0M} = 2\pi \times \overline{E_0M}.$$

As you see there are the formulas being valid too for both resistivity and SP-potentials. Note please that the main constant is dimensionless because we calibrate in chargeability, whereas, for registering of resistivity the main constant has dimension in [m]. The coefficient of focusing, formula (21) can be positive or negative; it is determined with the numeric size of the partial constants.

## 10.2 The 3-electrode array with focusing $U_N = U_M$ registering of the static chargeability $\kappa_e^{SIP}$

Here are electrodes  $E_0$  and  $E_0'$  away of the moveable electrode array and instead of them there is the only electrode  $E_\infty$ . According to fig.6 in an infinity distance you have three electrodes  $N_\infty$ ,  $B_\infty$  and  $E_\infty$ , or can be  $E_\infty$  and  $N_\infty \equiv B_\infty$ . The derived formulas hold however for both possible variances. It is valid for the all chapter 10. The best is again to register both voltages  $U_M$  and  $U_{M_0}$ , what presents the curve of the real chargeability of rocks as the ratio of both voltages, formula (54).

As electrode  $E_{\infty}$  is far it holds that  $k_{E_0M}^{-1} \rightarrow 0, k_{E_0N}^{-1} \rightarrow 0$ ; from formulas (21) and (55) you will get formula (26) and formula (56).

$$\eta = \left( \frac{k_{AN}^{-1} - k_{AM}^{-1}}{k_{EM}^{-1} - k_{EN}^{-1}} \right).$$

$$K_{SIP} = \left[ 1 + \left( \frac{k_{AM}}{k_{EM}} \right) \times \eta \right]. \quad (56)$$

Both currents  $I_A$  and  $I_E$  can flow in the same direction but too in the opposite direction. It is defined through the partial constants. For them holds  $k_{AM} = 2.195 \times a_{AM}$ ,  $k_{EN} = 2.195 \times a_{EN}$ ,  $k_{AN} = 2\pi \times \overline{AN}$ , and  $k_{EM} = 2\pi \times \overline{EM}$ .

## 11 Calibration of chargeability of rocks after the induced polarization method

For calibration you need to have a calibrator being the part of equipment. The chargeability of rocks is defined as the ratio of two voltages ( $U_1/ U_2$ ). It is dimensionless characteristic. The calibrator consists of two independent voltage sources having accurately calibrated their values in [mV]. The output of calibrator presents the voltage ratio ( $U_1/ U_2$ ) simulating a real chargeability. This ratio presents the standard-signal for calibration. If we use a linear scale, one ratio as standard of the real chargeability is enough; however, for non-linear scale you will need to have all set of such standards. Now we can define a standard of the simulated apparent chargeability:

$$\kappa_0 = \frac{U_1}{U_2} \times K = \kappa \times K, K = K_{SIP}. \quad (57)$$

where  $\kappa_0$  = the standard of the simulated apparent chargeability of rocks [ $\kappa$ ],

$K = K_{SIP}$  is the main constant of the electrode array; is dimensionless.

Deflection denoted as  $l_0$  answering to  $\kappa_0$  you get after this formula:

$$l_0 = \frac{\kappa_0}{n}, \quad (58)$$

where  $n$  = the step of linear scale [ $\kappa / 1\text{cm}$ ], and

$l_0$  = deflection reflecting value of standard [cm].

Formula (57) allows us to imply in the calibration an influence of the real electrode array that characterizes used focusing system.

## 12 The estimate of the standard calibration error of the induced polarization method

For calibration there are used two voltages simulating a real chargeability. As both of voltages have a certain error it presents that the simulated real chargeability must have an error too. Here is the way how to determine such error of a dimensionless characteristic. The simulated real chargeability is defined as ratio of two voltages:



$$\kappa = \frac{U_1}{U_2}. \quad (59)$$

For calculation of error you can use this formula:

$$\Delta\kappa = \sqrt{\left(\frac{\partial\kappa}{\partial U_1}\right)^2 \times (\Delta U_1)^2 + \left(\frac{\partial\kappa}{\partial U_2}\right)^2 \times (\Delta U_2)^2}, \quad (60)$$

where symbols  $\Delta U_1$  and  $\Delta U_2$  are errors of both voltages in [mV].

As it is very probable that errors are alike big, you can use identity that  $\Delta U_1 = \Delta U_2 = \Delta U$ . The formula (59) changes in the following:

$$\Delta\kappa = \Delta U \times \sqrt{\left(\frac{\partial\kappa}{\partial U_1}\right)^2 + \left(\frac{\partial\kappa}{\partial U_2}\right)^2}. \quad (61)$$

For both partial derivatives hold expressions:

$$\frac{\partial\kappa}{\partial U_1} = \frac{1}{U_2} \text{ and } \frac{\partial\kappa}{\partial U_2} = -\frac{U_1}{U_2^2}.$$

If these you imply into formula (60) you will receive:

$$\Delta\kappa = \Delta U \times \frac{1}{U_2} \times \sqrt{1 + \left(\frac{U_1}{U_2}\right)^2} = \Delta U \times \frac{1}{U_2} \times \sqrt{1 + \kappa^2}.$$

Through the next adjustment of formula after (58) you obtain the following expression:

$$\Delta\kappa = \Delta U \times \frac{1}{U_1} \times \left(\frac{U_1}{U_2}\right) \times \sqrt{1 + \kappa^2} = \Delta U \times \frac{1}{U_1} \times \kappa \times \sqrt{1 + \kappa^2}. \quad (62)$$

The formula can be express in this form:

$$\left(\frac{\Delta\kappa}{\kappa}\right) = \left(\frac{\Delta U}{U_1}\right) \times \sqrt{1 + \kappa^2}. \quad (63)$$

This is the basic formula for evaluation of the dimensionless characteristic; in this case it is chargeability. If we suppose the values that  $\Delta U = \pm 1\text{mV}$ ,  $U_1 = 1000\text{ mV}$  and  $U_2 = 100\text{ mV}$ , then are  $\kappa = 10$  and  $(\Delta U/U_1) = 10^{-3}$ . In such case holds that  $(\Delta\kappa/\kappa) = \sqrt{101} \times 10^{-3} = 0.01$  and  $\Delta\kappa = \pm 0.1$ . So the value of simulated chargeability is  $\kappa = 10 \pm 0.1$ . However, the simulated apparent chargeability  $\kappa_0$  is directed by formula (56). If we suppose that  $K = 30$  then holds that  $\kappa_0 = 300 \pm 3$ . This is unacceptable for the simulated standard of chargeability.

It is evident that error  $\Delta U = \pm 1\text{mV}$  is too big for calibration. We need to have a lower one. If  $\Delta U = \pm 0.1\text{mV}$ ,  $U_1 = 1000\text{ mV}$  and  $U_2 = 100\text{ mV}$ , then  $(\Delta U/U_1) = 10^{-4}$  and  $(\Delta\kappa/\kappa) = \sqrt{101} \times 10^{-4} = 0.001$ . In such case  $\Delta\kappa = \pm 0.01$  and  $\kappa = 10 \pm 0.01$ . For  $K = 30$  you will get  $\kappa_0 = 300 \pm 0.3$ . Such accuracy of the simulated standard for the apparent chargeability  $\kappa_0$  is all acceptable.

### 13 Discussion over variances of the surface electric measurements

The idea to apply the focused electric field in well-logging is very old. It was well used and made possible to create all new electrical methods as Microlaterolog and Laterolog that are the most known. Principles are described in various old textbooks yet. I can refer to DACHNOV (1965) and (1985), DOBRYNIN (1988) or even to DOLL (1950). However, not any of authors was concerned with question whether is possible to imply the focused electric field too for the surface measurements. The first who had such idea was MARUŠIAK, I.; however, he had not said more about how to realize it.

It needs to say the present way of electric measurements on the earth surface does not use the focused electric field. The existing electrical measurements are well explained by many authors. It is in GUPTA (2011), LLIBOURTRY (2000) and LOWRIE (2007). From Czech authors it is KAROUS (1989).

As for my paper this theoretical study proposes application of the focused electric field for surface electric measurements and analyses various electrode arrays for registering such characteristics as resistivity, the static and the selective SP-potentials and chargeability are.

I guess focusing of the surface measurement will not be as effective as it was in boreholes, because it is about a bit other geometry. It holds namely for all registered data from all current half-space. Field of current contours here forms a fictive lengthways-halved cylinder there; beside of **the vertical component** of field, determined with axis Z, there exists, too, **the horizontal component**, determined with axes X and Y, being strong influenced with conductive regolith.

Even though the current contours, namely in the vertical section view, penetrate deep into rocks below, an influence of the horizontal component with regolith is considerable. Therefore you need to separate common signal into two components: the vertical and the horizontal. Significant is the first, because carries highly true data about rocks below regolith in the vertical section view; mainly in certain geological conditions. The second carries only additional information about regolith.

I shall attempt to explain acting of focusing on measurement in the half-space. On condition that  $U_N = U_M$  the all horizontal component is eliminated from registering. What remains is only the all vertical component facing vertically downward. Influence of regolith is suppressed as if its resistivity had been infinite, yet the influence of rocks being below regolith is underlined. For condition  $U_N = 0$  holds that from registering the all vertical component is eliminated, whereas, the all horizontal component facing horizontally to the earth surface is underlined as if its resistivity had been zero. The influence of rocks being below regolith is simultaneously minimized. Thanks to fig.1 you can it well visualize.

Regolith contains mineralized water and sometimes conductive compounds of Fe and Al too. If has moreover large thickness, it all presents optimal conditions for implication. It is a case of regions having **humid climate**. In contrary there exist too regions with **arid**

**climate**; such regolith is highly dry and of low thickness. It can be even you measure directly on natural stone. In such case it is better to use non-focused methods of registering. For any of methods of the focused electric field holds focusing the electric field supports separating thin and very thin beds what under usual measurement cannot be. Such beds are namely in a thin layer flysch. If in thin sandy beds are hydrocarbons, the beds cannot be depicted as thin ones, because you will record only the only thick and undivided formation, when you use methods of the non-focused electric field.

The supposed electric arrays are seemed can be used both for vertical electrical sounding (VES) and horizontal electrical profiling (HEP). However, the main constant  $K$  remains permanently stable, because distances of the electrode array remain stable too. Therefore it cannot be vertical electrical sounding but only and only horizontal profiling even if enough special, maybe. It holds in general for all recordings, not only for resistivity. In the same way you can go when you register chargeability and SP-potentials; moreover, in all measurements you must hold the only condition of focusing  $U_N = U_M$ . The second one  $U_N = 0$  is not acceptable for total influence of regolith.

For the third main method, electrical resistivity tomography (ERT), it is worth thinking about how to apply the focused electric field for this method. I suppose it would carry new better results. As for software, there would be rather smaller adaptation there; however, hardware would need to have much larger adaptation. It is about all new electrode array having much more partial electrodes. Therefore the best of all would be to adapt three-electrode array of focused electric field in so way that each of two electrodes denoted as  $E_i \equiv N_i$  and  $E_i' \equiv N_i'$  where holds  $i = 1, 2, \dots, n$ , would be formed as the electrode set having the same number of single electrodes, whereas central electrode denoted as  $A \equiv M$ , would remain as the only one.

Similar array can be for 5-electrode system;  $A \equiv M$ ,  $E_0$  and  $E_0'$  on one side and electrodes  $E_i \equiv N_i$  and  $E_i' \equiv N_i'$  on the other side for  $i = 1, 2, \dots, n$ . As for me it is from the largest part of solution a technical problem. And further. Just such application of electrode array makes to apply principles of tomography not only for resistivity but too both for measurement of the static SP-potentials and for measurement chargeability of rocks after the method induced polarisation. It presents significant enlargement possibilities of measurements by methods of tomography.

What is very important is the current and potential electrodes form the only electrode array where the potential electrodes are positioned between feeding and guarding current electrodes. It holds too for three-electrode array what is a special array. As a result of that is the profile line in the plain being perpendicular to the Earth surface eliminates an influence of regolith. In such profile line the rocks being below regolith are intensified in contrary to regolith.

## 14 Conclusions

Thanks to all before information here are these conclusions:

- Method of the controlled current regulation can be used probably too for the surface registering with the focused electric field.
- The mud being in the borehole can be replaced for the surface by electrically-conductive regolith.

- Regulation of the electric field is made again under conditions either  $U_N = U_M$  or  $U_N = 0$ ; the last one is admittedly possible but not often really used.
- The current and potential electrodes form the only array where the potential electrodes are located between feeding and guarding current electrodes.
- In such case the profile line is in the plain being perpendicular to the Earth surface; an influence of regolith is suppressed and influence of the rocks below is intensified.
- From geophysical characteristics one can register resistivity of rocks, chargeability of rocks and the static SP-potentials if it is the focused electric field.
- If the characteristic is resistivity of rocks both the feeding and regulative currents are continuous and stabilized. The regulative current is multiple of the feeding one.
- If the characteristic are the static SP-potentials both the feeding and regulative currents are continuous and variables. The regulative current is again multiple of the feeding one, however, changes after the variable feeding current.
- If the characteristic is chargeability the feeding current has the stabilized, however periodically cut, value. In contrary the regulative current is permanently continuously stabilized and it is multiple of the feeding one.
- For all three fundamental electrode arrays I can recommend electrode arrays in two variances; either 3 or 5-electrodes. Number of electrodes ought to be as low as possible for practical reasons.
- Using of new electrode array is convenient for horizontal profiling (HEP); for vertical electrode sounding (VES) it would present very sophisticated adjustment being not well-used for practical measurement.
- In contrary to VES the electrical resistivity tomography (ERT) seems to be more perspective for surface measurements. One cannot exclude it can be about new very detailed tomography. However, it asks a certain adjustment of the existing hardware and software.
- Principles of measurement technologies both HEP and ERT can be enlarged for registering next characteristics as chargeability of rocks and the static SP-potentials are.

## References

- DACHNOV, V. N. *Elektritscheskie i magnitnye metody issledovania skvazhin*, Textbook, Nedra, Moskwa, 1967.
- DACHNOV, V. N. *Geofyzitscheskie metody opredelenya kollektorskich svoystv i neftegazonasystchenya gornych porod*, Textbook, Nedra, Moskwa, 1985.
- DOBRYNIN, V. M. *Interpretacya rezultatov geofyzitscheskich issledovanyi neftyanych I gazovykh skvazhin*, Textbook, Nedra, Moskwa, 1988.
- DOLL, H. G. *Selective SP-logging*, Journal of Petroleum Technology, No. 5, 1950.
- GUOZHU, N. and HUI, X. *Static SP measurement tool and its field applications*, Jiuyun Energy Technology Company, Beijing, China, presented on Annual Logging Symposium, The Woodlands, Texas, June 21 – 24, 2009.
- GUPTA, H.K. *Encyclopaedia of solid Earth geophysics*, Springer, 2011, 1530 s.
- KAROUS, M. *Geoelektrické metody průzkumu*, SNTL/ALFA, Praha, 1989, 423 s.
- LLIBOURTRY, L. *Quantitative geophysics and geology*, Springer, Praxis, 2000, 480 s.

LOWRIE, W. *Fundamentals of Geophysics*, Cambridge University Press, 2007, 381 s.

MARUŠIAK, I. *Princip kontrolovanej reguljacji toka mnogoelektroдных karotažnych zondov*, 1. část, Užitá geofyzika, 7, 1968.

MARUŠIAK, I., TĚŽKÝ, A., JONÁŠOVÁ, V. *Princip kontrolovanej reguljacji toka mnogoelektroдных karotažnych zondav*, 2. část, Užitá geofyzika, 8, 1969.

RYŠAVÝ, F. *Method of the controlled current regulation – Laterolog*, EGRSE Journal, vol. XX, no. 2, 2013, p. 67 – 85.

RYŠAVÝ, F. *Elimination of the Electrode Potentials for Well-logging electric Micro-systems*, Transactions of the VŠB – Technical University of Ostrava, Civil Engineering Series, No. 2, Vol. VI, p. 237 – 242, 2006.

RYŠAVÝ, F. *Method of the controlled current regulation – calculation of partial constants for cylindrical electrodes*, EGRSE Journal, vol. XX, no. 2, 2013, p.86 – 103.

SCHLUMBERGER, *Log Interpretation Principles /Applications*, Schlumberger Well Wireline & Testing, Sugar Land, 1989.

---

**Author**

<sup>1</sup> RNDr. František Ryšavý, Lesní 3, 695 03 Hodonín, Czech Republic, rysavy.frantisek@seznam.cz