THE SMOOTH SOUNDING GRAPH

A Manual for Field Work in Direct Current

Resistivity Sounding

by

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Preface

This manual shall be a practical guide to surveyors, field operators, technical assistants, i.e. to all those who have to do the "dirty" work collecting field data under more or less bad conditions.

Suffering under rough roads, hard climate and very often the lack of sufficient support by local officials a team "is thrown" into an area to be investigated. Such a team has to provide its office or company with field data. In our case these field data are so-called resistivity sounding graphs. A graph is a sequence of data, which can be combined (by hand) to a more or less smooth curve. This procedure is not possible, if the data form a "cloud". Knowing that a cloud will not be accepted by the interpreter in the office the field group has to offer in any case rather smooth curves. This is their problem. Provided with a map where a grid of measuring points is plotted -often following the 1 inch-1 mile network- they start. Comparing their map (usually many years old) they find out, that an accurate measurement with the prescribed lay-out of say 500 m will end in a lake or in a new industrial plant or in a green paddy-field. The chance of shifting the measuring point is usually very low, because the grid may not be disturbed. Now it depends on the conscience of the chief surveyor in the field, to tell the truth, i.e. that a smooth curve at the prescribed point and also in its neighbourhood is impossible. His scientific opinion cannot allow him to "cook data" even when being sure, that the interpreter will never control him.
Thinking on his own promotion the "field-man" is really in a bad situation. The authors know from experience collected in many countries all over the world about just this situation.

In order to make the best of it from the technical point of view this manual was written hoping that it may be a real help.

A short remark has to be added. Only real direct current is concerned here. There are equipments using alternating current with very low frequencies. Those equipments may get sufficiently good results using relatively short lay-outs. Investigating the deeper underground the skin-effect will come in and difficulties will arise which are not discussed within this manual.

Hannover, November 1976

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1. Basic rules

The first chapter deals with the fundamentals of direct current resistivity measurements. The attempt was made to give an elementary introduction into what really happens within the earth during a measurement. The physical process should be understood by the reader.
Each physical parameter will be checked with respect to its influence on the measured data. This will be done by reducing mathematical formulae to a minimum. A well-trained mathematician will sometimes have a bad feeling seeing the rigorous way of using mathematical "tools". But this manual is written for a field crew working with modern equipments on the earth's surface. Going on step by step in recording data they should follow up in mind the subsurface process, i.e. they should know what they are really doing.

One remark should be added: In the theoretical part of this chapter only one very simple integral appears. The authors would be very glad if readers could make any proposal to get rid of this integral in explaining the necessary background of direct current resistivity sounding.

1.1. Ohm's Law

Geo-electrical measurements are carried out on the earth's surface. The air space is assumed as an insulator and the earth's surface as a plane. The underground is an electrical conductor. A direct current is running from the surface through this conductive infinite half-space, limited above by the plane earth's surface. Which laws are valid for this current flow through the underground?

Regarding electrical currents we generally are accustomed to think of a wire. A wire has a certain resistance which can be calculated from Ohm's law. We regard (see Fig.1) a wire of the length a, measured in meters [m] with a cross-section ***q***, measured in [m^2]. Ohm's law then can be written as

$$\frac{U}{I} = R = \frac{a}{q}\rho \qquad (1)$$

where ***R*** is the resistance [Ohm] of the wire, ***U*** is the voltage [Volt] measured between the wire-ends when a current of an intensity ***I*** [Ampere] flows through the wire.

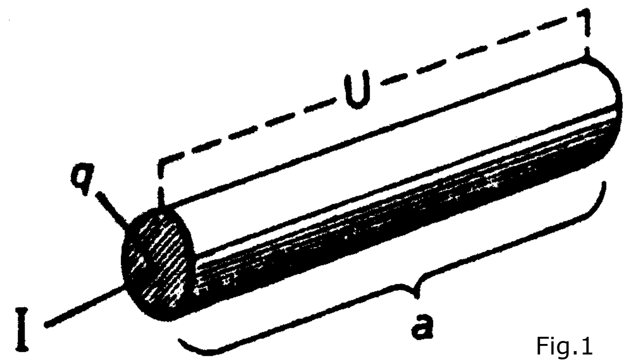


Fig.1

This means: the longer the wire, the greater the resistance, but the resistance decreases, when the cross-section is enlarged. The influence of the material of the wire (iron, copper) is expressed by a material constant ρ, i.e. the resistivity of the wire measured in [Ohm.m] or [Ωm]. This dimension can easily be proved from equation (1) in order to have equal dimensions on both sides.

Now we have to change our mind from the wire to the half-space. Some difficulties arise, because the infinite half-space possesses neither a length nor a cross-section. We also do not know in which direction the current flows. Obviously this problem depends on the points of grounding the electrodes. Between which points the voltage ***U*** has to be recorded? We now shall reduce these difficulties step by step. Starting from formula (1) valid for the wire (Fig. 1) we try to remove the length ***a*** and the cross-section ***q*** from this formula, transforming it into

$$\frac{U}{a} = \frac{I}{q}\rho \qquad (2)$$

At the left side appears a voltage normalized to the unit length and expressing the intensity ***E*** of the electric field. ***E*** has the dimension [Volt/m]. At the right side the quotient current/cross-section expresses nothing else then the density of the current within the wire.

This current density is marked as ***j*** measured in [Amp/m²]

$$\boxed{E \quad = \quad j\,\rho} \tag{3}$$

is a form of Ohm's law, valid at any point in the underground and not containing any boundaries. This so-called "infinitesimal" form is the fundamental formula to be used in the field of resistivity measurements.

1.2. The homogeneous underground

The homogeneous underground represents an electrical conductive half-space with the resistivity ρ. It is limited by the earth's surface (insulator).

A current electrode A will be placed at the earth's surface. A second electrode B is moved to infinity (this is necessary in order to complete the current circle). If the electrodes are supplied by a direct voltage, then a direct current ***I*** will flow through the earth. At the electrode in point A the current spreads radially (Fig.2). Now we consider in the subsurface the skin of a hemisphere with radius ***r*** and thickness ***dr***, which has its central point in A. We then determine the resistance of this hemispherical skin with respect to the current running radially from the "point source" in A. We apply Ohm's law for the wire (equ.1)

$$R = \frac{a}{q}\rho$$

The length ***a*** corresponds to the thickness ***dr*** of the spherical skin. The cross-section ***q*** corresponds to the surface of the hemisphere with radius ***r***, which is $2\pi r^2$, because the surface of the whole sphere is $4\pi r^2$. The resistivity is that of the homogeneous earth. Therefore the resistance ***dR*** of this thin skin is:

$$dR = \frac{dr}{2\pi r^2}\rho \qquad (4)$$

The next step will be to determine the resistance of a thick hemispherical body with an inner radius r_1 and an outer radius r_2 (Fig.3). We do this by summing up hemispherical skins the radius of which arises from r_1 up to r_2.

This is a simple integration of the skin-resistances ***dR*** from r_1 to r_2. Those who are not familiar with solving simple integrals will find the used formula in elementary mathematical tables given e.g. in any technical manual. The resistance $R_{1,2}$ of our hemispherical body is, using equation (4),

$$R_{1,2} = \int_{r_1}^{r_2} dR = \frac{\rho}{2\pi}\int_{r_1}^{r_2}\frac{1}{r}dr = \frac{\rho}{2\pi}\left[-\frac{1}{r}\right]_{r_1}^{r_2} = \frac{\rho}{2\pi}\left(\frac{1}{r_1}-\frac{1}{r_2}\right) \qquad (5)$$

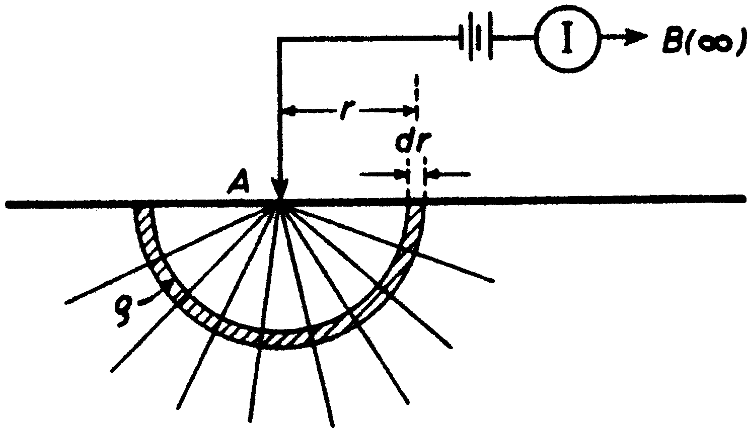


Fig.2

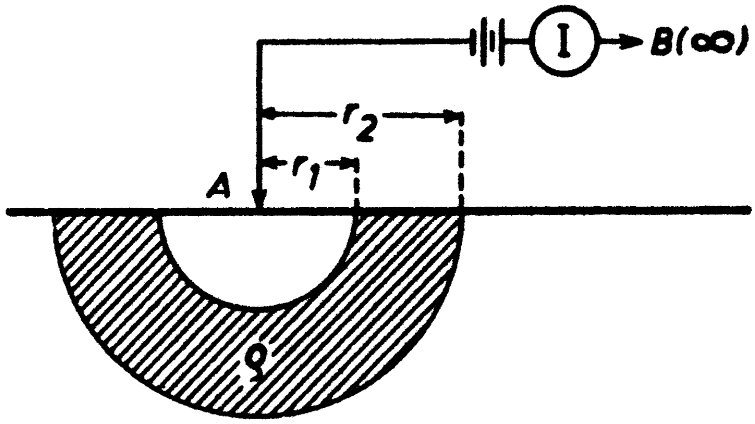


Fig.3

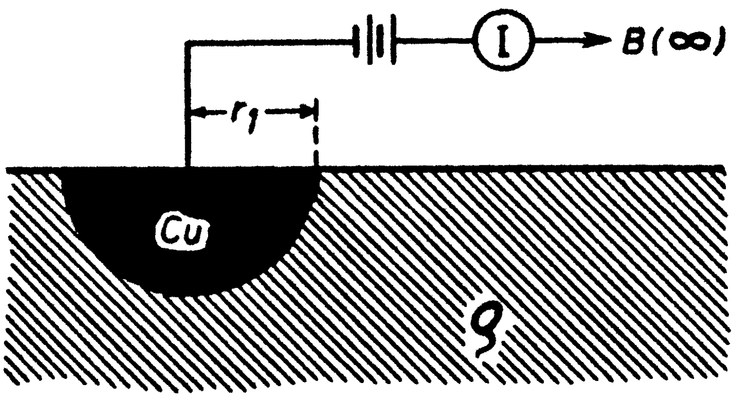


Fig.4

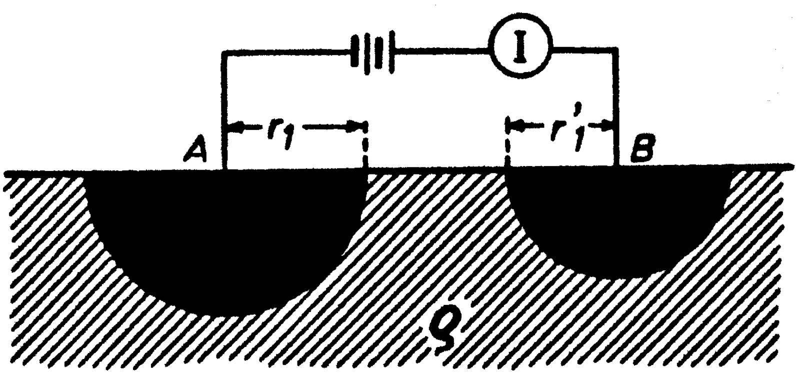


Fig.5

This formula has a fundamental consequence for geo-electrical field measurements: In order to bring a direct current into the earth we want a contact between the electrode and the ground. A perfect "point source" is technically impossible. The electrode must have a finite surface touching the earth. Suppose we use a spherical shaped copper electrode (Fig.4) with radius $\boldsymbol{r_1}$.

The resistivity of copper is compared with the resistivity ρ of the earth practically zero. From equation (5) results, that the resistance of the whole infinite half-space outside the electrode ($\boldsymbol{r_2} \rightarrow \infty$) is

$$R_{1,\infty} = \frac{\rho}{2\pi\, r_1} = R_A$$

This is a <u>finite</u> (!) value depending on the size of electrode A. The larger the contact surface $2\pi r_1^2$, the lower the resistance. Although the resistivity ρ of the homogeneous earth is contained in this formula, the resistance is mainly influenced by $\boldsymbol{r_1}$ and of course – not included in this formula - by the quality of the contact copper-earth (the formula is based on an ideal contact).

Adding the second electrode B (Fig. 5) with a radius $\boldsymbol{r_1'}$ we will measure a resistance

$$R_{A+B} = \frac{\rho}{2\pi}\left(\frac{1}{r_1} + \frac{1}{r_1'}\right) \qquad (6)$$

This resistance can be decreased by enlarging the contact surface of either A or B or both of them. As this cannot be controlled in field work we have no chance to calculate ρ by this 2-point electrode configuration. Remarkable is the fact, that equation (6) is independent of the distance between A and B!

1.3. <u>The four-electrode arrangement</u>

In order to be independent of the contact resistance at the current electrodes A and B, WENNER (1917, USA) and C. & M. SCHLUMBERGER (1920, France) proposed the so-called four-point-method, placing A and B symmetrically to a centre point and in addition in between also symmetrically to this centre two so-called potential electrodes M and N. From Fig.6 we see the current flowing from A to B through the earth. The current intensity ***I*** can be read from an ampere-meter. Along each current line in the underground the voltage from the power supply, say e.g. 200 V is decreasing from 200 V at A to zero at B. If we mark on all current lines points of equal voltage (e.g. for 180, 160, ..., 40, 20 V) and combine these points we get the so-called equipotential lines running perpendicular to the current lines and ending with a right angle at the earth's surface. At the surface there exists a potential distribution during the current flowing from A to B. This distribution, obviously depending on the resistivity ρ of the underground, can be observed by measuring the voltage ***U*** between the equipotential lines at the surface. Using the four point arrangement this will be done between M and N using a volt-meter. Now how to calculate the earth's resistivity from current intensity ***I*** and voltage ***U***? This can be done easily from equation (5) looking at Fig.3 and Fig.7.

If the distance AB between the current electrodes is ***L*** and the distance MN between the potential electrodes is ***a***, then the distance from A to M is

$$\overline{AM} = \frac{L}{2} - \frac{a}{2}$$

and the distance from A to N

$$\overline{AN} = \frac{L}{2} - \frac{a}{2}$$

In equation (5) developed from Ohm's Law,

$$R_{1,2} = \frac{\rho}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r_2}\right) = \frac{U_{1,2}}{I}$$

we simply have to replace $\boldsymbol{r_1}$ by $\left(\frac{L}{2} - \frac{a}{2}\right)$

and $\boldsymbol{r_2}$ by $\left(\frac{L}{2} + \frac{a}{2}\right)$

to get as a contribution from electrode A to the voltage between M and N

$$U_{MN}^{(A)} = \frac{I\rho}{2\pi}\left(\frac{1}{\frac{L}{2}-\frac{a}{2}} - \frac{1}{\frac{L}{2}+\frac{a}{2}}\right)$$

As the arrangement is symmetrical we get the same contribution from electrode B.

This results into

$$U_{MN} = U_{MN}^{(A)} + U_{MN}^{(B)} = 2\,U_{MN}^{A} = \frac{I\rho}{\pi} \times \frac{a}{(\frac{L}{2})^2 - (\frac{a}{2})^2} \qquad (7)$$

For the earth-resistivity ρ we then obtain

$$\rho = \frac{\pi}{a}\left[\left(\frac{L}{2}\right)^2 - \left(\frac{a}{2}\right)^2\right]\frac{U_{MN}}{I} \qquad (8)$$

or

$$\boxed{\rho = K\frac{U}{I}} \qquad , \qquad K = \frac{\pi}{a}\left[\left(\frac{L}{2}\right)^2 - \left(\frac{a}{2}\right)^2\right]$$

i.e. the well-known formula used in calculating the resistivity ρ from the current ***I*** between A and B and the voltage ***U*** between M and N.

K is called "factor of configuration" or "geometric factor". Its dimension is [m].

We now have to study the function of this factor ***K***. As a homogeneous underground is concerned ρ be a constant. Working with a constant current ***I*** - this is technically no problem because ***I*** depends after equation (8) only on the quality of grounding the current electrodes A and B (contact resistance) and not on their distance - the voltage ***U*** decreases by enlarging ***L***. This decrease is compensated by an increasing ***K***. The regulating function of ***K*** now shall be discussed regarding both electrode configurations used nowadays in practical field work.

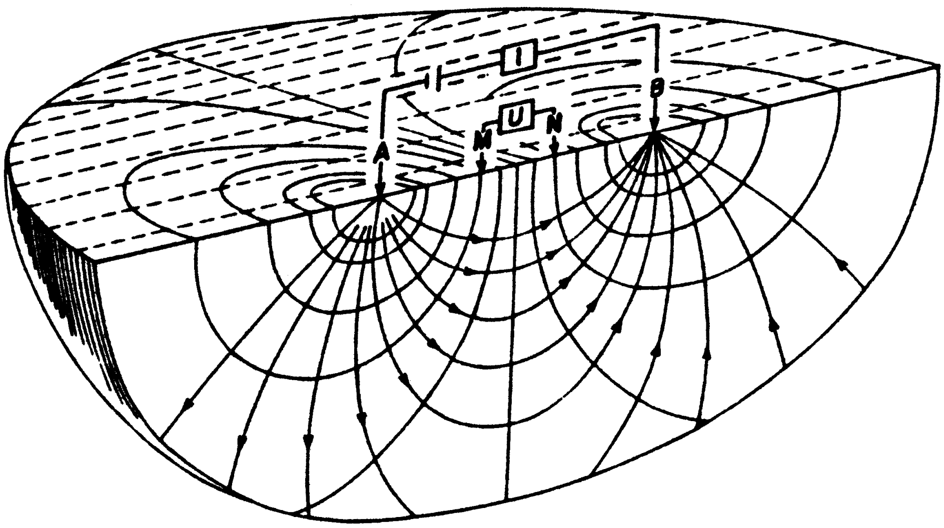


Fig.6

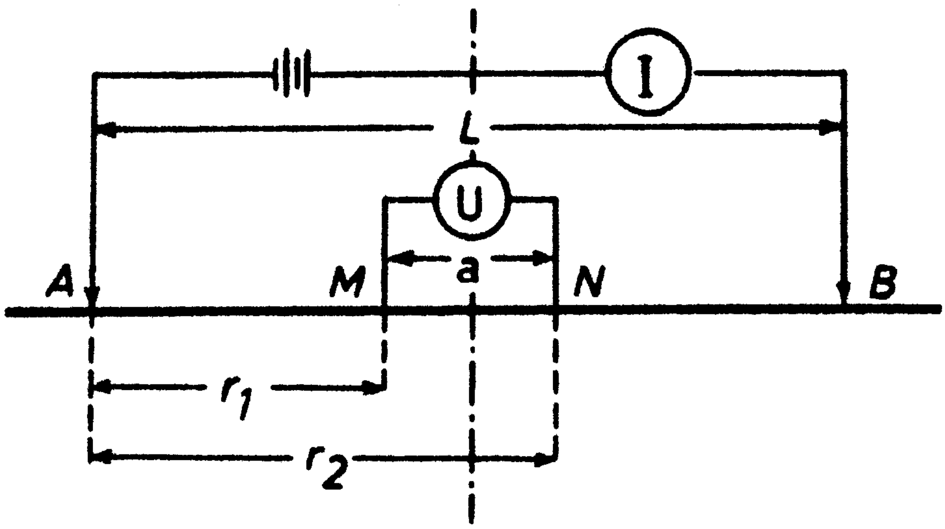


Fig.7

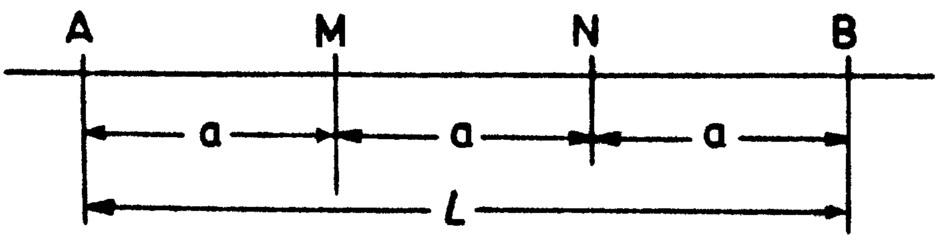


Fig.8

1.3.1. Wenner configuration (***L=3a***)

The proposal of Wenner was an equidistant electrode spacing AMNB with $\overline{AM} = \overline{MN} = \overline{NB}$ (see Fig.8).

Substituting ***L***=3***a*** in equation (8) we get

$$K = \frac{\pi}{a}\left[\left(\frac{3a}{2}\right)^2 - \left(\frac{a}{2}\right)^2\right] = 2\pi a \qquad (9)$$

This formula is very handy. But for field work on a non-homogeneous earth, where the electrodes M and N have to be shifted (see chapter 4.6), there are many disadvantages which were observed by C. Schlumberger who first applied the method in practice.

1.3.2. Schlumberger configuration (***a<<L***)

Here the potential electrodes M and N are placed close to each other at the centre-point (dipole) with a constant spacing a. For ***L***>10***a*** we can reduce the formula (8) for ***K*** with an error less than 1 % to

$$K = \frac{\pi}{a}\left(\frac{L}{2}\right)^2 \qquad (10)$$

Compared with Wenner, where ***K*** shows a linear increase with ***L*** here ***K*** is increasing with $\boldsymbol{L}^2$. The decreasing of ***U*** with the same square rate affords a more sensitive voltmeter within the measuring equipment.

Now before proceeding to the non-homogeneous earth we shall regard again Ohm's law for unlimited electrical conductors:

$$E = j\,\rho$$

and apply it to the four-point-arrangement in the form

$$\frac{U}{a} = j\,\rho \qquad (11)$$

As ρ and a are constant in the Schlumberger configuration the voltage ***U*** between the potential electrodes is a measure of the current density along the "skin of the soil just under our feet" between M and N. Changes in ***j*** will proportionally cause changes in ***U***.

If we compare equations (10) and (11) i.e.

$$K = \frac{\pi}{a}\left(\frac{L}{2}\right)^2 \qquad \text{and} \qquad \frac{U}{a} = j\,\rho$$

and replacing in the general formula (8)

$$\rho = K\frac{U}{I}$$

valid for the homogeneous underground the constant resistivity ρ, we get

$$\frac{U}{a}\frac{1}{j} = \frac{\pi}{a}\left(\frac{L}{2}\right)^2\frac{U_{MN}}{I}$$

$$I = j\pi\left(\frac{L}{2}\right)^2 \qquad (12)$$

From this equation we can see very clearly the regulating function of the geometric factor ***K***: Enlarging the spacing ***L*** of the current electrodes on the surface of a homogeneous earth the same current intensity ***I*** will produce a decreasing current density ***j*** between the potential electrodes M and N. This decrease is compensated by $\pi(\boldsymbol{L}/2)^2$ that means in Schlumberger configuration (***a***=const.) by ***K***.

The reader should study carefully these just described physical connections between ρ, U/a, I, L, K and especially j, to get a real feeling for the process of running a direct current through a homogeneous earth.

1.4. The layered underground

The aim is to analyse quantitatively a layered underground by aid of the four-electrode arrangement according to Schlumberger.

Case 1 (Fig.9)

We observe a two-layer-case and assume that an electrode spacing is very small compared with the depth of the first layer boundary.

We are measuring according to the formula $\rho = K\frac{U}{I}$. Because the distance of the second layer is far enough, the course of current lines is hardly influenced. In this case we get approximately $\rho \approx \rho_1$.

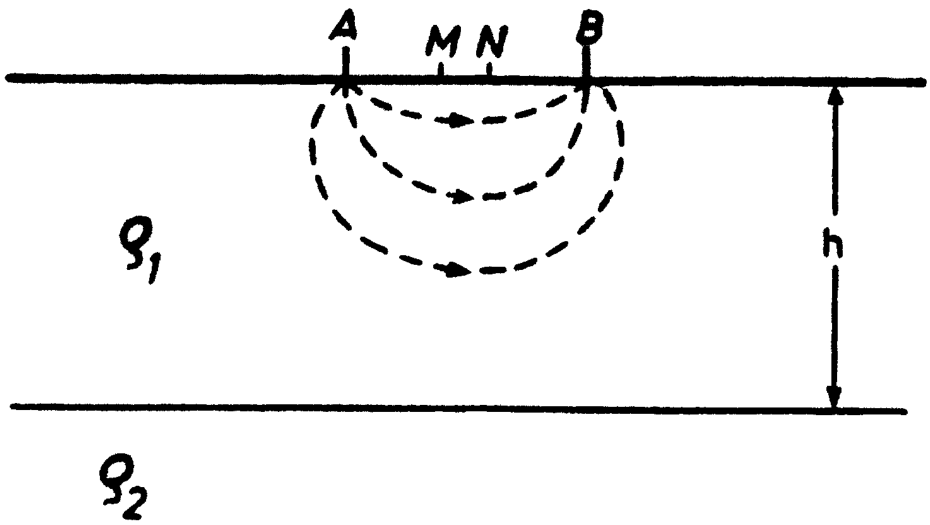


Fig.9

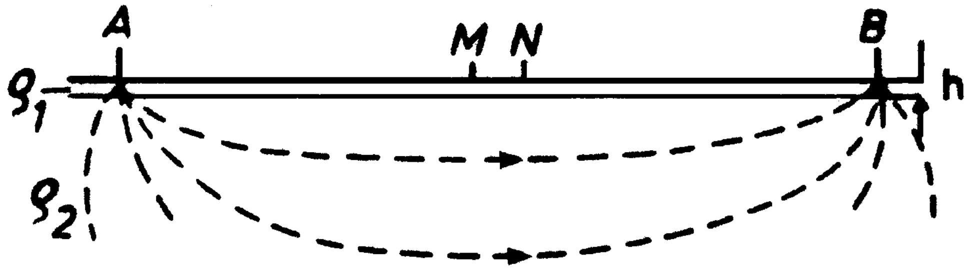


Fig.10

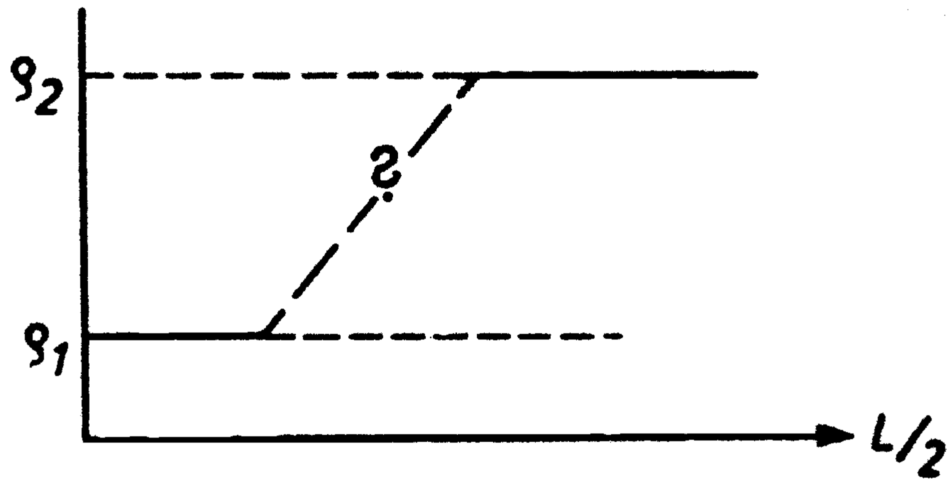


Fig.11

Case 2 (Fig. 10)

Now we observe a very thin layer at the surface with the resistivity ρ_1 underlain a layer with the resistivity ρ_2 down to infinity. The spacing of current electrodes between A and B is now very large. In the middle between them there are the potential electrodes M and N. Thus the case will result, as if the current electrodes touch the second layer: $\rho \approx \rho_2$

If we calculate by aid of the formula $\rho = K\frac{U}{I}$, we obtain two different ρ-values for both cases. In the following this fact shall be explained in Fig.11.

The distance of the current electrode from the centre point ***L***/2 is marked on the abscissa (***L***/2-scale) and the resistivity ρ, which is measured using the formula $\rho = K\frac{U}{I}$ on the ordinate. In the first case we have $\rho \approx \rho_1$ and in the second $\rho \approx \rho_2$. Now we have to ask how to reach ρ_2 starting from ρ_1. Which way the ρ-values calculated by the formula $\rho = K\frac{U}{I}$ will run from ρ_1 to ρ_2 depends on the depth of the layer boundary in comparison to the actual distance ***L*** of the current electrodes. If we do not know anything about the underground, and if we simply use the values from the formula for the homogeneous underground, the resistivity ρ will not keep constant. Intermediate values of ρ between ρ_1 and ρ_2 will occur. These intermediate values are named "apparent resistivities ρ_a", which really do not exist in the underground. Therefore these apparent resistivities have to be defined as a function of the electrode spacing. We do this by using the formula for the homogeneous earth

$$\boxed{\rho_a \underset{def}{=} K\frac{U}{I}} \qquad (13)$$

The graph combining the values for the apparent resistivities ρ_a and running from ρ_1 to ρ_2 is the so-called "sounding graph" $\rho_a(L/2)$.

We summarize: The apparent resistivity depends on theelectrode arrangement on the earth's surface. Its values must not really occur in the underground. They are no "true" resistivities. The reason for using them is our ignorance about the real resistivity distribution in the underground.

ρ_a results from using a not permitted formula (only valid for a homogeneous earth) and because a homogeneous underground has no boundaries and therefore nothing depending on a depth-scale, the apparent resistivity thus defined is merely a function of $\boldsymbol{L}/2$ and of course the potential electrode spacing a (Schlumberger $\boldsymbol{a} \rightarrow 0$, Wenner $a=\boldsymbol{L}/3$).

In other words: There is no apparent resistivity in the underground at any depth. Thus the question often asked during a measurement to the operator at the instrument :
"How deep are you now?" is senseless.

1.5. The fundamental principle for geoelectric sounding on a layered earth

At first we shall explain by a simple model the current density within a layered underground.

Case 1 (Fig.12)

For explanation we only look at the electrodes A and B on the earth's surface and their distance ***L***. The layer below the surface has a resistivity ρ_1. Its thickness be ***h***. It is underlain by a second layer infinitely extended. We assume that this second layer is an insulator ($\rho = \infty$). When we observe the distance ***L*** in relation to ***h***, we can see that the current can extend normally within the first layer, that means be hardly influenced by the insulator.

Case 2 (Fig.13)

We have again the same electrode distance ***L***, but the thickness h of the first layer has been reduced. By this of course the geology is changed, the measuring configuration however is still the same. When we look again at the distance ***L*** in relation to ***h***, we can see that the current lines seem somehow pressed to the surface. As result we can derive: If ***h*** becomes smaller at the same electrode configuration, the current lines will be compressed more and more. Therefore the current density increases and consequently does the voltage at the potential electrodes. To zoom the insulator means increasing the current density "below our feet" at the centre point.

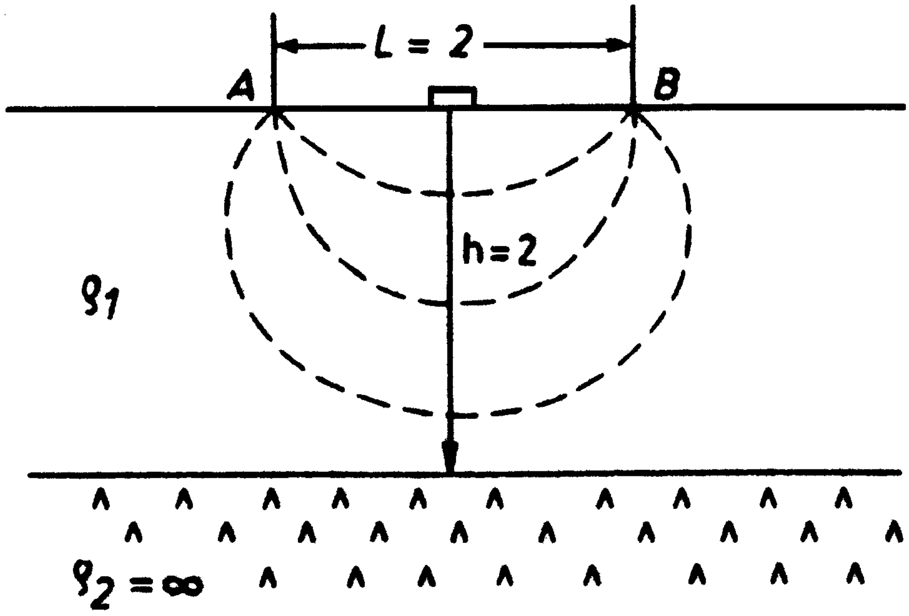


Fig.12

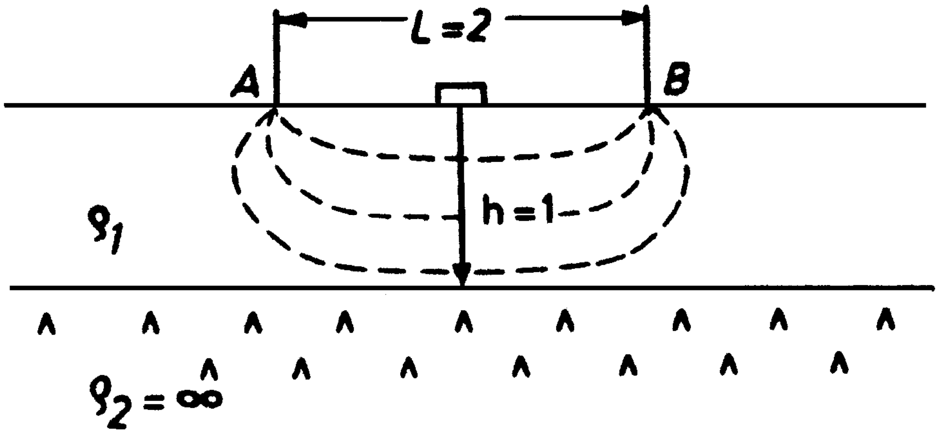


Fig.13

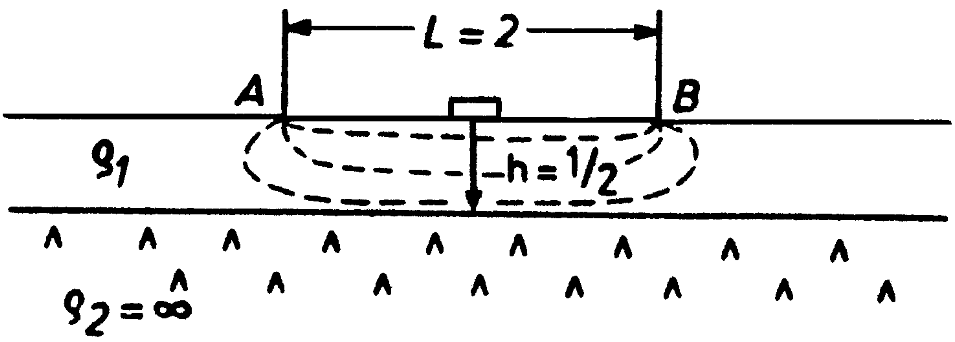


Fig.14

Case 3 (Fig.14)

The electrode distance ***L*** is again the same, but the thickness ***h*** in relation to ***L*** is now very small. Therefore the current density will be increased again.

In the cases 1 to 3 mentioned before, the electrode configuration on the surface persisted constant, but the thickness of the first layer was changed.

In practice, however, one cannot change the geology, i.e. the thickness ***h*** but there is the possiblity to change the configuration on the surface (Fig.15).

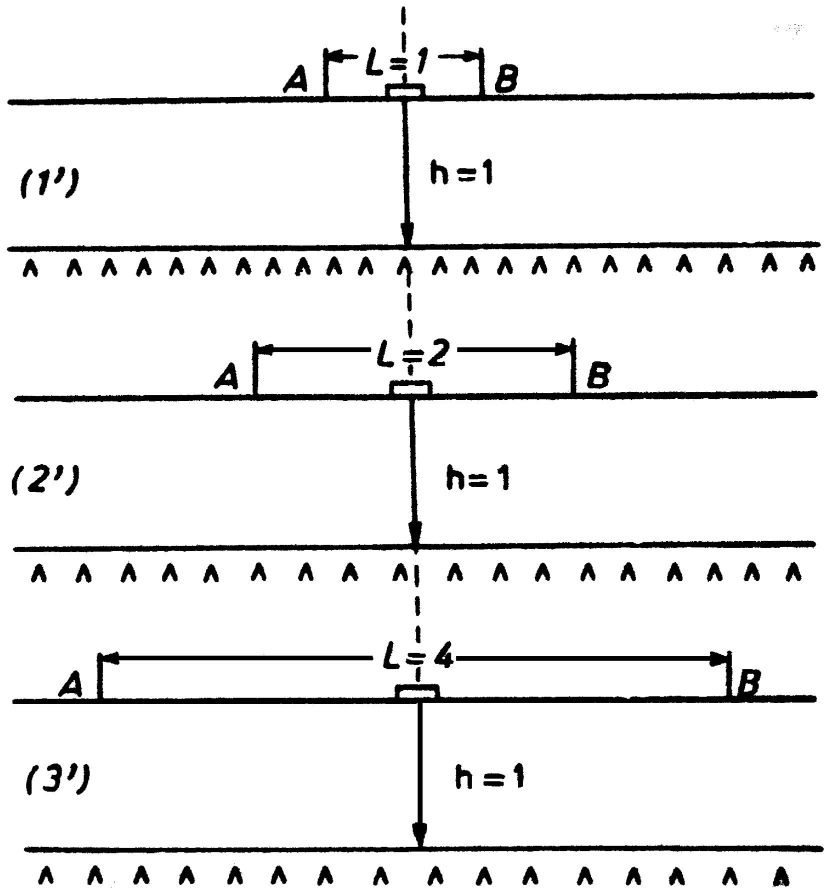


Fig.15

Regarding the ratio $\frac{L}{h}$ the thickness ***h*** has been reduced in cases 1 to 3 assuming ***a*** constant ***L***. Practically ***h*** is constant, and therefore the variation of the current density can be simulated by an enlargement of the distance ***L*** between A and B.

The following equivalent cases are the result of an enlargement of ***L***.

Case 1 in Fig.12 where ***L*** is equal to ***h***, corresponds consequently to case 1' in Fig.15.

In case 2 in Fig.13, ***L*** is twice of ***h*** corresponding to case 2' in Fig.12.

Case 3 in Fig.14 where ***L*** is four times as large as ***h***, corresponds to case 3' in Fig.12.

Comparing the cases 1 to 3 with the cases 1' to 3' they obviously correspond in the quotient $\frac{L}{h}$**.** However there is no congruence. With respect to the real current density we have to transform 1-3 into 1'-3' by a geometrical factor. This factor is just the constant ***K*** in the now already well-known formula (13)

$$\rho_a \underset{def}{=} K\frac{U}{I}$$

At this point the reader will think that concerning the geometric factor ***K*** he would have found similar sentences before and that the authors have only repeated what they already have written. The reader is right. The role of ***K*** has been discussed in chapter 1.3. but under another aspect. Or is it the same aspect? The reader may decide by himself and then perhaps may get a deeper insight into the physical content of the
two formulas

homogeneous earth	layered earth
$\rho = K\frac{U}{I}$	$\rho_a \underset{def}{=} K\frac{U}{I}$
"true"-resistivity	"apparent" resistivity

with just the same factor ***K***.

After this we now return to our two-layer case discussed by aid of Fig.12-15 and shall proceed to plot the result in a diagram. i.e. we want to construct a "sounding graph" $\rho_a(L/2)$ as already mentioned at the end of chapter 1.4.

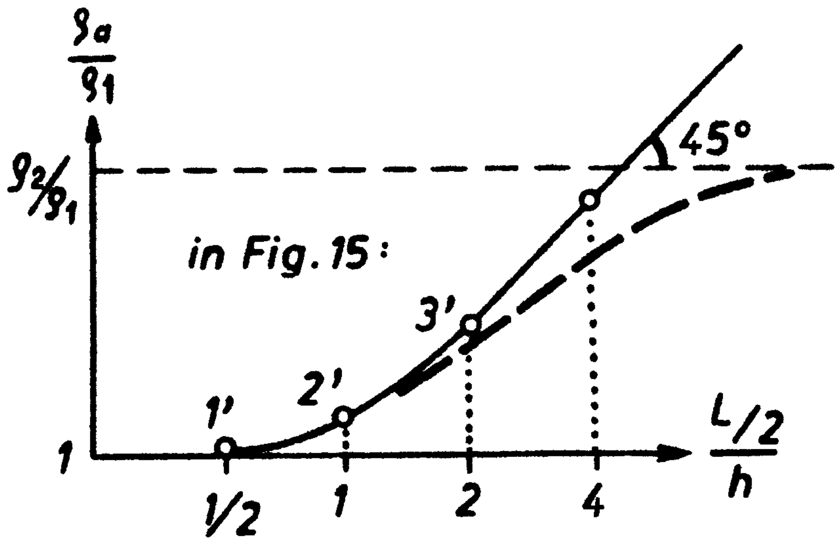


Fig.16

As $\frac{L}{h}$ is a quotient within the description of the zooming process, the adequate measure would be a logarithmic scale. Normalizing the apparent resistivity to the resistivity ρ_1 of the top layer we get another quotient $\frac{\rho_a}{\rho_1}$. Consequently this leds to a bi-logarithmic diagram. From the historical development instead of the distance ***L*** between the current electrodes the distance from the centre point is in use, i.e. $\frac{L}{2}$. Taking $\frac{L/2}{h}$ as abscissa and $\frac{\rho_a}{\rho_1}$ as ordinate the three data of the normalized apparent resistivities for the cases 1′-3′ in Fig.15 will result in the three points plotted as open circles in Fig.16. Combining them to a curve we get an ascending branch asymptotically starting at $\frac{\rho_a}{\rho_1} = 1$ according to case 1 in Fig.12.

Looking at Fig.14 we find, that the current is al ready flowing nearly parallelly to the surface at the centre point. Reducing the thickness ***h*** again to $\frac{1}{2}$ we will get twice the current density at the centre point. This means that the ascending branch of our sounding graph will continue under an angle of 45° in the bi-log. diagram.

If ρ_2 has a finite value greater than ρ_1 then the sounding graph has to run asymptotically into the horizontal line $\frac{\rho_2}{\rho_1}$.Thus the question asked by aid of Fig.11 in chapter 1.4. is answered. Since the zooming process is a steady one the sounding graph combining ρ_1 and ρ_2 asymptotically must be a smooth curve. Any breaks or steps are impossible. On one side this is a great advantage in field work: If the curve on a horizontally layered earth is not a smooth one, it is either disturbed by lateral effects, inhomogeneities in the underground or mistakes in the record. On the other hand difficulties arise in the interpretation because interfaces of

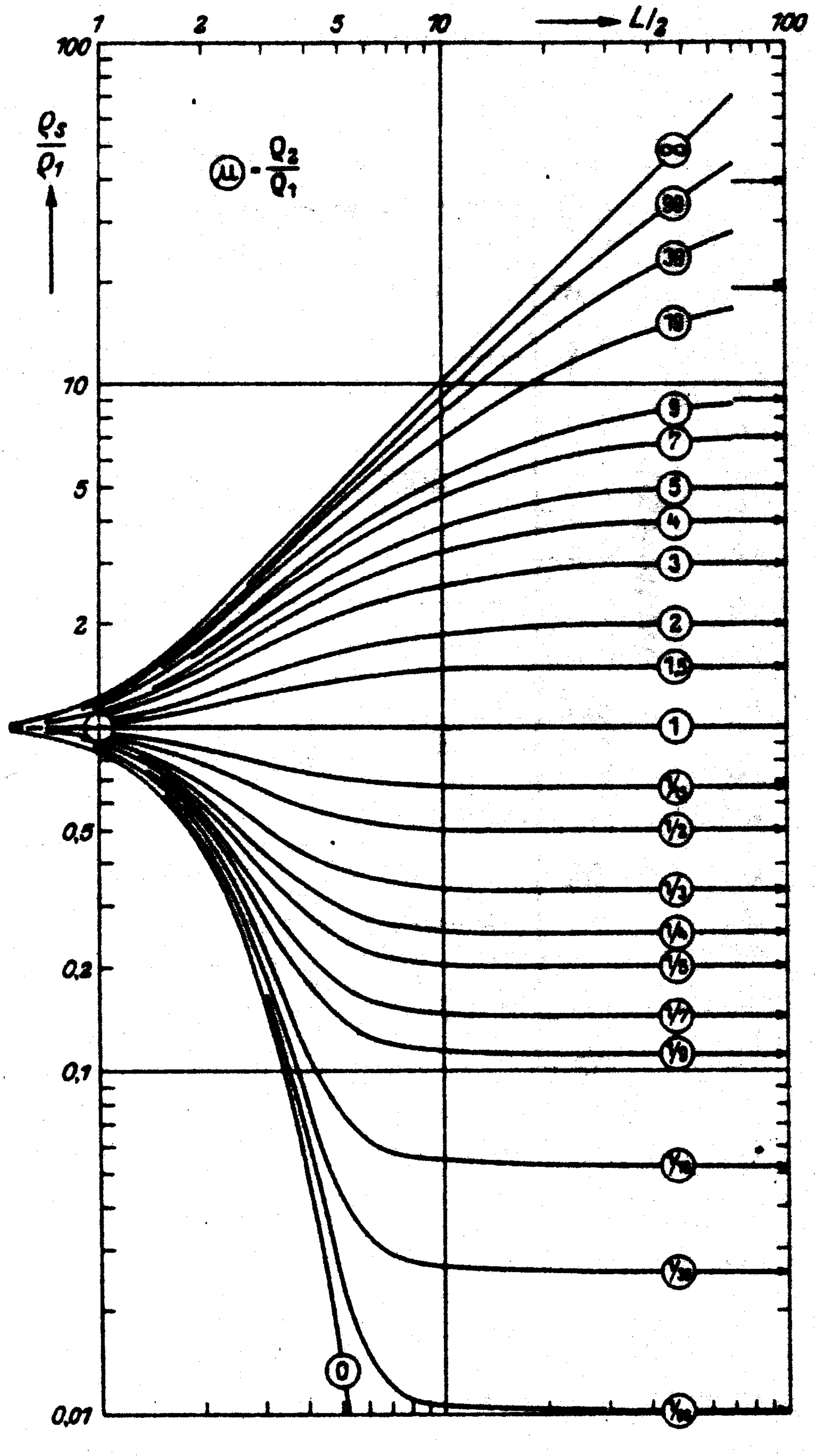


Fig17

layers with different resistivities cannot be seen just looking at the curve (as f.i. possible in refraction seismics from the travel time record). Master curves have to be calculated theoretically. Just for instruction the 2-layer master curves are shown in Fig.17. Here the $\frac{\rho_a}{\rho_1}$ values are plotted as functions $\frac{L/2}{h}$ for different ratios μ of the resistivities of the two layers.

2-layer master curves were available before 1930. In 1933-36 CGG (Compagnie Generale de Geophysique), Paris, calculated 3-layer master curves. Since 1955 master curves for any number of layers can be provided. Nowadays within a few seconds by electronic computers.
But the interpretation does not belong to the scheme of this manual. We therefore continue keeping in mind that a sounding graph has to be smooth in order to guarantee a quantitative interpretation.

depth [m]	resistivity [Ωm]	
0-2	100	overburden
2-6	2000	dry sand
6-26	10	clay
26-	100	aquifer (fresh water)

Let us add some remarks for better understanding the zooming process. This shall be done by discussing a 4-layer case very often occuring in hydrogeological prospecting for groundwater. The layer sequence is given in Fig.18 in logarithmic scale.

Observing the current density ***j*** between M and N at the surface the high resistant second layer will increase ***j*** at the beginning of the zooming process quite simitar to the simple 2-layer example in Fig.12-14. The current lines are pushed onto the surface. Continuing the process, however, the well conducting third layer will collect the current lines (pull them downwards) thus causing a decrease of ***j*** at the surface. Finally the aquifer, i.e. the fourth layer (100Ωm) will push again the current upwards.

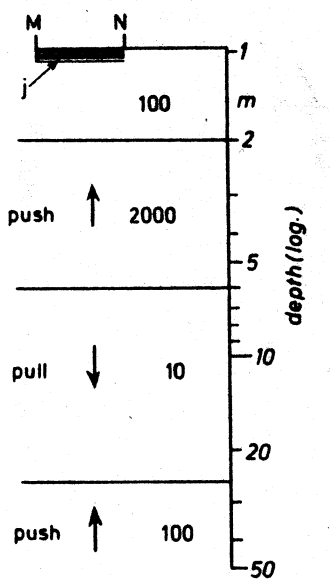


Fig.18

Simulating this zooming by enlarging the distance ***L*** between the current electrodes we shall record a sounding graph $\rho_a(L/2)$ as shown in Fig.19.

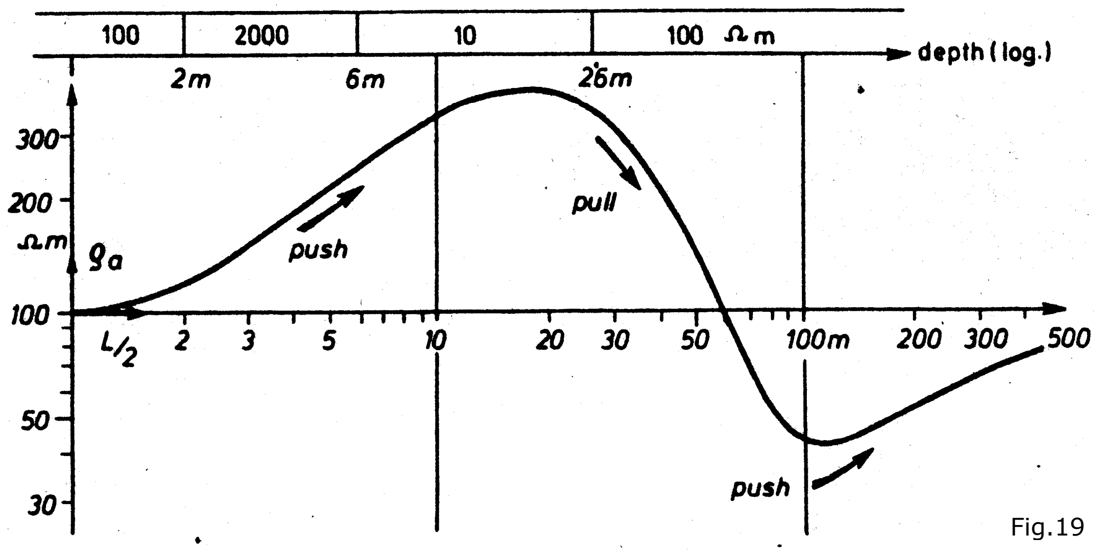
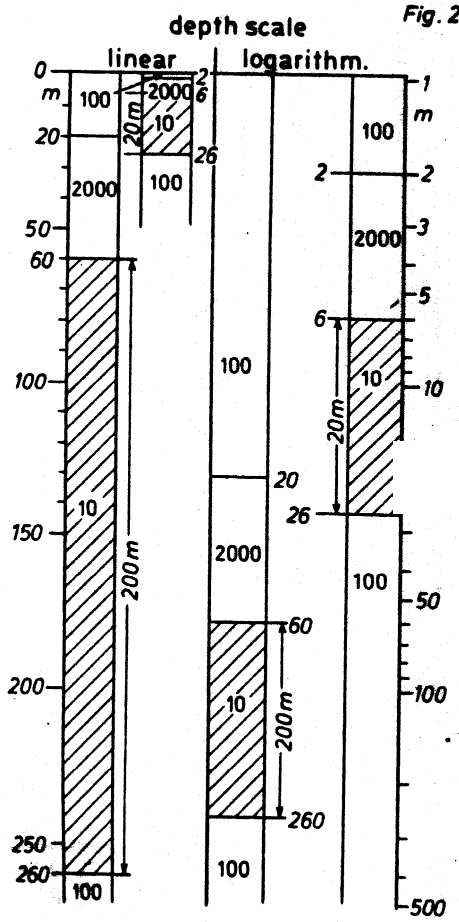


Fig.19

The "push and pull"-process can easily be recognized. But looking at the depth scale on top using the ***L***/2-scale simultaneously we will find no connection between these two scales with respect to the depth of the layer interfaces and the maximum and minimum of the curve. An optical check will only result in the resistivity of the first and of the last layer and the fact that a 4-layer case is concerned. This seems to be a striking illustration to the final remark in chapter 1.4.: "How deep are you now?"

Fig. 20



The zooming process underlines very clearly that the logarithmic scale is the adequate measure for geoelectrical sounding. Looking at Fig.20 we find at the right the log. profile of our 4-layer case (see Fig.18) with interfaces at 2m, 6m and 26m depth. If we multiply these depths by 10 we get interfaces at 20m, 60m and 260m below surface. This profile is also plotted in log. scale and we see at once that it is congruent to the first one only shifted along the depth scale. Now "zooming" just means "shifting along the depth scale" .If we start with the latter case (20, 60, 260m) we will pass during zooming the former case (2, 6, 26m) .The shape of the sounding graph will not change, i.e. the quality of information will always be the same. This has important consequences concerning the power of solution in sounding graphs. Comparing the profiles in linear scale on the left side of Fig.20 with the log. profiles on the right side we find that f.i. the clay-layer (10 Ωm) of 200m thickness in 60 m depth causes the same minimum in the sounding graph as a 20 m-clay layer in 6m depth.

The authors know that they surpass the aim of this manual by adding these remarks. But from our opinion the field surveyor should know these facts to bring him to an advanced level especially in discussions with geologists: Geologists are thinking "linearely" (bore profiles, well-logging and even reflection seismics) .In geoelectrics we have to think "logarithmically". Here to find a common language is already necessary during fieldwork; i.e. belongs to the field surveyors duty. If not he will drop back into a level which can be described by: "He doesn't know what he does!"

1.6. Shifting of potential electrodes

In using the Schlumberger arrangement the potential electrodes M and N are left in their position and only the current electrodes are shifted along the AB-layout. Of course there will be a limit depending on the sensitivity of the direct voltage amplifier recording the voltage ***U***. This means that reaching this limit we are forced to enlarge the spacing MN = ***a***. There then arise consequences from the theoretical point of view and the change in surface conditions (lateral effects) around the centre point as well. In this chapter only the theoretical part shall be discussed. We shall do this by aid of the 4-layer graph from chapter 1.5. We know that ρ_a depends on the electrode configuration at the surface. There is a difference between the apparent resistivity $\rho_a^{(S)}$ after Schlumberger and $\rho_a^{(W)}$ after Wenner. In Fig.21 both curves $\rho_a^{(S)}$ and $\rho_a^{(W)}$ are plotted in the same ***L***/2-diagram.

We observe that the Wenner-curve is a bit "lazy" compared with the Schlumberger-curve: The $\rho_a^{(W)}$ curve seems to be pushed to the right; ascending and decending is not as steep as in $\rho_a^{(S)}$; maximum and minimum of $\rho_a^{(W)}$ are less extreme than in $\rho_a^{(S)}$.This is an important fact to be taken into account when shifting the potential electrodes.

We will follow this process looking at Fig.22. The initial position of the four electrodes usually is ***L***/2=1,5m, ***a***/2=0,5m, i.e. we start with Wenner. Enlarging ***L***/2 and leaving the potential electrodes in their initial position ***a***/2=0,5m. the recorded ρ_a-data will smoothly change over from $\rho_a^{(W)}$ to $\rho_a^{(S)}$. We get the curve branch *(1)*.

At ***L***/2=15 m the ***U***-values recorded by the direct voltage amplifier become very low*. We observe that at least at ***L***/2 = 20 m we will have to shift the potential electrodes. Branch *(1)* now is running within the real Schlumberger curve. Changing the spacing ***a***/2 from 0,5 m to 5 m means a changing over from Schlumberger to Wenner. The $\rho_a^{(W)}$-value at ***L***/2=15m "drops down" into the Wenner-curve, thus starting branch *(2)*.

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*This is only assumed for the present example. In practice we mostly can run the first branch up to greater ***L***/2-values.

The process will be repeated: Enlarging ***L***/2 and keeping ***a***/2=5m fixed we get a smooth change from $\rho_a^{(W)}$ into $\rho_a^{(S)}$. Assuming we are forced to shift the potential electrodes again at ***L***/2=60m the $\rho_a^{(W)}$-value "jumps" again but now upward into the dotted Wenner-curve forming the starting point of branch *(3)*. At ***L***/2=120m we just pass the curve minimum. Due to the instrument another shifting of the potential electrodes is necessary. In this position we will record crossing branches *(3)* and *(4)*.The field operator should not be irritated. His record is correct because it is a consequence from theory. As this chapter is only dealing with basic laws, practical advices concerning the shifting of potential electrodes will be given later on in chapter 2 but making use of the theoretical knowledge just described.

As there will be no description of instruments in this manual only one remark should be made concerning unpolarisable potential electrodes. The main principle is a copperstick put into a solution of copper sulphate contacting the earth via porous porcelain. The type used in our institute is shown in Fig.23. There are other types, f.i. having a larger bottom or being porous only in the deeper part. The principle is the same and we must take care that no crust on the porcelain will interrupt the contact to the surrounding earth.

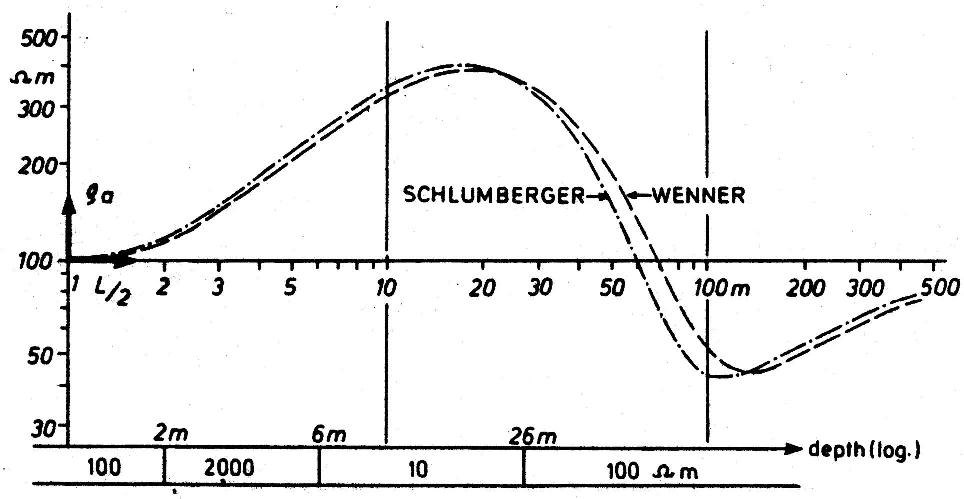

Fig.21

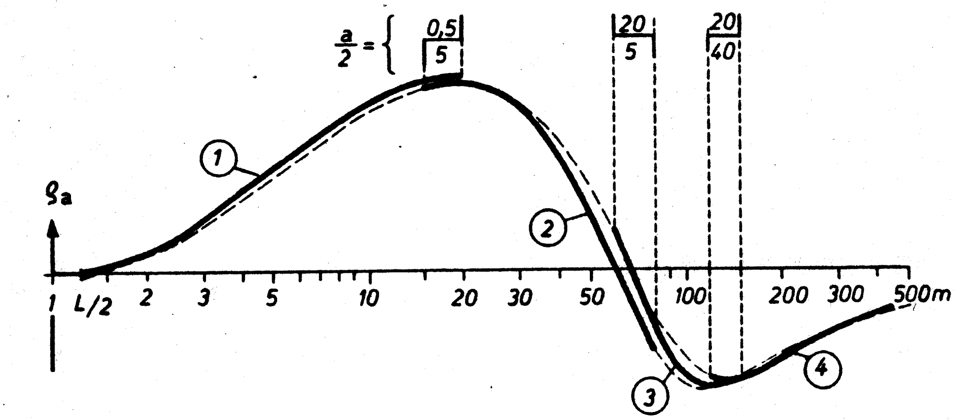

Fig.22

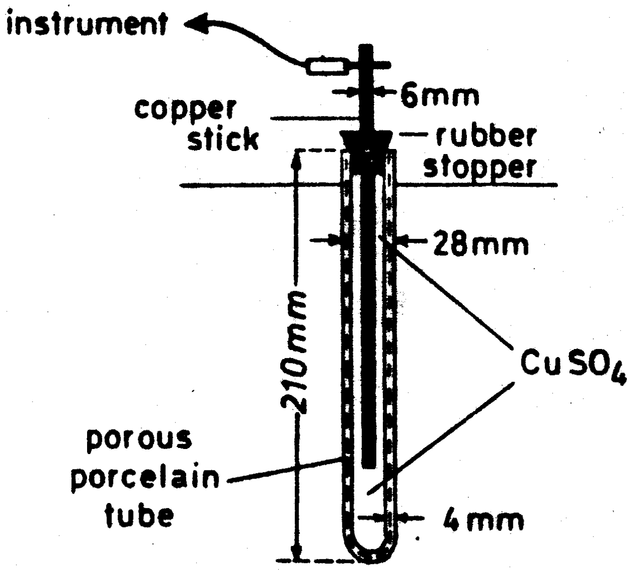

Fig23

2. Field activities

This second chapter should be a guide for field work based on what has been discussed in the first chapter. It contains advices to the field crew how to go on to supply the interpreter with optimal data, i.e. the smooth sounding graphs without errors. From this aim the following - of course important - points will not be discussed.

1. Instruments: There is a large variety of instruments offered at the market to carry out direct current resistivity measurements: power supply by batteries, generators, D.C. amplifiers to feed the current electrodes A and B, voltmeters as compensators (zero-instruments) or direct voltage amplifiers to get the voltage between the potential electrodes M and N. The advices in this manual are independent of the kind of instrument. But for simplicity a car-borne equipment is taken for demonstration. The advices can easily be transformed to portable equipments.

2. Safety: As high voltage power (200 V and more) is used safety is a very severe problem. The assistants at the current electrodes A and B can be provided by rubber gloves and boots, the steel electrodes can be insulated, an electrical grounding control can be installed at the instrument etc. Here general advices can of course not be given because the danger depends on the local situation and the safety is within the responsibility of the chief surveyor.

2.1. <u>How to carry out a field measurement</u>

Now we drive on a measuring car into the field to record a sounding curve. For this we choose a suitable point in the considered measuring area, which is the centre point of the measuring lay-out. One shall pay attention to the potential electrodes. Their site should always be on naturally grown earth.

The direction of the lay-out can be determined by an angle reflector. Then the measuring car will drive into the right position to the site of the potential electrodes.

In Fig.24 we show a wrong placing of the car. The distance between measuring car and the potential electrodes is too small, so that already low leakage currents can more or less influence the potential electrode voltage. Those leakage currents flow into the earth either via the car or the cable drums, depending on the resistivity of the first layer.

In Fig.25 the right placing of the measuring car is to be seen. The distance to the potential electrodes should amount to at least 20m and the car as well as the cable drums should stand on the "0"-line between the potential electrodes, running vertically to the potential electrode extent. This placing of the measuring car should be desirable in every case.
The following processing is schematically demonstrated in Fig.26. When the car has the right position, the measuring lay-out can be built up. The cable drums are taken out of the car and set to ground. In order to enlarge the insulation between the cable drums and the ground, it is recommended to pose a rubber-mat below each cable drum (Fig.27). On each drum there is in addition to the electrode cable a 100m long measuring tape (wire of insulating material), on which points are marked for usual electrode distances according to the table with the geometric factors ***K*** (on page 36). The assistants are walking (or better running) in opposed directions pulling the measuring tapes. By a stick they fix these measuring tapes at both ends.

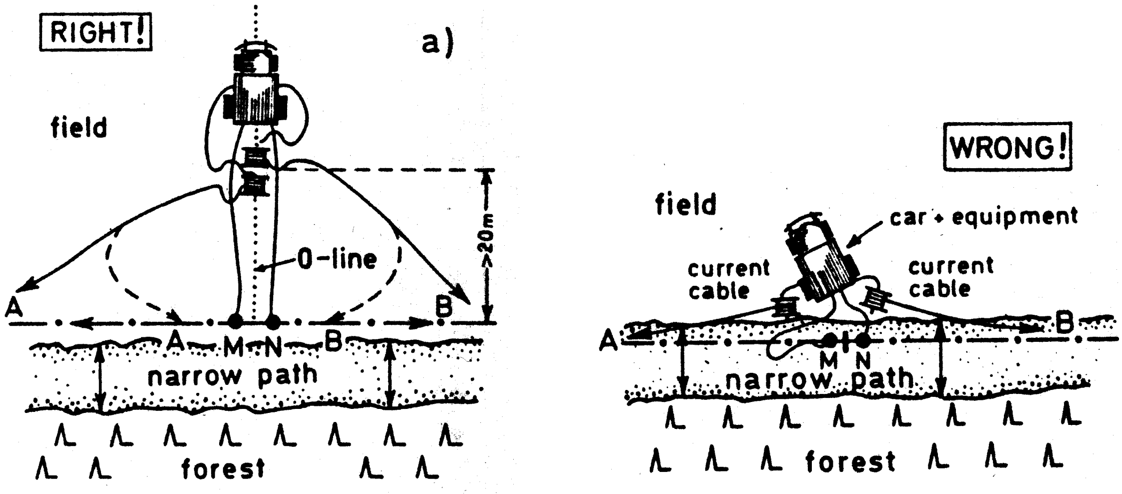

Fig.24

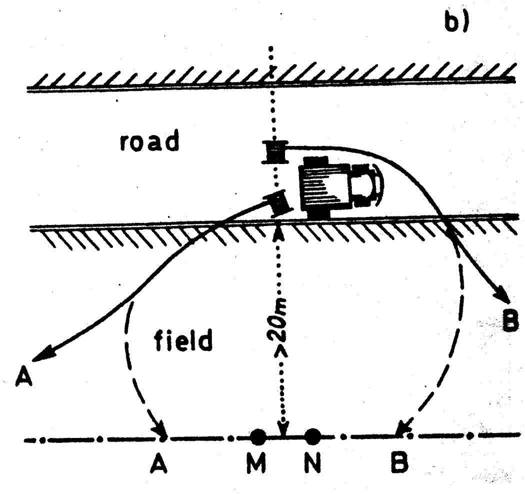

Fig25

Fig.26

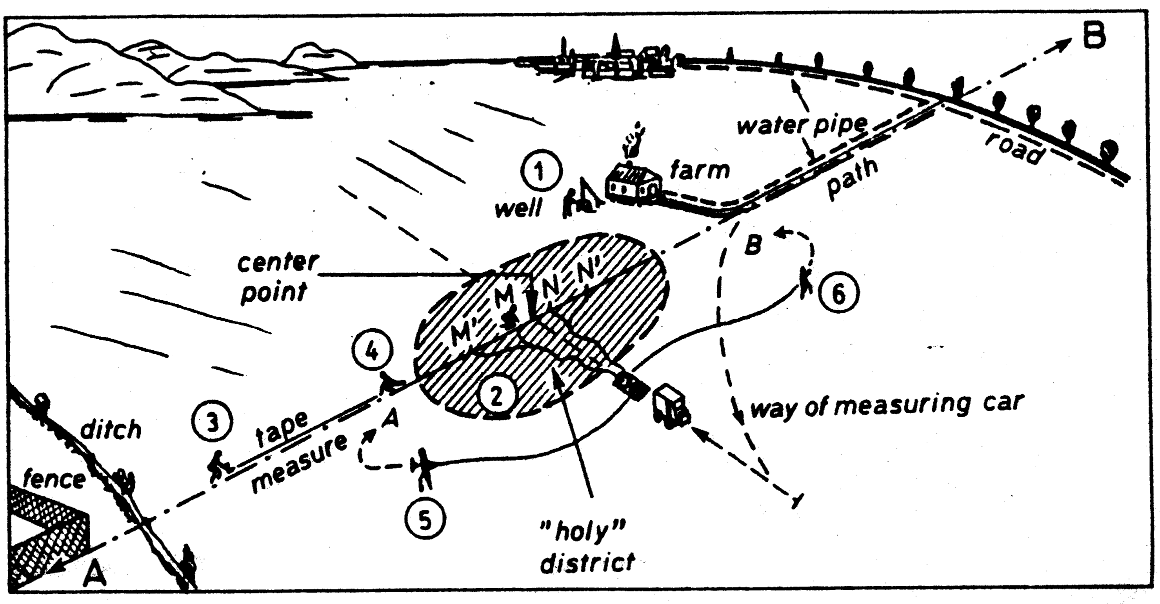

Table of ***K***-factors

a / 2 L / 2	0,5	1	2	2,5	5	10	20	25	50
1,5	6,28								
2	11,8								
2,5	18,9								
3	27,5	12,6							
4	49,5	23,6							
5	77,7	37,7							
6	112	55,0	25,1						
(7,5)	176	86,8	41,0	31,4					
8	200	990	47,1	36,3					
10	313	155	75,4	58,9					
12	452	225	110	86,5					
(12,5)	490	244	120	94,2					
15	706	352	174	137	62,8				
20	126	627	311	247	118				
25	196	980	488	389	189				
30	383	141	704	562	275	126			
40	503	251	125	100	495	236			
50	785	392	196	157	777	377			
60	113	565	282	226	112	550	251		
(75)	177	883	441	353	176	868	410	314	
80	201	100	502	402	200	990	471	363	
100	314	157	785	628	313	155	754	589	
120	452	226	113	904	452	225	110	865	
(125)	491	245	123	981	490	244	120	942	
150	707	353	177	141	706	352	174	137	628
200		628	314	251	126	627	311	247	118
250		982	491	393	196	980	488	389	189
300		141	707	565	283	141	704	562	275
400			126	100	503	251	125	100	495
500			196	157	785	392	196	157	777
600			283	226	113	565	282	226	112
800			503	402	201	100	502	402	200
1000			785	628	314	157	785	628	313

The necessary holes for potential electrodes are drilled (f.i. by a cylindrical tube) on those points, which have special signs on the measuring tape.

One has to pay attention to the holes, which are drilled slightly greater in comparison to the diameter of the potential electrodes. After the potential electrodes have been placed into the bore-holes and additionally pressed closely, in order to maintain the transition resistance between potential electrodes and ground very low, the cables are connected to the measuring equipment. Finally the electrodes are brought into the initial position and also connected to the cable drums and measuring equipment respectively.

In order to avoid any influence on the potential electrode voltage the surrounding of the centre point should be kept free ("holy" district). This district - to say it again - should be large enough for, even if the cables are perfectly insulated, "weak" points cannot be avoided where the metal core is connected to the drums (Fig.27).

Another version of building up the lay-out not using the 100m-measuring tapes is often applied by field parties where enough labourers are available, i.e. at least two (better three) of them on the A-direction and the B-direction as well. By help of a normal tape measure (25m long) small sticks are put into the ground at the ***L***/2-distances from the centre point according to the table of K-factors. These sticks carry the ***L***/2 values in [m] (Fig.28).

No leakage currents then can creep along the measuring tape because this does not exist. Errors are avoided because each single stick shows the exact distance.

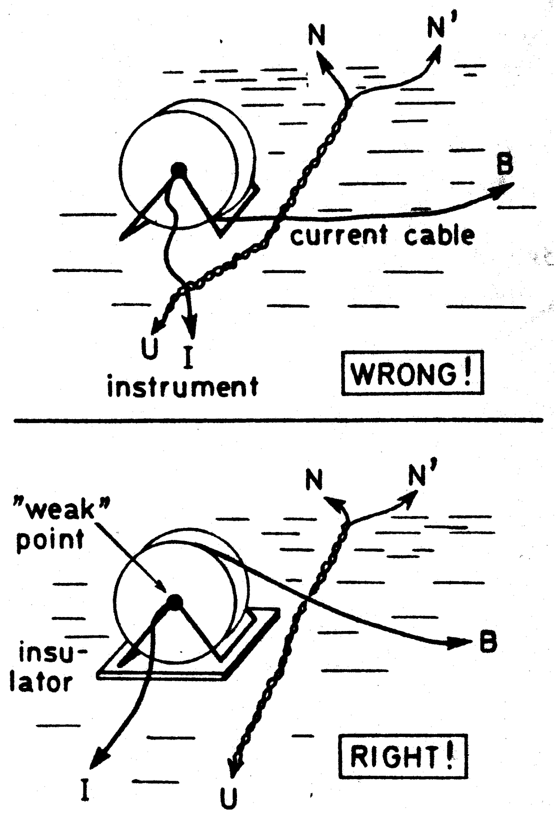

Fig.27

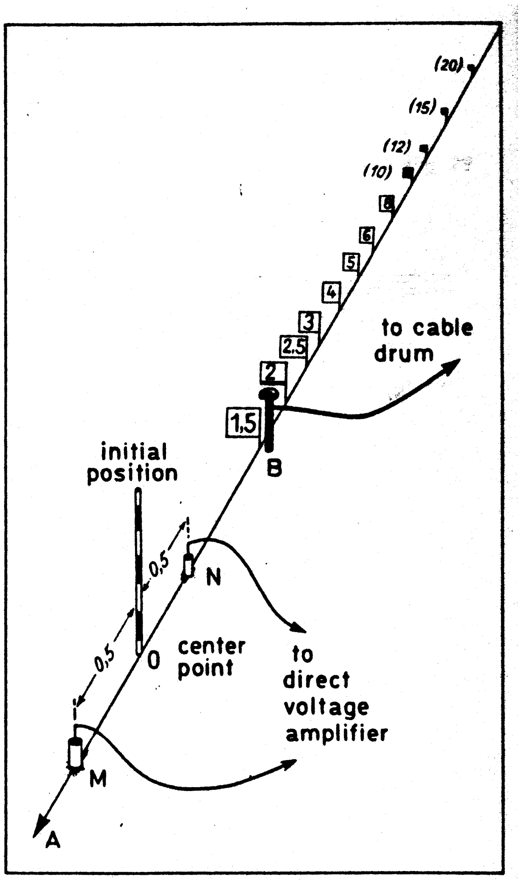

Fig.28

Before we start the measurement we will repeat the preparations looking at Fig.26 and adding some details:

1 The chief surveyor checks the well at the farm. The depth of the water table may be of interest for the interpretation of the sounding graph.

2 The "holy" district has to be chosen very carefully. It is recommended to plant 4 potential electrodes at the very beginning: $\overline{MN} = 1m$ and $\overline{M'N'} = 10m$ and connect them to the equipment by a double wire (Fig.27). This brings great advantages :

a) during measuring with the smaller distance MN the potential electrodes M′ and N′ get already "accustomed" to the ground;

b) the overlapping of the Schlumberger branches (see chapter 1.5) can be done by the operator at the instrument, because calling the labourers at the current electrodes back and forward again often leads to errors.

3+4 Assistants marking the lay-out by a tape measure.

5+6 Labourers pulling the current cable to the initial position in a wide bend around the "holy" district. On the drums the cable always should run from the top (Fig.27).

Now the measurement can start; at each point along the measuring tape the apparent resistivity ρ_a is calculated from current ***I***, voltage ***U*** and factor ***K***. In order to determine immediately the right order of the resistivity, with which the curve starts, significant importance is due to the calculation of the first value for the apparent resistivity. For ***L***/2=1,5m and ***a***/2=0,5m the geometrical factor ***K*** is 2π=6,28 (exactly 2π***a*** after Wenner, see chapter 1.3). If now the electrode current ***I*** will be adjusted numerically to the factor ***K***, the potential electrode voltage ***U*** is numerically equal to the apparent resistivity ρ_a. This results from formula (13) in chapter 1.4

$$\rho_a = K\frac{U}{I}$$

In practice normally the following three possibilities at the starting point result from this:

a.) $\rho_a[\Omega m] = \frac{U[mV]}{0{,}628mA}\times 6{,}28m = U[mV]\times 10$

b.) $\rho_a[\Omega m] = \frac{U[mV]}{6{,}280mA}\times 6{,}28m = U[mV]\times 1$

c.) $\rho_a[\Omega m] = \frac{U[mV]}{62{,}80mA}\times 6{,}28m = U[mV]\times 0{,}1$

Using dry batteries the process ***I***=***K*** cannot be realized. ρ_a then has to be calculated on a slide rule or nowadays on a pocket-computer.

The ρ_a-data are directly plotted on bi-logarithmic transparent paper, and for a better control written in a minute-book.

Besides the date, site (with height above m.s.l.) and number of the sounding this minute-book should also contain the measured electrode current ***I***[mA], the measured potential electrode voltage ***U***[mV] and of course the apparent resistivity ρ_a. An additional column seems desirable for remarks like industrial current, tellurics, weather (rain, sun, wind, thunderstorm) and perhaps a short description of the field (mash-wire fence, ditch) especially, if the ***U***-data are very low and in the most sensitive ranges of the instrument. For a communication between the operator and the assistants at the current electrodes surely a loud-voiced calling is sufficient, and later the motor-horn of the measuring car. For larger electrode distances a walkie-talkie should be used. Signals can also be given by coloured flags especially if a portable equipment is used and

L/2	a/2	M.B. [mV]	M.B. [mA]	$\rho_a = K\frac{U}{I}$
		(164)	(6,28)	
1,5	0,5	300	10	164
2,5	0,5	300	30	248
4	0,5	300	100	282
6	0,5	300	300	270
8	0,5	300	300	255
10	0,5	300	1000	242
12	0,5	300	1000	220
15	0,5	30	100	149
20	0,5	30	300	106
25	0,5	10	300	83,5
25	5,0	100	300	85
30	0,5	10	300	76
30	5,0	100	300	77
40	0,5	10	1000	85
40	5,0	10	1000	82
50	5,0	10	100	90
60	5,0	10	300	97
75	5,0	30	300	108
100	5,0	3	100	121
125	5,0	3	100	126
150	5,0	3	100	143
175	5,0	3	100	157
200	5,0	3	300	164
		(0,99)	(100)	
250	5,0	1	100	194

wireless communication is not permitted.

Knowing how to go on from the initial arrangement ***L***/2=1,5m, ***a***/2=0,5m we shall proceed step by step looking into the minute book dated 11.Sept.1974 during a survey in the Kalantan-delta around Kota Bharu in Malaysia near to the coast of the South China Sea. Sounding graph 54 is concerned. The original data are given on page 40.
As an exercise the reader now should take a sheet of transparent bi-log. paper and plot the sounding graph after the minute book and the advices given in the following text.
The initial reading with ***L***/2=1,5m, ***a***/2=0,5m is 164 within the ***U***-range of 300 mV putting the current intensity to 6.28 within the 10 mA-range. This means from formula (13) an apparent resistivity ρ_a=164Ωm. We plot this value on the transparent bi-log paper and write it in order to be sure on the scale just at this point in the diagram. As long as we use the technique of putting ***I***=***K*** we only write the range of mV and mA in the minute book and denote the ρ_a-value at the right.

Going on with ***L***/2=2,5 m we get an ascending branch up to a maximum at about ***L***/2=5m. After this a descending branch is recorded until below 100Ωm (***L***/2=25m) the ***U***-voltage decreases below 10mV. Here we shift the potential electrodes following the description in chapter 1.6 by a process of overlapping the curve branches. In the bi-log. diagram the left branch should be plotted in small circles (◦) the following branch in crosses (+). As we shift within the curve minimum we get crossing branches due to the theory explained in chapter 1.6 (Fig.22).
In this case both pairs of potential electrodes MN and M'N' were connected to the instrument by using double coil as shown in Fig.26 and 27. Thus the overlapping could be done by switching from ***a***/2=0,5m to ***a***/2=5m at the instrument at 3 positions of the current electrodes: ***L***/2=25, 30, 40m. The advantage of this procedure is obvious: The assistants at the current electrodes A and B will not be aware of the overlapping process. They are marching straight on without being irritated. Calling them back and forward which cannot be avoided when using only single coils to the potential electrodes often mistakes will happen as known

by experience. The measurement is now continued up to ***L***/2=250m (***K***=196).
As under the given circumstances 196mA for the current intensity ***I*** could not be verified, the ***I***=***K*** technique was replaced by taking the reading in the 100mA range using the full scale. A voltage U=0,99mV was recorded in the 1mV range. The result was ρ_a=294Ωm.

Normally the ***I***=***K*** technique is very handy for the operator at the instrument. But running down into lower ranges especially in the ***U***-range, he should try to use the highest power available for the current end to take the reading at the right part of the scales on this instrument in order to get a better accuracy.

In our example ***L***/2 surpasses 100m, i.e. the final point of the measuring tape or - using the lay-out in Fig. 28 - the last stick. In order to get the exact distances ***L***/2 at 125m, 150m… coloured marks fixed on the current cable can be used controlled by a surveyor at the centre point. This is the most simple way if only one assistant is pulling the current cable. If two men are working at each current electrode, they can fix the next position for the electrode by a tape measure (see f.i. *(3)* + *(4)* in Fig.26).

In curve 54 under discussion one will miss the readings at ***L***/2= 2, 3 and 5m. To spare time these data are not necessary because the top layer is not of much interest. We must only know the rough structure of the first 10m in Kota Bharu-area but details in greater depth. To get these details the curve has to be smooth in its rear branch for an optimal interpretation. "Jumping" data from say f.i. ***L***/2=100m will bring no information here and could be thrown off.

If the sounding is finished the assistants at A and B will get a signal by horn, flag or wireless. They have to disconnect the cable from the electrodes, drop the cable and return with the electrode <u>only</u> to the centre point. Never take back the end of the cable! The cable has to remain in a straight line! Otherwise complication may arise in pulling it back to the cable drums. Rewinding it on the drums can be done either by hand or by an electro-motor driven by the car batteries.

Depending on the surface conditions pulling the current cables very often is a hard work in case of ***L***/2-distances >300m. This difficulty can be overcome by adding additional drums brought to A and B by car. Connecting them to the ends of the first cables has to be done carefully with respect to the insulation. This is a really "weak point". We must be sure that there will be no "leakage" of current. Finally it should be mentioned that the unpolarisable potential electrodes (see chapter 1.6) are to be transported - all four of them - within a big plastic bottle filled with a saturated solution of copper sulphate. Thus the porous porcelain is surrounded by the fluid from in- and outside and cannot dry out. In any case the electrodes have to be controlled before starting the next measurement that there is enough fluid inside and no crust outside in order to get a good contact to the ground within the "holy" district.

2.2. Possible errors influencing the measurement

It sometimes happens that one or more points of a sounding graph drop out. The resulting curve cannot be smooth. Some of these possible reasons shall be explained in the following.

2.2.1. Current electrode wrongly grounded: remain standing

When an assistant has not noticed the signal for shifting the electrode and is remained standing, while the other is moved on, then the distance between the electrodes A and B is too short in comparison to the configuration factor $\boldsymbol{K}$. The $\boldsymbol{K}$ used for calculating ρ_a is therefore too large. This means, that the apparent resistivity ρ_a will be too high, i.e. when an assistant is remained standing the point drops out upwards.

2.2.2. Current electrode wrongly grounded: surpassing

When an assistant has missed the following $\boldsymbol{L}/2$ mark after the signal for shifting the electrodes and has surpassed it, then the distance between the electrodes A and B is too large in comparison to the configuration factor $\boldsymbol{K}$. The $\boldsymbol{K}$ used for calculating ρ_a is therefore too small. A too small $\boldsymbol{K}$, however, means that a lower apparent resistivity ρ_a will be recorded. i.e. when an assistant has surpassed an $\boldsymbol{L}/2$-mark the point drops out downwards.

2.2.3. Wire-mesh-fence (Fig.26/27)

We assume that a wire-mesh-fence in its lower part touches the ground. With this, a conductive connection to the underground parallel to the measuring range exists. When the electrode reaches the beginning of the wire-mesh-fence, there are still no effects at the sounding graph. But when the electrode passes the wire-mesh-fence and is grounded near to the fence, it seems that the current flows into the ground at the beginning of the fence; that means: when the electrode is shifted from the beginning to the end of the fence, it seems that the electrode effectively has not been moved at all. According to case 2.2.1. the point drops out upwards.

This result seems to be a paradoxon as we believe that now a nearly perfect conductor (wire-mesh-fence) exists and consequently the resistivity should be reduced. But just the opposite happens, because the current already flows into the ground nearer to the centre point. This fact shall be explained once again by observing the current density ***j*** between the potential electrodes M and N.

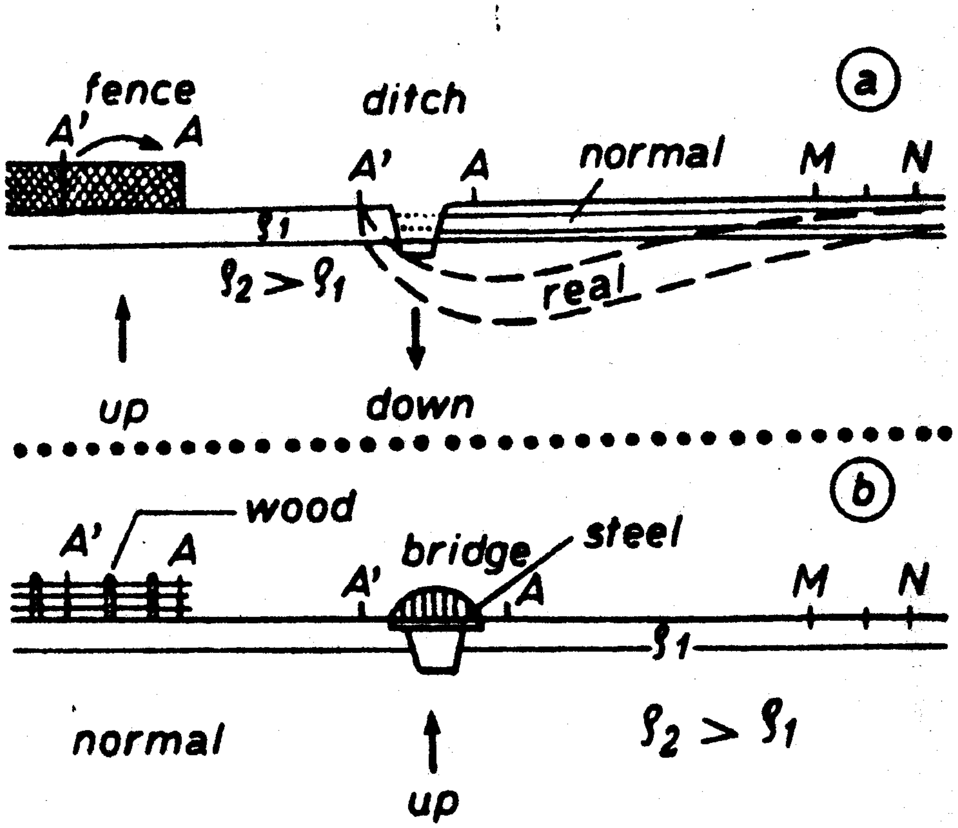

Fig.29

The current electrodes are in position A and B on the surface. In the centre of the lay-out between the potential electrodes M and N the current density "below our feet" will be recorded by formula (11) in chapter 1.3. Without the wire-mesh-fence the current density in position A is greater than in position A′. But with the wire-mesh-fence it seems after moving from A to A' that we still have the same current density as in the position A, i.e. higher than it should be in A'. A higher density effects a higher voltage between the potential electrodes: the ρ_a point at A' drops out upwards.

On the other hand passing a wooden fence when the connecting wires are not touching the ground (Fig.29b) the curve will remain smooth.

2.2.4. Crossing a ditch (Fig.26/29)

The importance of observing the current density between M and N may be demonstrated now in the case of a good conducting thin surface layer (ρ_1) underlain by a second layer of higher resistivity ($\rho_2 > \rho_1$). This very often happens in nature, f.i. sand with a thin clayey overburden. We assume that the current electrode A is crossing a dry ditch cut through the clay as shown in Fig.29a.

When the electrode A reaches a position just before the ditch, we observe a high, but a quite normal current density due to the clay cover. But when the electrode is just behind the ditch (A') the current lines within the clay are interrupted. The current has to pass the second layer underneath the ditch (dotted current lines).

The current density between the potential electrodes will be reduced and the ρ_a-point drops out of the sounding graph downwards.

Our conclusion is: when a good conductor (wire-mesh-fence) appears as a disturbance, the point of a sounding curve drops out upward, when a bad conductor appears (ditch cutting the first layer) the point drops out downwards. This is due to the definition of the apparent resistivity. The apparent resistivity doesn't deal with the distribution of resistivity in the underground, but with the current density at the potential electrodes between M and N.

The current density ***j*** is the parameter which is fundamental at all considerations in field works. One has to think in current densities, in order to get the right conclusions out of the possible disturbances.

2.2.5. Water-pipe parallel to the measuring lay-out (Fig.26/30)

The effect of a water-pipe buried parallel to the measuring lay-out is similar to that of a wire-mesh-fence, but much more dangerous for interpretation if both the pipe and ***L***/2-line are running close to each other along a road or path up to the end of the lay-out. We look at the electrode B in Fig.26 and 30.

Up to the beginning of the water-pipe (dotted line) no effects will influence the sounding graph. But when the electrode is grounded along the pipe it seems to remain standing at the beginning of the water-pipe. We get the upward trend described in 2.2.1. but here as a steady process. The result is a smooth rear curve branch which may be interpreted as a high resistant bedrock in greater depth.

If the field surveyor has a bad feeling looking at this ascending branch which perhaps only appears in just this single sounding and not in graphs measured at stations in the surrounding area, he has either to try to detect the water-pipe or, if this is not possible because the pipe is buried, to help himself by a special technique now to be described:
The AB-lay-out normally should be a straight line. A simple trigonometric calcu-lation, however, shows that the relative error in the ρ_a-value is less than even 1% if one electrode is placed 20% of the ***L***/2 distance perpendicular outside of the straight lay-out. With other words:
At ***L***/2=100m the electrode can be shifted perpendicular to the AB-line 20m aside having an error in the sounding graph only in "pencil-thickness" on the log-log paper.

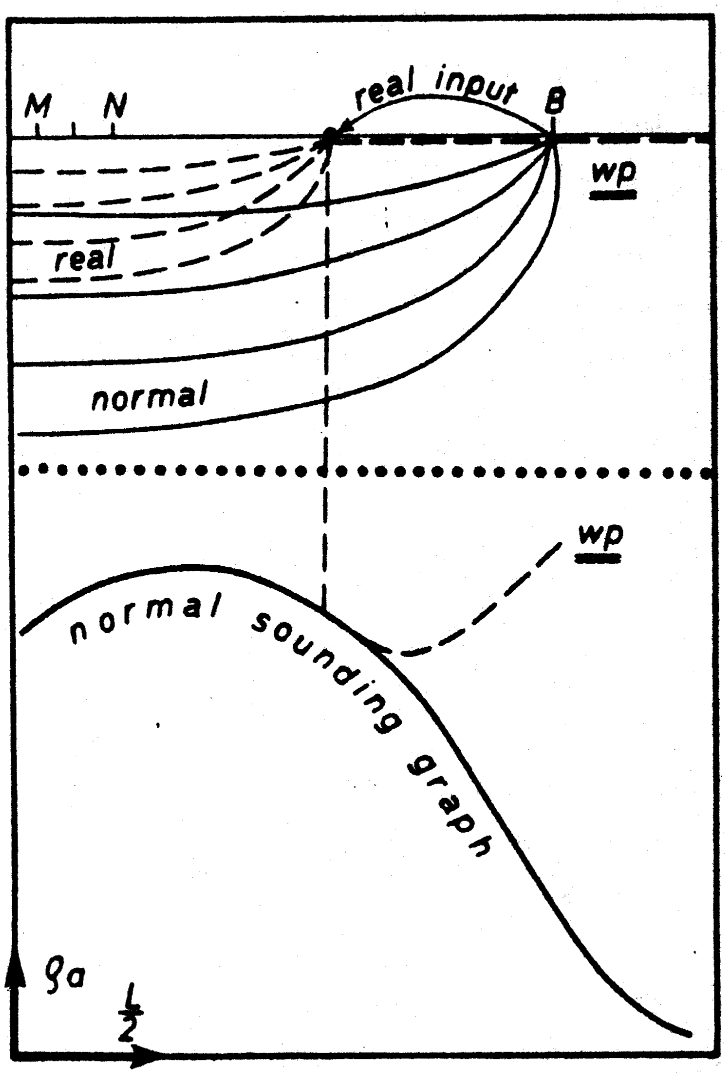

Fig.30

This surprising fact is mostly kept as a "secret" not to irritate the assistants and labourers building up the field array. If they know that accuracy is not so important they may perhaps be lazy in measuring the distance from the centre point to the electrode. But this ***L***/2-distance must be accurate because as we have already seen the ***K***-factor is of great influence and 1% error in ***L***/2 causes 1% error in the sounding graph.

In order to check whether the electrode is placed on top of a water-pipe (or on a buried cable) the electrode may be shifted aside perpendicular to the normal lay-out. (Doing this one has to take care on a correct right angle!)
If there is a change in the recorded ρ_a-value, than the curve is disturbed; the ascending branch is not real. The same can be done passing a wire-mesh-fence, and also to by-pass obstacles (houses, small lakes, etc.). Last not least measuring along a railway or a saltwater channel it can be check whether there is any influence or not.

Crossing a pipeline which runs somehow perpendicular to the lay-out a kick will be observed in the graph because just on top of the pipe the point-electrode will be changed into a line-electrode. Further on the influence will vanish but difficulties remain for the interpreter because at first he has to smoothen the graph by hand.

2.2.7. Leakage in the cable

We assume that by shifting the electrodes A and B from ***L***/2=75m to 100m the insulation of one of the electrode cables will be spoiled. This point of leakage may be invisible for the operator and assistant on the ground near to one of the potential electrodes. Then the current will run to ground not only at the grounded electrodes, but additionally at the point of leakage. This cannot to be observed on the ampere meter, because the amount of leakage current will be relatively small according to the high contact resistance at the point of leakage. As this point lies near to a potential electrode, this additional current flows into the ground, the current density between M and N increases, and the ρ_a point consequently drops out of the sounding graph in upward direction.

To get a smooth graph we have to stop the measurement at once and look for the reason:

1. We check the position of the current electrodes A and B whether one of the assistants has remained standing accordingto2.2.1.. If this is alright, then
2. the assistant at A is asked to disconnect his current cable from the electrode and hold the end of the cable (of course where it is insulated!) in his hand high up in the air so that the real end is free. Then we supply power and look at the voltmeter putting the ***U***-range down to high sensitivity. As now current can flow between A and B the voltmeter has to remain on zero. If there is no reaction we do the same at B. On one side there must be a reading on the voltmeter of the instrument.
3. We now check the cable at that side by lifting it up step by step and will quickly find the spoiled spot. After having insulated the cable we can continue the measurement.

2.2.8. Insulation and leakage current

The insulation presents one of the most important problems in geoelectrics. In the following quite real case we may use 200V direct voltage for the power supply of the electrodes A and B. Between the potential electrodes M and N approximately 2mV are assumed to be measured. In this example the voltage ratio would be 100 000:1.

One could have the opinion, that a sounding curve is susceptible against leakage current, when the first layer has a perfect conductivity. That is however a wrong thinking. The poorer the conductivity of the first layer is the more susceptible is a curve against leakage current. Another paradox? We have to study this fact in detail.

From chapter 1 we know that the information about the resistivity distribution in the layered underground is reflected to the earth's surface by the current density ***j*** "below our feet" between the potential electrodes M and N. As we cannot measure ***j*** directly we do it by recording the voltage ***U*** between M and N using the formula from chapter 1.3:

$$U/a \quad = \quad j\,\rho \qquad (11)$$

From this voltage ***U*** the apparent resistivity is calculated after formula (13) given in chapter 1.4:

$$\rho_a \quad = \quad K\frac{U}{I} \qquad (13)$$

We now compare two cases

I. high resistivity of the surface layer: $\rho_1^{(I)}$=10 000 Ωm

II. low resistivity of the surface layer : $\rho_1^{(II)}$= 10 Ωm

We now assume that our measurements are carried out by using the same current intensity ***I*** and that this current ***I*** creates by leakage anywhere outside or inside the instrument an additional current density ***j'*** between M and N. This means that this ***j'*** will keep its value if there is no change in ***I***.

Taking into account this "disturbing" ***j'*** we have to write formula (11) in the form

$$U/a \quad = \quad (j + j')\,\rho_1$$

and formula (13) will then be

$$\rho_a = K\frac{U}{I} = \frac{K}{aI} j\rho_1 + \frac{K}{aI} j'\rho_1$$

For our two cases I and II this means

$$\text{I.} \qquad \rho_a = \frac{K}{aI} j^{(I)} \times 10\,000 + \frac{K}{aI} j' \times 10\,000$$

$$\text{II.} \qquad \rho_a = \frac{K}{aI} j^{(II)} \times 10 + \frac{K}{aI} j' \times 10$$

Comparing the current densities $\boldsymbol{j^{(I)}}$ and $\boldsymbol{j^{(II)}}$ and keeping in mind that only here the information from the underground with respect to its resistivity distribution is concentrated we see that $\boldsymbol{j^{(I)}}$ is only 1‰ (promille!) of $\boldsymbol{j^{(II)}}$ because the ratio $\boldsymbol{\rho_1^{(II)}}:\boldsymbol{\rho_1^{(I)}}$ is 1:1000.

From this simple calculation we learn that measuring the same voltage ***U*** between M and N the information from the underground is 1000 times weaker in the case of a highly resistive surface (case I) than in the case of a well conducting surface (case II).

Now we look on the second term in the last two formulas containing the disturbing "quasi-constant" current density ***j'***. Perhaps the reader was a bit surprised on the form of these last formulas I. and II. because the two terms on the right side are written in a different way. But in the second "disturbing" term the quotient $\frac{j'}{aI}$ is constant in both cases I. and II. The remaining $K \times \rho_1$ is 1000 times larger in case I. than in case II. The result of comparing both cases will be:

In case I. the first term shows a 1000 times weaker $\boldsymbol{j^{(I)}}$ - that is the underground information - than in case II. On the other hand the "disturbing" second term with ***j'*** is 1000 times larger in case I. than in case II. The conclusion will be that in case I. the first term can be neglected as during continuing the measurement we get into the situation

$$j^{(I)} << j'$$

The formula reduces to

$$\text{I.} \qquad \rho_a^{(I)} = 10\,000 \times K\frac{j'}{aI} \quad , \quad \frac{j'}{aI} = const.$$

Translating this into our sounding graph we will obtain the ***K***-curve multiplied by a constant factor. The ***K***-curves are given in the diagram in

Fig.31. They are ascending with an angle of ~63.5° (i.e. arctan(2) from formula (10) in chapter 1.3), drawn in bi-log. scale.

The result:

On a highly resistive surface a disturbing leakage current will suppress the underground information ($\boldsymbol{j}^{(1)}$) and finally the sounding graph will run into a 63.5° ascending rear branch. This will happen if $\boldsymbol{j}'$ is positive, i.e. really added to $\boldsymbol{j}^{(1)}$.

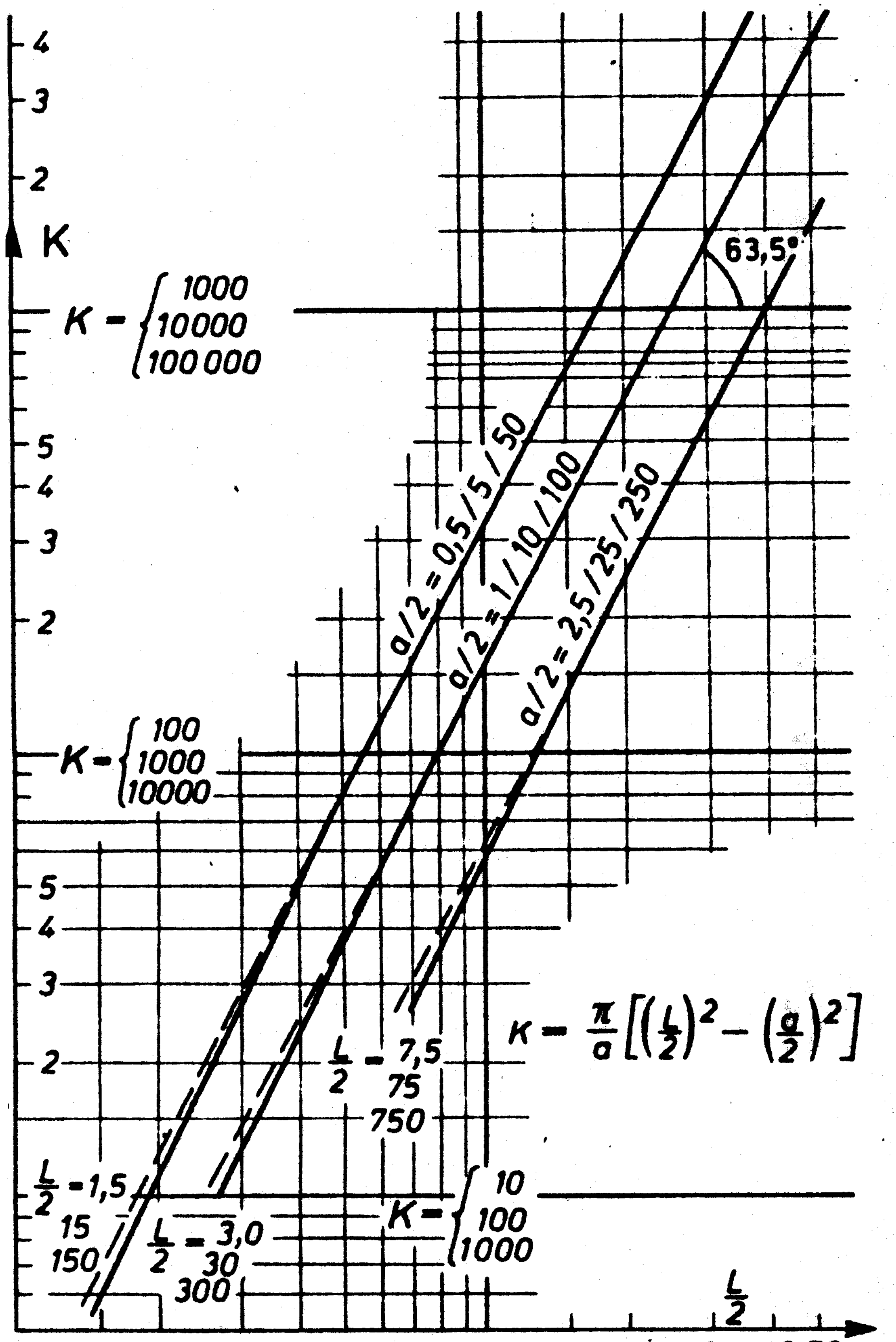
K
4
3
2
K = 1000 / 10000 / 100 000
5
4
3
2
K = 100 / 1000 / 10000
5
4
3
2
63,5°
a/2 = 0,5 / 5 / 50
a/2 = 1 / 10 / 100
a/2 = 2,5 / 25 / 250
$K = \frac{\pi}{a}\left[\left(\frac{L}{2}\right)^2 - \left(\frac{a}{2}\right)^2\right]$
L/2 = 7,5 / 75 / 750
L/2 = 1,5 / 15 / 150
L/2 = 3,0 / 30 / 300
K = 10 / 100 / 1000
L/2
1
1,5
2
3
4
5
8
10
15
20
30
40
50

Fig.31

If ***j'*** is negative, i.e. the disturbing leakage acts against the $j^{(1)}$ than in the sounding graph we will get in the ρ_a-values a trend steeply downwards ending in negative resistivities.
But from experience we know, that already before reaching these final stages, so-called "clouds" in ρ_a-values will be a signal, that there is something wrong.

We have to ask for the origin of these "clouds" .Looking at the last equation where $\frac{j'}{aI}$ is assumed to be a constant and the surface resistivity ρ_1= 10 000Ωm as well and take into account influences from outside (e.g. wind and rain) than remembering the very low voltages concerned we should not be surprised, that a few raindrops may change these parameters. Repeating the measurement will bring then of course different ρ_a-values. This is the result of simple physics. If we try to get out of the difficulties caused by the factor $\frac{j'}{aI}$ the only chance would be increasing the distance a of the potential electrodes. This can only be done up to ***a***=***L***/3 (Wenner-arrangement). So-called "Over-Wenner" would bring the potential electrodes into the neighbourhood of the current electrodes A and B causing additional difficulties not to be discussed here. Increasing the spacing ***a*** of the potential electrodes will bring at the utmost a factor 10, increasing the underground influence from 1‰ to 1%.
Comparing this effect with the ratio 1:1000 in ρ_1, this will not be a real help. Increasing ***I*** will cause an increasing of the disturbing current density ***j'*** and therefore be no help at all.
The only chance is to look for a surface layer with higher conductivity before starting a measurement. If there is no chance for finding a centre point at a surface <1000 Ωm we have to do our best following the rules given at the beginning of chapter 2:

a) respecting the "holy district",
b) having the current cables far away from the potential electrodes,
c) repeat the measurement several times. If there is no difference then we can go on.

But we will get those differences if it is raining. Then we have to stop the measurement at once because wet cables are bad and to dry them will take a long time. The cable drums should always remain dry, as far as measurements are bound to a high-resistant surface.

This last chapter should be studied very carefully. A final remark - and this is an important one - shall be added:
Before opening and checking the instrument always look around outside the car. Errors occur outside!