ANOMALIES FROM HORIZONTAL METAL PIPES IN RESISTIVITY AND IP FIELDS

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Abstract

In urban and industrial areas geophysical methods are frequently applied to locate metal pipes in the ground or for other problems in their vicinity. Study of such pipes' influence can include: 1 - detection of a pipe (its position, orientation, depth), 2 - estimation of pipe technical condition (corrosion, quality of insulation), 3 - distorting influence of a pipe on the fields of electrical and EM methods in the investigation of various geological problems. I.e. the pipes can be both object of study and noise. For resistivity and IP methods pipes more often appear as noise, though from these methods some pipes' parameters can be determined.

It is possible to apply numerical methods to model the influence of pipes on apparent resistivity and IP fields. For a simple problem such as a rectilinear indefinitely long pipe - the application of analytical method based on the boundary and starting conditions of the Laplace equation is possible. The analytical method allows the estimation of the influence of a pipe over a wide range of pipe and environment parameters. The problem is evaluated for a horizontal cylinder with a coating in an electrical field generated by a point current source.

The influence of several pipe's parameters was investigated. Among these are depth and orientation of the pipe, pipe and coating resistivity, influence of array and current electrodes' distance from the pipe axis. In all cases IP values are more sensitive to pipe's parameters changes in comparison with apparent resistivity. Pipe influence increases with current electrode proximity to the pipe axis and with decreasing resistivity of the pipe coating.

Introduction

This paper is a result of a need to estimate the technical condition of pipelines and evaluation of some geophysical methods' possibilities.

Frequently industrial objects such as buried metal pipes, instead of natural ones become the objects of geophysical studies. The focus of such pipes studies can be: 1 - detection of a pipe (its position, orientation, depth), 2 - estimation of pipe technical condition (corrosion, quality of insulation, leakage of liquid or gas, quality and functioning of cathodic protection, etc.), 3 - distorting influence of a pipe on the fields of electrical and EM methods during various pure geological problems. I.e. the pipes can be both object of study and noise. For resistivity and IP methods pipes most often appear as noise (Parra, 1984), although some pipe parameters: such as position, depth and quality of insulation, can be determined.

It is possible to apply various numerical methods to study a pipe's influence on apparent resistivity and IP fields. However, for a simple model such as a rectilinear, indefinitely long pipe - the application of an analytical method based on the boundary and starting conditions of the Laplace equation is possible. The analytical approach allows estimating the influence of a pipe over a rather wide range of pipe and environment parameters, in particular over a wide range of specific electrical resistivity.

Metal cylinder with a coating in a field of a point current source.

Let's consider the problem of calculating the induced polarization field over an infinitely long, covered horizontal cylinder at electric field excitated by a point current source. Let's consider that the cylinder and the coating can have volumetric or surficial polarization. The electronic conductor represented as a metal body (metal pipe), has no volumetric polarization, but only surficial polarization; its polarization is possible only through oxidation-reduction electrochemical reactions on the surface of the cylinder, i.e., at an interface of a solid phase – (metal surface) - and liquid phase – (moisture in rock pores). Nevertheless, anomalies from a cylinder with volumetric or surficial polarization are very similar and for modeling we can use either type of polarization.

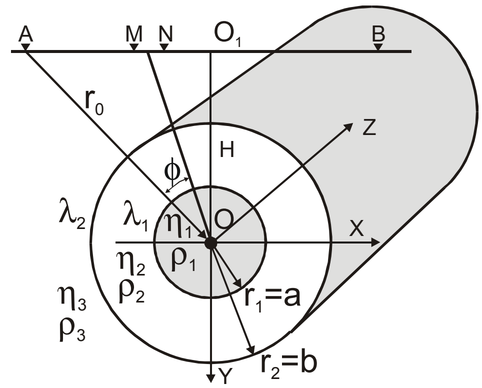

Fig. 1. Model of horizontal cylinder.

The problem's setting.

The polarizable infinitely long horizontal circular cylinder has specific electrical conductivity σ_1 and chargeability η_1. The cylinder is surrounded by a coating with a specific electrical conductivity σ_2 and chargeability η_2. The cylinder and coating reside in a homogeneous halfspace with conductivity σ_3 and chargeability η_3. The surficial polarization at the boundary of the cylinder with the coating (at r_1=a) is equal to λ_1, and at the boundary of the coating with the environment (at r_2=b) is equal to λ_2. Outside of the cylinder at distance AO there is a point current source creating a primary electric field with intensity E_0. Let's choose a cylindrical coordinate system with the z-axis directed along the cylinder's axis. The point of origin of the cylindrical coordinate system is at the point O in a plane perpendicular to the cylinder axis, which passes through the current source A (fig. 1). The basic reason for most surface electrical survey is to determine the electric field distribution outside of the cylinder. Therefore, let us calculate the electric field only for the external environment. Combining various parameters of this model, it is possible to calculate many variants of ρ_a and IP fields. For example, suppose ρ_1 is low and ρ_2 is high. This model would represent a metal cylinder with an insulating coating. By making ρ_2 low we can model a metal tube with a central hole filled with resistive (oil) or conductive (water) liquid.

Assuming surficial polarization, the boundary conditions for the potential function will look like:

$$U_2 - U_1 = \lambda_1 \frac{\partial U_2}{\partial r}, \qquad \sigma_2 \frac{\partial U_2}{\partial r} = \sigma_1 \frac{\partial U_1}{\partial r} \qquad \text{For boundary } r_1=a \qquad (1)$$

$$U_3 - U_2 = \lambda_2 \frac{\partial U_3}{\partial r}, \qquad \sigma_3 \frac{\partial U_3}{\partial r} = \sigma_2 \frac{\partial U_2}{\partial r} \qquad \text{For boundary } r_2=b \qquad (2)$$

The potential function of a source should tend to zero at infinite removal from a current source, and in infinitesimal neighborhood of a current source should tend to function determining electrical potential in homogeneous medium, which in cylindrical system of coordinates looks like:

$$U_{20} = \frac{I\rho_2}{4\pi} \frac{1}{\sqrt{r^2 + r_0^2 - 2rr_0\cos\theta + z^2}}\ . \qquad (3)$$

Let's carry out the Laplace equation solution:

$$\frac{\partial^2 U_i}{\partial r^2} + \frac{1}{r}\frac{\partial U_i}{\partial r} + \frac{1}{r^2}\frac{\partial^2 U_i}{\partial \theta^2} + \frac{\partial^2 U_i}{\partial z^2} = 0, i \in \{1,2,3\} \tag{4}$$

by Fourier method, assuming, that the partial solution is a product of three functions:

$$U_i = R(r) \cdot Z(z) \cdot \Theta(\theta)$$

Having substituted this function in (4) and after separation of variables we get three ordinary differential equations, each of which depends only on one parameter:

$$\begin{aligned} &R''(r) + \frac{1}{r}R'(r) - \left(m + \frac{n^2}{r^2}\right)R(r) = 0, \\ &Z''(z) + m^2 Z(z) = 0, \\ &\Theta''(\theta) + n^2\Theta(\theta) = 0. \end{aligned} \tag{5}$$

The private solutions of (5) are the cylindrical functions of *n*-th order from imaginary argument - $I_n(mr)$, $K(mr)$, and also *cos (mz)* and *sin (mz)* - for the second equation in (5) and $\cos(n\theta)$, $\sin(n\theta)$ - for the third one. In view of model symmetry to the chosen system of coordinates, the equation parts containing functions *sin (mz)* and $\sin(n\theta)$ should be canceled, and values of the parameter *n* in $\cos(n\theta)$ should be only integers.

Under these conditions the solution of system (5) can be presented in the following form:

$$U_i = \sum_{n=0}^{n=\infty} \cos n\theta \int_0^{\infty} [C_i(n,m) I_n(mr) + D_i(n,m) K_n(mr)] \cos mz \, dm, \tag{6}$$

where $C_i(n, m)$ and $D_i(n, m)$ - some functions not dependent on coordinates r, z, which values are determined from boundary conditions.

For the environment, in which there is a current source, the function U_i has an additional term, which determines the potential near to the source. In this case in medium with index "3" the additional term looks like:

$$U_3 = U_0 + U_{3'},$$

where U_3 - total solution; U_0 - function determining potential of a point current source in space; $U_{3'}$ - solution of Laplace equation in the form (6).

Using Weber integral, we shall write potential of a point source U_0 in infinite space in the form, convenient for the consequent solution:

$$U_0 = q\sum_{n=0}^{\infty} \cos(n\theta) \int_0^{\infty} [(2 - \delta_{0,n}) I_n(mr) K_n(mr_0)] \cos(mz) \, dm, \tag{7}$$

where r is a distance between an axis of the cylinder and point M, in which electrical potential is determined; r_0 - distance between the source A and axis of the cylinder.

In view of formula (7) general solution for the first, second and third media is expressed as:

$$\begin{aligned} U_1 &= \int_0^{\infty} \sum_{n=0}^{\infty} A_n I_n(mr) \cos n\theta \cos(mz) dm \\ U_2 &= \int_0^{\infty} \sum_{n=0}^{\infty} [B_n I_n(mr) + C_n K_n(mr)] \cos n\theta \cos(mz) dm \\ U_3 &= q\sum_{n=0}^{\infty} \int_0^{\infty} [(2 - \delta_{0,n}) I_n(mr) K_n(mr_0) + D_n K_n(mr)] \cos(n\theta) \cos(mz) \, dm \end{aligned} \tag{8}$$

Substituting (8) in (1-2), we get a system of equations for definition of the unknown coefficients A_n, B_n, C_n, D_n. As we are interested only in the field in the external medium, only D_n is needed:

$$
\begin{aligned}
&a_{11}A_n - a_{12}B_n - a_{13}C_n = 0\\
&a_{21}A_n - a_{22}B_n - a_{23}C_n = 0\\
&a_{31}A_n + a_{32}B_n + a_{33}C_n - a_{34}D_n = b_3\\
&a_{41}A_n + a_{42}B_n + a_{43}C_n - a_{44}D_n = b_4
\end{aligned}, \tag{9}
$$

where

$$a_{14}=a_{24}=a_{31}=a_{41}=0;$$

$$a_{11} = I_n(ma); \quad a_{12} = I_n(ma) - \lambda_1 I_n'(ma); \quad a_{13} = K_n(ma) - \lambda_1 K_n'(ma);$$

$$a_{21} = \sigma_1 I_n'(ma); \quad a_{22} = \sigma_2 I_n'(ma); \quad a_{23} = \sigma_2 K_n'(ma);$$

$$a_{32} = I_n(mb); \quad a_{33} = K_n(mb); \quad a_{34} = K_n(mb) - \lambda_2 K_n'(mb);$$

$$a_{42} = \sigma_2 I_n'(mb); \quad a_{43} = \sigma_2 K_n'(mb); \quad a_{44} = \sigma_3 K_n'(mb);$$

$$
\begin{aligned}
&b_3 = q(2-\delta_{0,n})[I_n(mb) - \lambda_2 I_n'(mb)]K_n(mr_0);\\
&b_4 = q\sigma_3(2-\delta_{0,n})I_n'(mb)K_n(mr_0)
\end{aligned} \tag{10}
$$

From system (9) in view of designations (10) and after transformations we get the required expression for coefficient D_n:

$$D_n^* = \frac{(b_3a_{42} - b_4a_{32})(a_{13}a_{21} - a_{11}a_{23}) + (b_3a_{43} - b_4a_{33})(a_{11}a_{22} - a_{12}a_{21})}{(a_{44}a_{32} - a_{34}a_{42})(a_{13}a_{21} - a_{11}a_{23}) + (a_{44}a_{33} - a_{34}a_{43})(a_{11}a_{22} - a_{12}a_{21})}, \tag{11}$$

where

$$D_n = \frac{D_n^*}{q}; \quad q = \frac{I}{2\pi^2\sigma_3}.$$

Having substituted (11) in the third equation (8), we get the expression which accounts for the potential in the given point M, removed a distance r from an axis of the cylinder with coating:

$$U_3 = \frac{I}{4\pi\sigma_3}\left(\frac{1}{\sqrt{R_{AM}^2 + z^2}} + \frac{2}{\pi}\sum_{n=0}^{\infty}\int_0^{\infty} D_n K_n(mr)\cos(n\theta)\cos(mz)\,dm\right). \tag{12}$$

Usually the calculation of potential (potential difference in ground electrical survey) is made along a definite line located on the earth surface, and the distances up to a point M are marked from the source, i.e. a coordinate system is used, whose center is the current source. In this case, taking into account the earth - air boundary in the electric field calculations, the calculated values are doubled, and an angle θ and distance r, used in the formulas (11-12), are expressed through distance R_{AM} – (the distance from a point M up to a source A) under the following formulas:

$$
\begin{aligned}
&r = \sqrt{R_{AM} + r_0 - 2R_{AM}r_0\cos\alpha},\\
&\cos\theta = \frac{r_0 - R_{AM}\cos\alpha}{r},\\
&\cos\alpha = \frac{R_{AO'}}{r_0}, \quad r_0 = \sqrt{R_{AO'}^2 + h^2},
\end{aligned} \tag{13}
$$

where R_{AO} is the distance from a source A up to a point O_1, formed by the crossing of the projection of the cylinder axis at the given plane and a perpendicular line to this projection going through a point A; h is the distance from a point O_1 up to the cylinder axis, - which actually is the cylinder depth; r_0 - distance from a point A up to the cylinder axis.

The formulas (11-12) were used for programming the solution. Following the algorithm of

V.A.Komarov - H.O.Seigel (Komarov, 1980), the calculation of IP field was made using the following assumptions:

1. Input of values describing model properties and an array: σ_1, σ_2, σ_3, λ_1, λ_2, η_1, η_2, η_3, a, b, length of AB line, distances of M and N points from A electrode, using the A electrode as the origin of the coordinate system.

2. Accounting under the formulas (11-12) the potentials in M and N points from A and B sources at given model parameters with IP. Accounting ΔU_{MN} from two sources A and B under the formula: $\Delta U^*_{pr}(MN) = U^*_{pr}(AM) - U^*_{pr}(AN) - U^*_{pr}(BM) + U^*_{pr}(BN)$, where $\Delta U^*_{pr}(MN)$ is ΔU_{MN} with IP.

3. Accounting the potential difference in MN line from two sources A and B without the IP under the formula: $\Delta U_{pr}(MN) = U_{pr}(AM) - U_{pr}(AN) - U_{pr}(BM) + U_{pr}(BN)$, where $\Delta U_{pr}(MN)$ is ΔU_{MN} without IP.

4. Accounting ρ_a and η_a values under the formulas:

$$\rho_a = K\frac{\Delta U_{pr}(MN)}{I},$$

$$\eta_a = \frac{\Delta U^*_{pr}(MN) - \Delta U_{pr}(MN)}{\Delta U_{pr}(MN)}$$

where K is a geometrical coefficient of array; I is a current value.

5. Calculations repeat N times, where N is a quantity of MN positions.

On the basis of this algorithm the program "Truba3d.exe" has been made, which is used for an estimation of pipe influence and for study of apparent resistivity and IP fields' behavior.

The program "Truba3d.exe" was tested by comparison of apparent resistivity and chargeability with results of the programs for a cylinder and a pipe in a homogeneous field, and also with the programs evaluating similar models by final differences and integral equations' methods.

Study of pipe and coating parameters influence

Among examples of calculations with the program "Truba3d.exe" we show the dependency of anomalous resistivity and IP fields on pipe resistivity, pipe depth, orientation of array, pipe axis and a quality of insulation. All calculations presented here were made mainly for electrical sounding with a Schlumberger array. Such technology gives more full representation of electric field character.

The influence of pipe resistivity (without insulation) is investigated in an interval from 10^{-3} up to 10^{-7} Ohm.m (fig.2). Parameters of environment are: resistivity 10 Ohm.m; chargeability 2%. Pipe parameters are: superficial chargeability 0.155 m; radius 0.2 m; depth of pipe axis 2 m. Pipe resistivity is: 1 -10^{-7}, 2 - 10^{-6}; 3 - 10^{-5}; 4 - 10^{-4}; 5 - 10^{-3}. Apparent resistivity and chargeability diagrams are mirror-like to each other (fig.2). With spacing increasing, the apparent resistivity at first decreases, and then increases, while chargeability at first increases, and then decreases. The analysis shows that the area of influence of a pipe grows with the decrease of specific electrical resistivity. The anomalies of apparent resistivity and chargeability have «*anomalous tails*» in space both for long

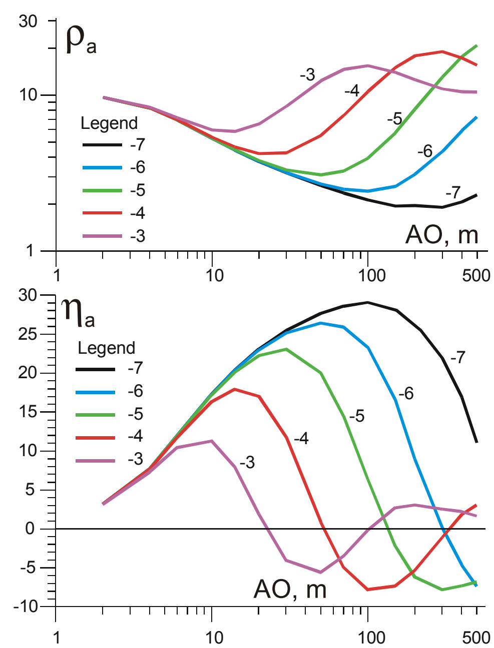

Fig. 2. Influence of pipe resistivity. Diagrams ρ_a, η_a for array orientation along pipeline. The pipe axis is under AMNB array. AB length is 1200 m.

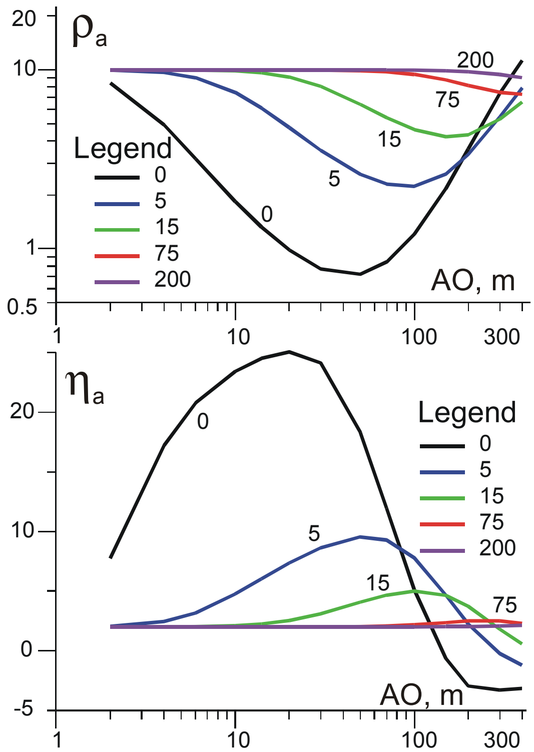

Fig.3. Changes of ρ_a and η_a diagrams with parallel removal of array from the pipe.

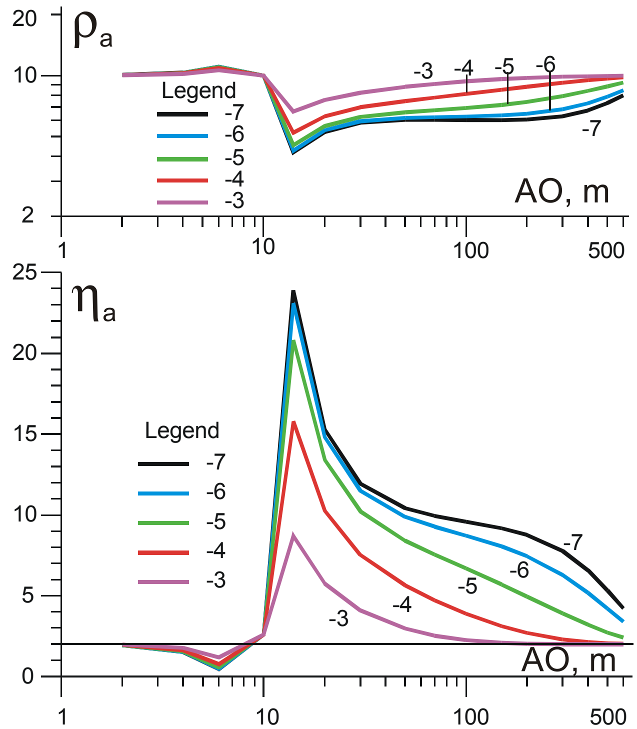

Fig. 4. Influence of a pipe resistivity on the form of ρ_a, η_a diagrams for array orientation perpendicular to the pipe. A electrode is in 10 m from the pipe.

AB/2 separations and large distances from the array to the pipe. The existence of such a "tail" must be taken into account when interpreting results of a survey executed in an area containing pipes.

With decreasing pipe resistivity (fig. 2) extremes of apparent resistivity and chargeability are displaced to larger AO spacings, which creates the illusion of increasing vertical thickness of an anomalous body. When an array staying parallel to the pipe goes away from it (fig.3), apparent chargeability decreases to a value approaching the background environment. At a distance greater than 75 m the influence of the pipe is negligible. Extremes of ρ_a and η_a anomalies with array removal are dismissing to the greater AB/2 distances. This also creates the illusion of an anomalous body at some depth.

For a perpendicular array position (fig. 4) sharp extremes on the ρ_a and η_a diagrams are marked at the moment of pipe position crossing with MN line. These extremes help to estimate pipe position.

In fig. 5 ρ_a and η_a graphs resulting from varying depth of a pipe of radius 0.4 m are displayed. Radius of the cavity in a pipe is 0.2 m, its resistivity is 10^4, and

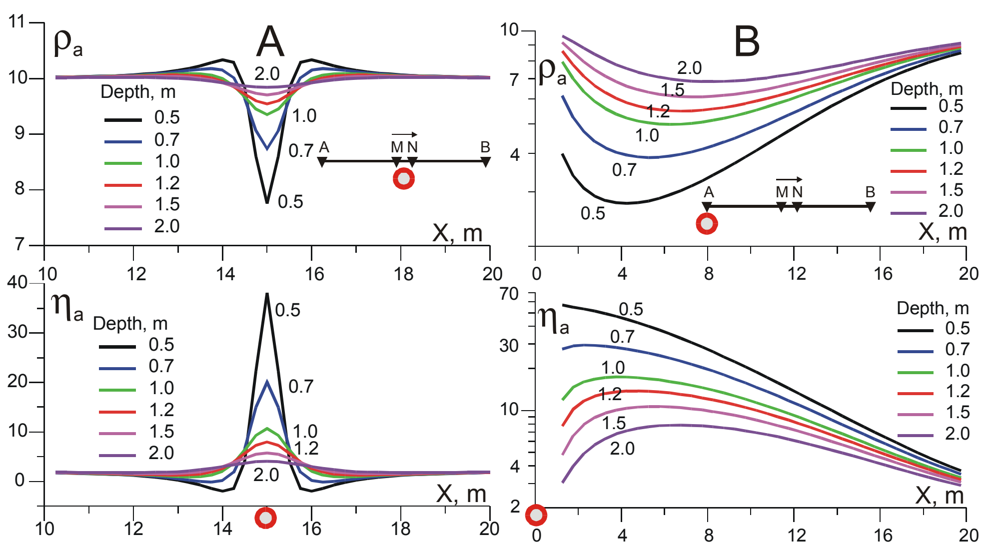

Fig. 5. Influence of pipe's depth on the form of ρ_a and η_a diagrams. A – tube is in the center of array. B – tube is beneath A electrode.

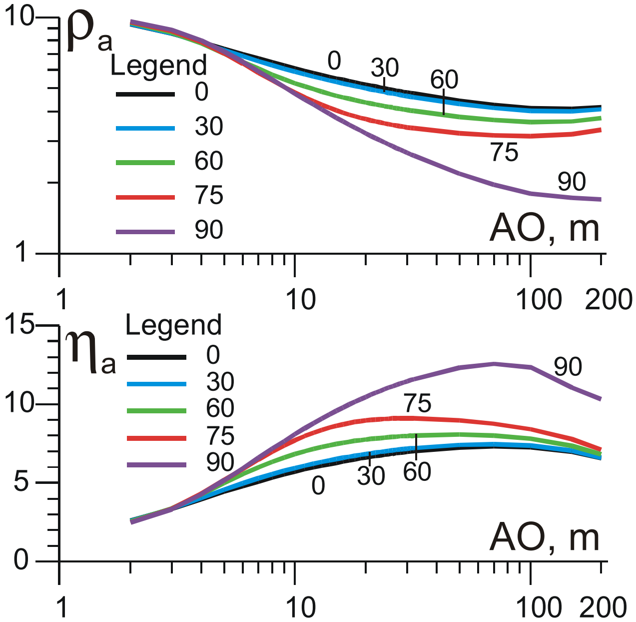

Fig. 6. A electrode is above the pipe. Curve parameter is azimuth of array's orientation from the pipe axis.

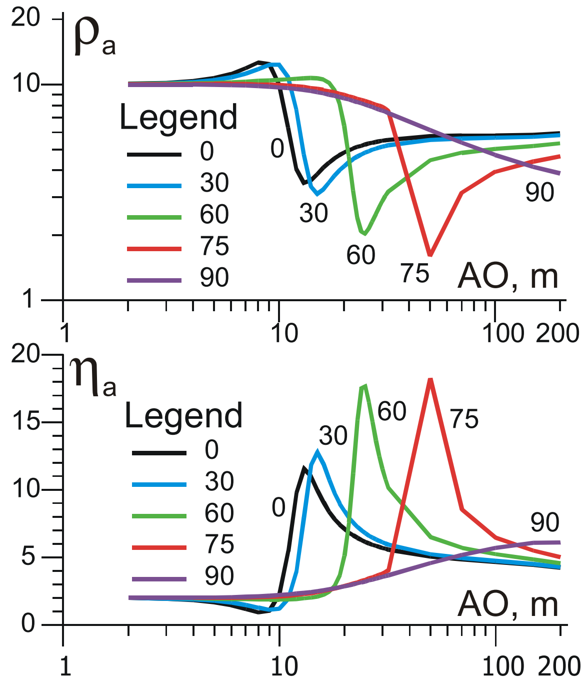

Fig. 7. A electrode is in 10 m from the pipe. Curve parameter is azimuth of array orientation from the pipe axis.

pipe resistivity is 10^{-4} Ohm.m. Surficial chargeability of the pipe is 0.155 m. Resistivity of the background environment is 10 Ohm.m, chargeability is 2 %. Depth of the pipe is: 0.5, 0.7, 1, 1.2, 1.5; 2 m. AB=30 m. The array is perpendicular to the pipe and the pipe is under the array center (15 m from electrode A) (fig.5,A). On fig.5,B current electrode A is above the pipe axis. Influence of pipe depth changing is more noticeable on IP anomaly, and more for case B.

On figs. 6 and 7 the influence of array orientation relative to the pipe axis is shown. Parameters of the background environment are: resistivity 10 Ohm.m; chargeability 2 %. Surficial polarization of the pipe is 0.05 m; pipe resistivity is - 10^{-7} Ohm.m. Array azimuth is: 1-0°; 2-30°; 3-60°; 4-75°; 5-90°. Resistivity of a cavity in a pipe is 10^6. External pipe radius is 0.2 m, internal radius is 0.16 m. Two cases are submitted: when the current electrode is exactly above a pipe (fig. 6), and when it is dismissed on 10 m from a pipe axis (fig. 7). In the second case on the diagrams there are extremes, appropriate to areas of crossing a pipe projection by measuring electrodes.

In figs. 8 and 9 the influence of insulation resistivity on a pipe surface is shown. The model is a cylinder with a resistive coating. Distance from the source up to the pipe axis AX is 6 m. The array is orthogonal to the pipe. AO spacings are from 2 up to 600 m. Surficial polarization is 0.05 m. Volumetric polarization applies only to the background environment and equal 2 %. Resistivity of the background environment is 10 Ohm.m. On fig. 8 curves 6-2 are

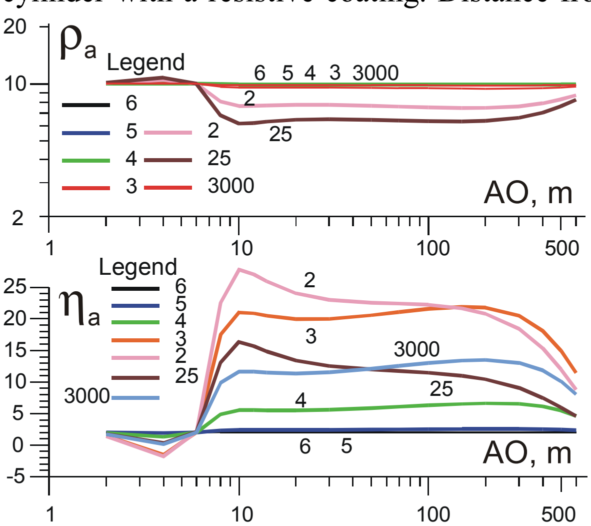

Fig. 8. Insulation resistivity influence.

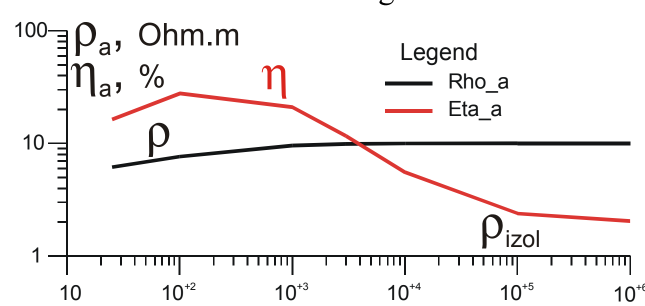

Fig. 9. Changes of ρ_a and η_a for 10 m AO spacing (from fig.8) as a function of insulation resistivity.

degrees of 10 for insulation resistivity, 25 and 3000 Ohm.m are direct resistivity values. Chargeability reacts to change of insulation quality more strongly than does apparent resistivity. The apparent resistivity varies more strongly at insulation resistivities below 10^3 while chargeability varies appreciably at insulation resistivity below 10^5 and more strongly, than the apparent resistivity.

Conclusions

1. With reduction of pipe wall specific resistivities at a constant value of surficial polarization, apparent chargeability increases.

2. The area of pipe influence on induced polarization field depends on specific resistivity of the pipe wall and its distance from the current electrodes. At pipe specific resistivity close to metal, the area of influence is maximized. The maximum area of influence is observed in a case, when one of current electrodes A (or B) is in the immediate vicinity of a pipe.

3. The maximum apparent chargeability values depend on the distance between the center of the measuring line and either current electrode. Therefore, the initial value of apparent chargeability increases with the distance of the MN line from the current electrode, and then begins to decrease.

4. The value of apparent chargeability for pipes with insulation depends on the specific resistivity of the insulation. At specific electrical resistivity of insulation equal to 10^6 Ohm.m and more, the pipe does not create an IP field because of the absence of sufficient current density on the pipe surface. With the reduction of specific resistivity of the insulation, the IP field is increased, creating the preconditions for the development of a method to estimate the value of the pipe's insulation.

Acknowledgments

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