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Electrical and electromagnetic methods to estimate position and technical conditions of pipelines and decision of ecological problems.

Introduction

The modern civilization is characterized by the advanced system of underground communications. From the beginning of 20th century many thousand kilometers of various pipes and cables were stacked in ground on depth from 0.5 to 5-6 meters. Their large part concentrates in cities. Among these - communication lines, power electrical cables, water, gas, hot water and water drain pipes etc. Especially large density of the communications there is on territory of the industrial enterprises. As a result of long groundwater influence, electrochemical and mechanical processes in the earth, the communications decay. For an acceptance of the engineering decisions it is necessary to know a real condition of the underground communications. Now in this area many problems require the decision. We consider this part of geophysics as separate branch and call it technical geophysics.

The pipelines are the integral part of the underground communications system. The non-stop operation of the majority of pipelines can last within 20-25 years. During this period and especially after it, the estimation of pipelines technical condition should be made. The normal pipelines' functioning is a basis of economic stability of many oil-exporting countries. Therefore support of pipelines' working condition is a problem with the highest priority. The majority of pipes are shipped in ground. At long interaction of pipes with an environmental ground, pipes corrosion is developing, a ground deformations cause stress and mechanical damage of pipes, resulting to fractures formation. There are a lot of the reasons of fractures formation: damages at excavation works, displacement of ground, wrong pipe construction, not compact connection of different sensors. Quite often non-authorized connections to working pipelines are made. To protect pipelines against corrosion the cathodic protection of pipelines by direct current potential is applied. At cathodic protection the negative potential is applied to a pipe, while the positive one is connected to the grounding system outside the pipe. At damage of pipe's isolation, in places of this isolation's damage the current flows out and protects this part of a pipe from corrosion. The corrosion danger depends on rock resistivity, the lower is the resistivity, the higher is the corrosion danger. Many pipes are under the high pressure; contain dangerous combustible or toxic substances. The failures on pipelines occur rather frequently, some bring enormous damage, and their elimination requires the large expenses. The replacement of pipes after termination of the pipeline operation time is especially expensive operation. At pipelines usage the constant control over their condition, timely detection of various defects in pipes condition and their repair are necessary.

The geophysical methods can help at the decision of many problems of the pipes condition control. The first task is a careful study of the area before pipeline construction, especially in the most responsible places, for example on river crossings. Recently as more reliable has become considered the project of pipe laying beneath the river in a horizontal borehole placed in the safest rock layer.

When the pipe laying is completed a number of other tasks will appear. Among these there is a control of pipe position in a plan and at depth. The actual position can differ from that, planned at construction. The depth can be changed during pipe laying or later. At river crossing the pipe can be covered first by loose sediments and then take out at the river bottom. Grounds around pipe on all its way can have a different degree of corrosion danger. The important tasks are: the control of cathodic protection, control of a physical pipe condition (for example pipe wall's thickness), detection of micro fractures, outflows from pipes, etc. These problems have different complexity and the opportunities of their successful decision by geophysical methods are different.

Among methods of pipelines inspection prevail pipeline tracers and georadar surveys. On our view the list of methods can include resistivity (sounding and profiling), measurement of cathodic protection potentials (CPP) and study with magnetic antenna (inductive detector) of electromagnetic field, exited in a pipe by different EM sources: by industrial noise, by alternative component of cathodic protection or by other artificial EM source. The resistivity, SP and EM instrument ERA, producing in St.-Petersburg, allows to carry out all these kinds of work with one set of tools. ERA instrument works at 0, 4.88, 625 Hz and additionally on 50 (60) and 100 (120) Hz with different sensors: metal and non-polarizing electrodes, magnetic and electric antennas and some others.

In urban areas the pipes are in ground, which surface can be covered with asphalt or concrete. For pipes study in urban areas non-contact EM methods are required. With ERA instrument it is possible to perform resistivity sounding and profiling in urban areas on low frequency alternating current without galvanic grounding (Bolshakov et al., 1996).

Last years geophysical methods' application sharply has grown at oil pipelines service and for ecological inspection of territories near oil industrial objects: oil refining and petrochemical factories and oil storages. It is connected both with recognition of ecological problems, and with growth of geophysical methods' opportunities. Generally speaking, the remote geophysical methods can be applied at all stages of search, prospecting, exploitation, transportation, processing and distribution of oil. We shall concern only question of the pipelines control and some problems of ecology.

Gradually accuracy of geophysical methods grows. But the complexity of the tasks under decision and that of physical conditions also grows. The migration of geophysical survey to urban areas, industrial agglomerations, factories and technical stations has resulted in occurrence of the large number of additional problems. Firstly, level of industrial electromagnetic and vibrating noise sharply has increased. Secondly, level of geological noise, or degree of inhomogeneity of the top part of the earth also has increased. Let's explain this situation. The work in rural area assumes, that geophysical sensors are placed the on ground surface, which was changed only by natural factors. The industrial landscape assumes a plenty of underground communications, trenches, fills, enrockments, changed relief, etc. In result between object of study and our detectors the so-called "broken glass” layer is located, which prevent us from clear seeing some deeper objects. Thirdly, the significant parts of cities and industrial objects' surfaces are covered with asphalt or concrete, which sharply worsen grounding conditions (that is condition of sensors arrangement). The progress in the development of the geophysical instruments, field technology and data processing compensates worsening of conditions for field geophysical survey.

For electrical and EM methods pipelines are objects with low resistivity, electronic conductivity and high self and induced polarization activity, which allow to apply for pipelines' inspection resistivity, self potential (SP), induced polarization (IP) and EM methods. Very often pipelines are covered with some isolation layer, having high resistivity and protecting pipeline from interaction with the environment. But in places of isolation damage this interaction grows. EM methods can estimate pipeline position and some properties through its isolation. The specific electrical resistivity of metal is very low and, as a rule, is less than 10^{-5} Ohm.m. The resistivity of iron is $9{,}8 \cdot 10^{-8}$ Ohm.m. If the pipeline interior is filled with gas or oil, its specific electrical resistivity is great, - more than 10^4 Ohm.m. Resistivity of tube isolation can be $10^2 – 10^6$ Ohm.m.

At fig.1 there is an example of the analytical forward problem decision (Ryjov, Shevnin, 2001) for a single metal tube without isolation, placed in the ground at different depths. Anomalies of apparent resistivity and chargeability (for time domain induced polarization measurements) are shown here. The array is perpendicular to a pipe. Influence of pipe depth changing is more noticeable on IP anomaly, and more for case B, when current electrode A is exactly above the tube axis. That means that IP method is more sensitive for pipeline inspection in comparison with resistivity.

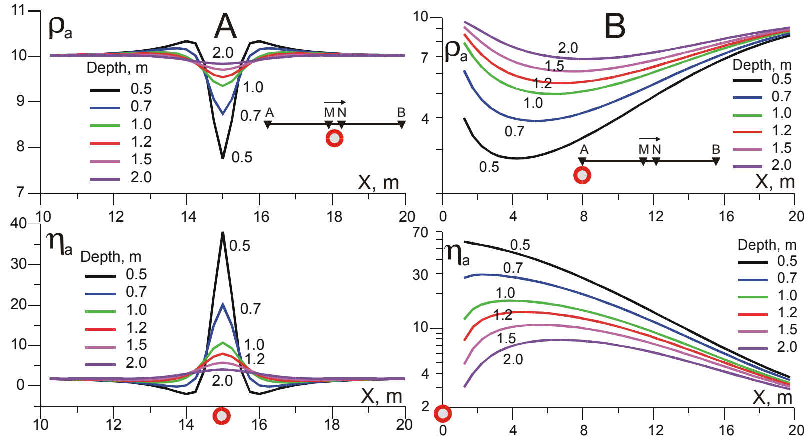

Fig.1. Graphs of apparent resistivity and chargeability above pipeline without isolation for different pipe depths: A - at the middle of AMNB array; B - with A electrode above pipe; AB=30 m.

Pipeline distorts resistivity sounding data (fig.2). This distortion makes more

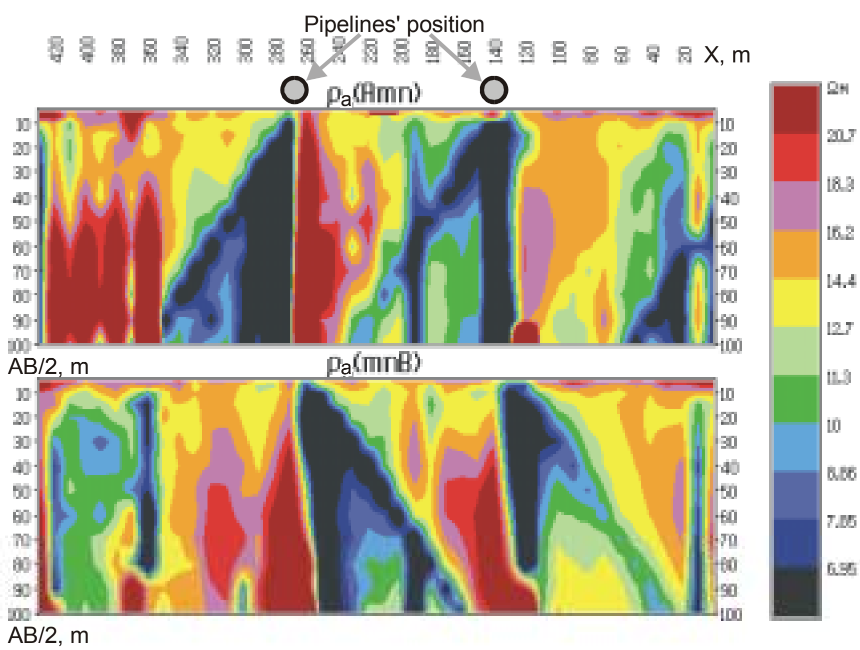

Fig.2. VES ρ_a pseudo-sections with distortion effects from pipelines influence. TES technology.

difficult VES data interpretation, but can be used for estimation of pipeline position. Theory of distortions, caused by near-surface inhomogeneities (NSI), developed at Moscow state university (Modin et al., 1997), helps to separate influences of near-surface inhomogeneities and surrounding objects, to estimate pipelines position, to cancel NSI influence and to fulfill VES interpretation with great accuracy.

Stations of cathodic protection are placed through the certain intervals along pipeline. These develop a constant low voltage potential on a tube. The cathode (negative pole) joins to a pipe, and anode (positive pole) joins to the specially drilled boreholes with metal casings. For cathodic protection the electrical power source of industrial frequency 50 (60) Hz with the subsequent current rectification is used. The rectification results in appearance of the direct current and the alternative current with frequency of the second harmonic 100 (120) Hz of spectrum, whereas the deviations from harmonicity give a wide spectrum of frequencies, that is why the measurements on 625 Hz are also possible. The last frequency signal is more noise resistive.

If pipe isolation is ideal, between the anode and cathode there is no current, and pipe potential is not transferred in an environment. At isolation damage in separate places, the current from a pipe flows to places of isolation damage and through them leaves to ground. The pipe continues to remain under negative potential preventing corrosion, but the value of potential is transferred in an environment.

The cathodic protection current, flowing out through defects of isolation, entails a

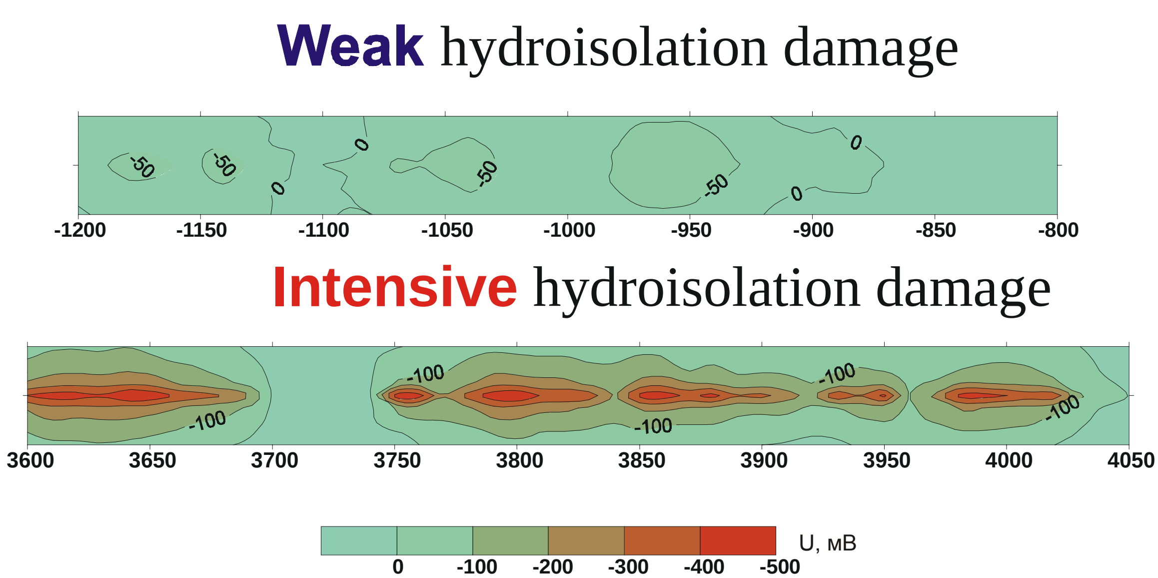

Fig.3. Two maps of cathodic protection potentials (CPP) above pipeline’s areas with weak and intensive isolation damage.

number of the phenomena, which can be measured: the alternative electrical current component in a pipe creates alternative magnetic field; which in places of current outflows in ground decreases a little. Above a pipe in places of isolation damage will arise negative anomalies of DC cathodic protection potentials (CPP). Their origin is similar to "mise a la masse" method, because metal tube has very low resistivity in comparison with that of surrounding, whereas field measurement technology is closer to SP method and needs non-polarizing electrodes. The more is isolation damage, the more is negative amplitude of CPP anomaly (fig.3).

The survey with magnetic antenna with the ferrite core (inductive sensor) (fig.4) with measuring unit ERA is very convenient for alternative magnetic field measurement and estimation of pipe position in plan and on depth. It is possible to apply for this purpose several techniques:

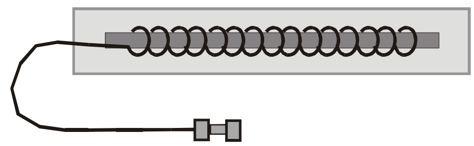
Fig.4. View of magnetic antenna.

1. Revealing a pipe position at industrial frequency 50 (60) Hz (passive detection). In an environment there is a significant background of EM noise from nearby and distant industrial EM sources. This noise causes occurrence in a pipe of induced EM currents, and above a pipe occurrence of magnetic field anomaly at 50 (60) Hz. At measurements of horizontal components of magnetic field, perpendicular to a pipe axis with the help of magnetic antenna, the maximum Hy will be observed. Lack of this technique is a high level of industrial frequency noise acting simultaneously with other sources of signals.

2. When the pipe is under cathodic protection, its detection and trace can be carried out with the help of a magnetic antenna on

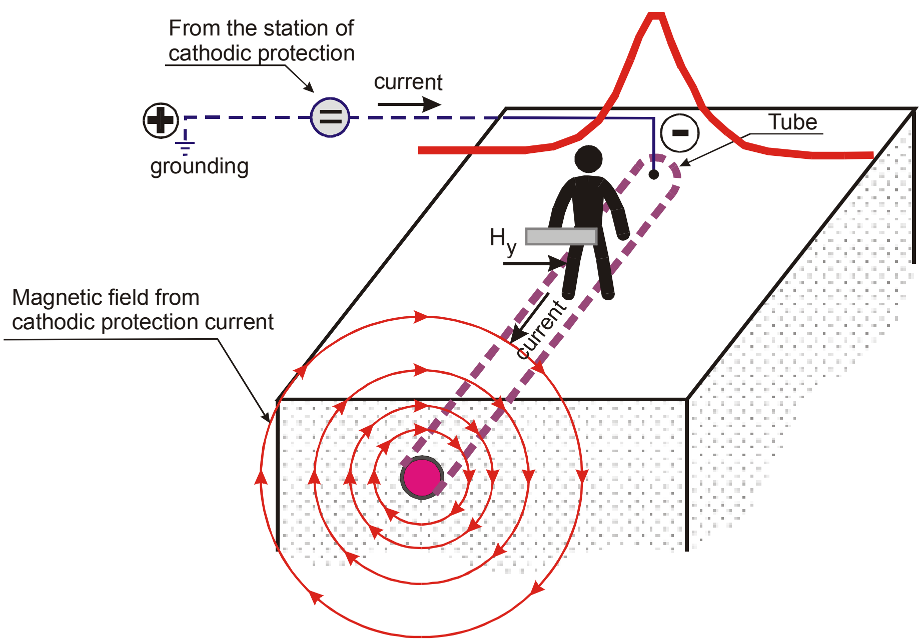

Fig.5. Estimation of tube position in space and depth by measuring magnetic field from AC component of cathodic protection.

doubled industrial frequency 100 (120) Hz (fig.5).

3. When it is possible to connect one or two poles of current line from 625 Hz portable ERA generator to a pipe, it is easy to trace a pipe with the help of a magnetic antenna on frequency 625 Hz (fig.6).

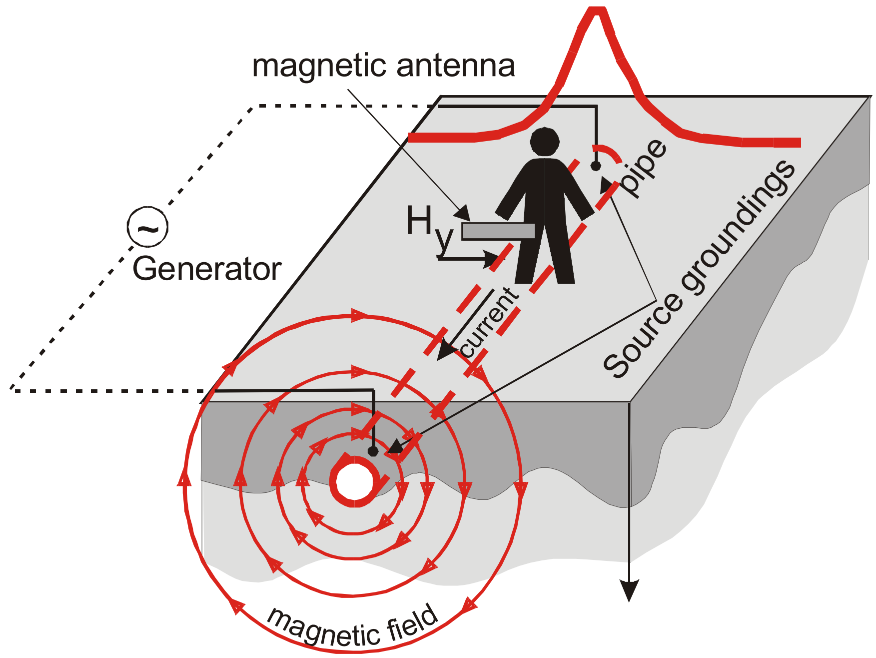

Fig.6. "Mise-a-la-masse" technique with magnetic field measurement.

4. If parallel to pipe put a wire, supplied by a current from 625 Hz ERA generator, the pipe, exited by this current, can also be found with the help of a magnetic antenna (fig.7).

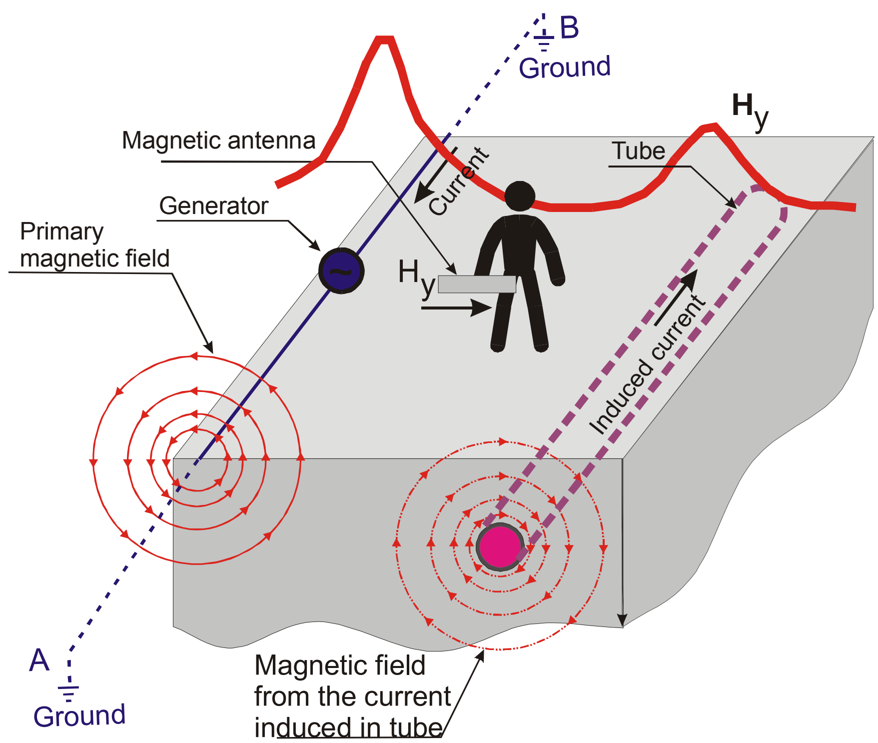

Fig. 7. Pipe detection with the help of magnetic antenna.

For an estimation of pipe depth it is necessary to know a place of the pipe projection on the earth surface and its direction. Departing from pipe axis at perpendicular direction, it is possible to receive a maximum of a signal on a distance, equal to depth of its center (fig. 8) with magnetic antenna, oriented vertically (3) or inclined under 45° (2).

Results of estimation of pipeline condition in the field, received in Western Siberia (Russia) are shown below.

The measurements were carried out at winter period with non-contact resistivity profiling, study of DC cathodic protection potential (CPP), measurement of alternative component of cathodic protection field with magnetic antenna on frequency 100 or 625 Hz.

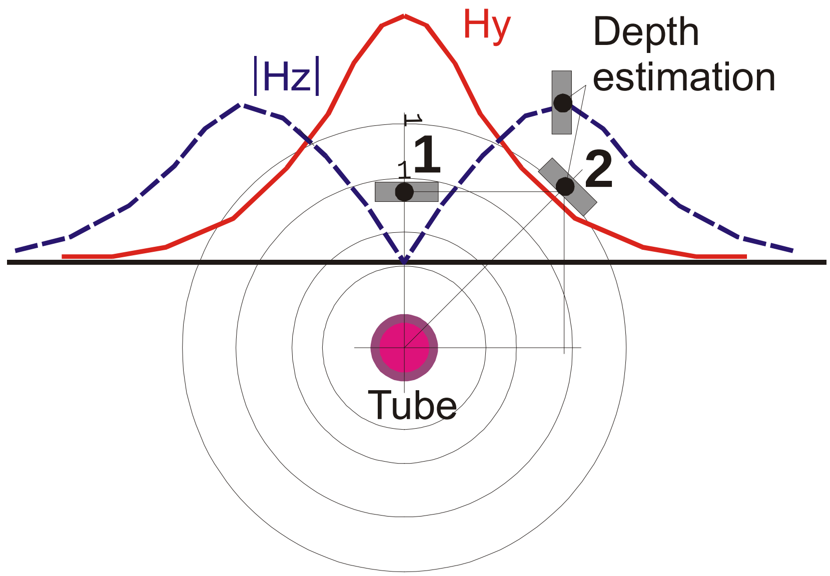

Fig.8. Tube's position and depth estimation with magnetic antenna.

It is possible to consider these CPP anomalies, as potentials of a "mise a la-masse" method, because cathodic protection potential passing in environment in places of isolation damage is actually measured. On our experience at the control of pipeline isolation quality, small negative CPP anomalies (with amplitude up to 10 mV) can be not taken into account, the CPP anomalies from 10 up to 50 mV correspond to sites of weak isolation damage, the sites with average isolation damages give anomalies 50-100 mV, and sites of strong damages give negative CPP anomalies more then 100 mV. At CPP registration it is more convenient to use potential gradient field survey with the subsequent results recalculation into potential. With MN line of 50 m length it is possible to trace anomalies with the spatial periods of 100-300 m. The measurements of potential on some sites, remote from pipe axis are carried out through every 1-1.5 km along the pipe. These measurements help to transform gradient measurements into united map of CP potentials (fig. 3).

Measurements of horizontal components of alternative magnetic field from cathodic protection can be fulfilled on frequency 100 (120) or 625 Hz. An alternative component of pipe cathodic protection is used as the source of this signal. The maximum of Hy (perpendicular to pipe) component is exactly above the longitudinal axis of pipeline. The pipe depth is estimated on a vertical component Hz. The extreme values of Hz field are achieved at removal from a pipe on a distance x=z (fig.8).

The estimation of cathodic protection current in a pipe can be carried out on Hy amplitude in a maximum of anomaly, which is proportional to current value in a pipe. In

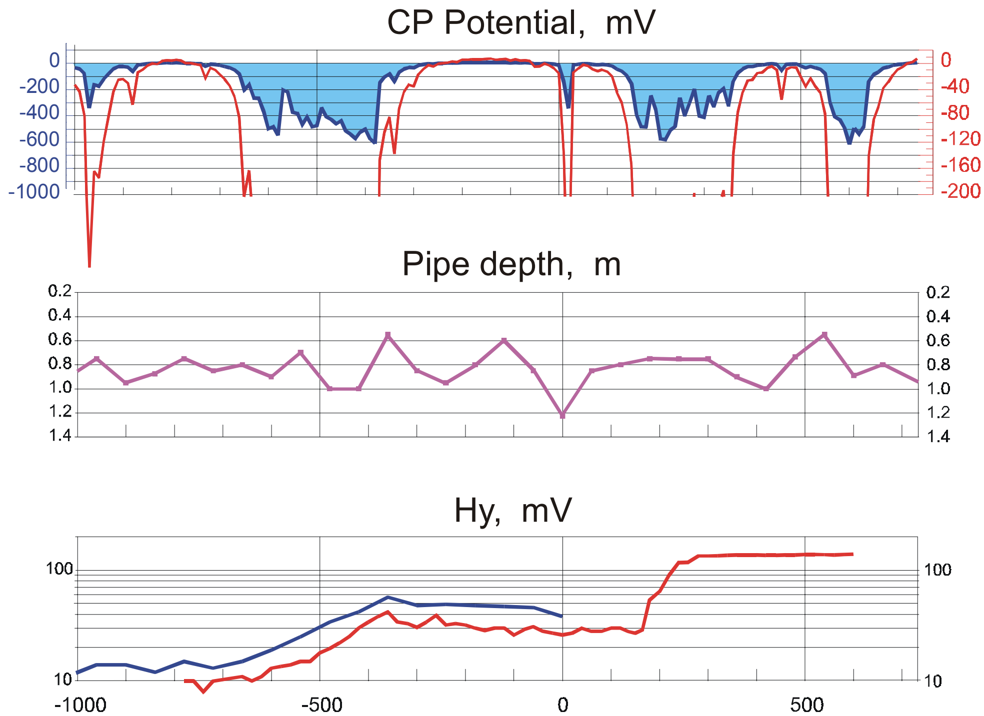

Fig.9. Example of cathodic protection potentials, depth estimation and Hy amplitude measurements above pipeline segment.

places of significant isolation damage the current leaves from pipe in ground and the magnetic field Hy decreases. Joint comparative examination of magnetic field Hy and CPP anomalies has shown, that the zones of CPP minima well coincide with places of magnetic field Hy reduction (fig.9). That allows localizing areas of isolation damage.

For detection of low resistive zones with increased corrosion danger resistivity profiling is applied. It can be carried out as traditional profiling, and as non-contact electrical profiling on frequency 625 Hz with a non-contact electrical antenna for electrical field measurements and with trailing wire joined by one end to an electrode A as a field source (fig.10). Only two persons

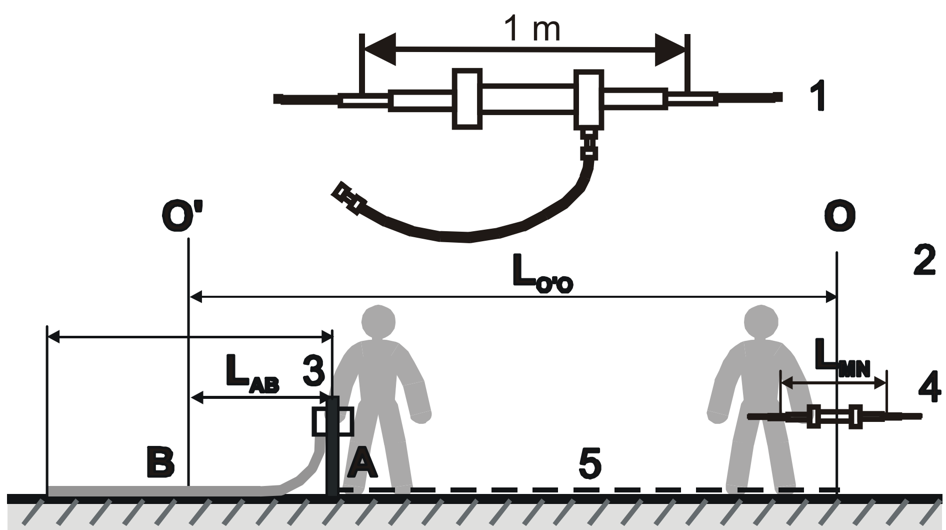

Fig.10. Non-contact electrical profiling. 1 – a view of electrical antenna; 2 – a view of array with current (3) and measuring (4) parts, 5 – cord to support distance.

instead of four can fulfill non-contact measurements

Ecological studies of oil pollution.

Ecological studies of oil pollution on the department of geophysics MSU were carried out several years, including oil-refining factories in town M (1994), town N (1994-

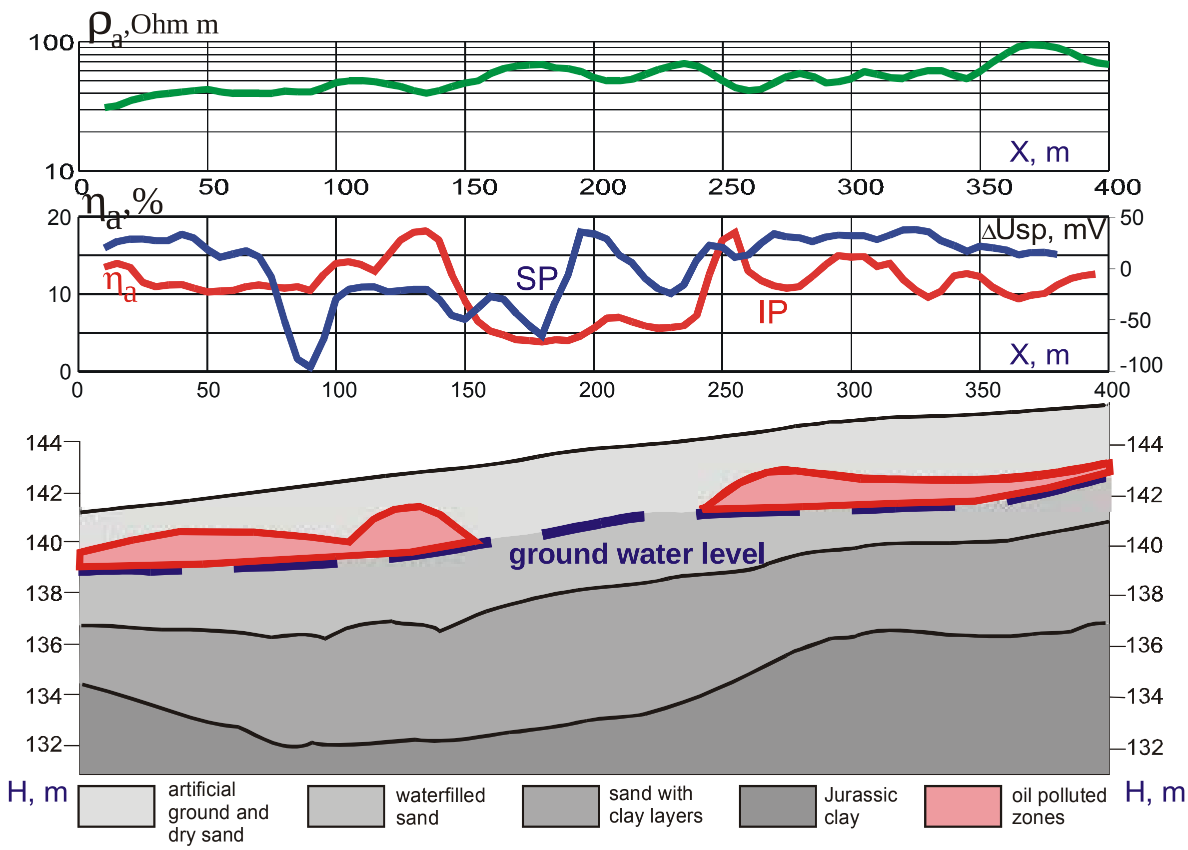

Fig.11. Results of electrical survey above shallow-depth oil pollution.

96) and town S (1995-96) and some other places. The depth of polluted zones was from 0.5 up to 50 m and the time of their formations from several months till 50 years.

The first example is oil-refining factory in town M. On this factory oil polluted zone is placed at the depth of several meters. For its study several methods VES, SP, resistivity and IP profiling, GPR were applied (fig.11). A geological situation is typical for town M region. On depth about 10 m the waterproof layer of Jurassic clay is situated, and higher of it is sand, the lower part of which is filled with water. The groundwater level is on the depth about 1.5 m. On that boundary the oil pollution is placed, being existed constantly for a long time. The top part of a cross-section with the thickness of 2-3 m is an artificial ground, which is typical for urban areas and has extremely changeable properties. Just in this layer several anomalous zones with intensive oil pollution are located. These zones are confidently mapped on IP, SP, GPR and resistivity methods' data. Polluted object is appeared similar to ore body, because it shows lower resistivity, negative SP potential, higher IP response. GPR shows low dielectric parameters in polluted area.

Such anomalies of low resistivity in oil-pollution areas were also found by H.Vanhala (1997). Why does oil pollution seem to be low resistive object? In accordance with investigations some scientists: Bailey N.J.L. (1973), Milner C.W.D., et al. (1977), Dostalek M. (1975) oil-transforming bacteria are probably responsible for that. In upper part of the cross-section bacteria are very active, they transform upper layer of the oil film into some acids. Acids react with rocks and iron ions in water and result in high groundwater conductivity, karst processes and pyrite creation. Pyrite gives increased IP response.

The GPR data were interpreted independently, and other methods -- in integration. The GPR data were possible to reveal layered structure and the sites of pollution only after processing. The total electrical sounding - TES was used as a structural method for tracing ground-water level (GWL) and a clayey basement. With the help of an integrated parameter of pollution it became possible to find out its distribution in the area and on depth. A priory information about the thickness and exact places of pollution at the reference profile was used. To characterize pollution, such parameters like the relative thickness of a polluted layer (fig.12) and its bottom's depth were applied. These values were estimated on the regression dependence between these two parameters and some anomalous values of the measured geophysical fields and their dispersions (fig.12). For localization of pollution in plan IP method gave the maximum contribution, about 80% of the all information. GPR

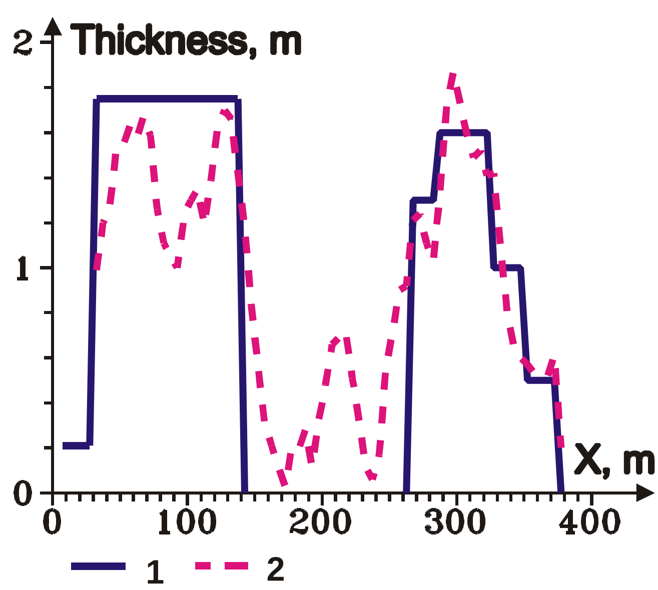

Fig.12. Results of polluted layer thickness estimation on regression with geophysical data. 1 – a priory thickness of oil-polluted layer; 2 – that on regression of geophysical data.

shown wider polluted areas than geological data. We suppose that GPR could see the whole area of pollution whereas the direct geological methods could estimate only the strongest pollution.

In town N the study of territory around the oil-refining factory was carried out for estimating ecological consequences of this factory activity. In upper part of a geological

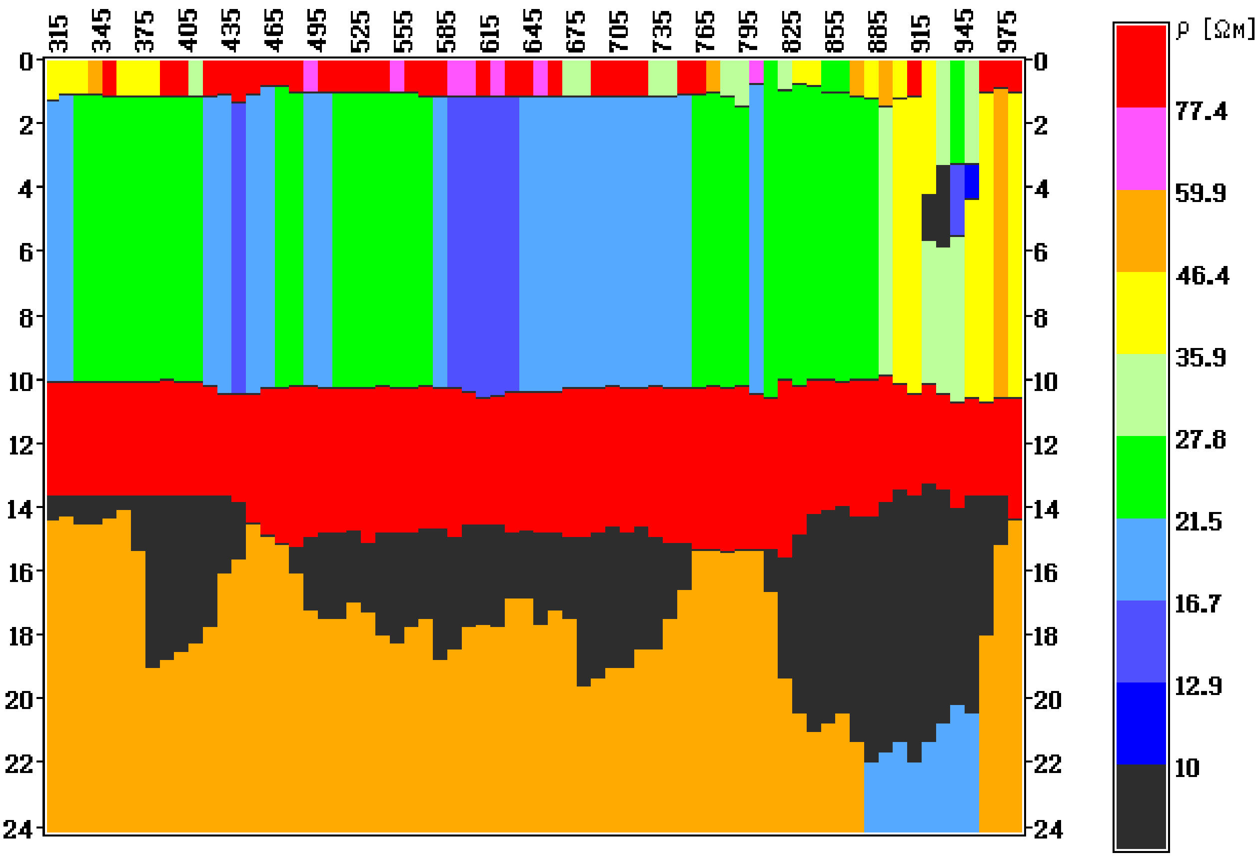

Fig.13. Results of TES interpretation over zone of oil pollution, concentrated in limestone, town N.

cross-section on depths up to 50 m during several decades of factory activity in the result of oil leakage from pipelines and storehouses the significant amount of oil products was collected in subsurface. That collection can be considered as a secondary oil deposit with rather great economic interest for this region. The pollution spread to significant distance (6-7 km), despite extremely low values of rock permeability along some paleovalleys. Oil pollution has moved below groundwater level, because oil density became slightly more then that of water after oil-transforming bacteria activity.

The geophysical study in town N was carried out with the total electrical sounding technology (Geoecological inspection..., 1999). TES allows to cancel geological noise, to raise interpretation accuracy and therefore to estimate fine geological features, including effects of pollution. The study of the area (taking into account a priory data and

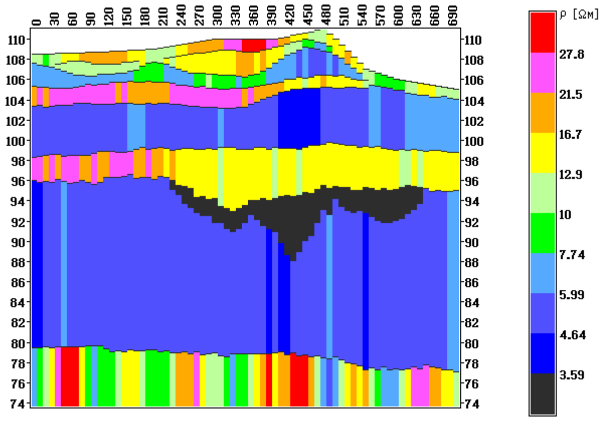

Fig.14. Town S. Profile 4. VES results with traces of oil pollution.

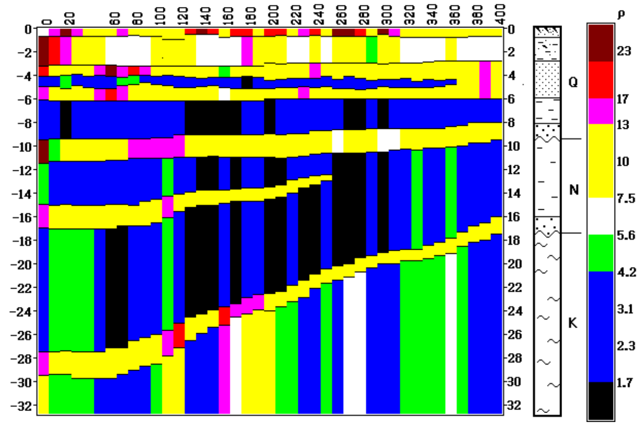

Fig.15. Town S. VES results with traces of oil pollution on profile 2.

results of drilling) has allowed to reveal layered structure of a cross-section and to find out paleovalleys, filled with loose deposits. The system of such paleovalleys serves the most probable ways of oil pollution spreading at significant distances. This example shows that not only background cross-section, but some anomalous features in it as paleovalleys, which play the important role in pollution state and movement. TES is the main method for such pollution study.

Town S. is not far from town N., and oil-refining factory is quite similar. Pollution on the surface is the same or even stronger, but secondary oil deposit is not found yet. Background cross-section is sandy with thin clay layers. Some small oil concentrations (fig.14) and traces of pollution spreading downward (fig.15), noticeable on TES method data were only found, but secondary oil deposits were not found.

Conclusions.

1. For pipeline tracing, estimation of it position, depth and location of isolation damage several electrical and EM methods can be used: resistivity and IP, SP (or CPP), measurements with magnetic antenna.
2. Oil pollution can be studied with of superficial electrical and EM methods: resistivity and IP, SP and georadar.
3. Oil pollution gives non-contrast anomalies; for their estimation integrated geophysical interpretation or the total electrical sounding technology with canceling geological noise should be used. Oil pollution frequently appears as low resistive object due to activity of oil transforming bacteria in near-surface condition.

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References

Ryjov A.A., Shevnin V.A. Anomalies from horizontal metal pipes in resistivity and IP fields. Report, presented at SAGEEP - 2001 conference in Denver. In print.

Geoecological inspection of oil industrial enterprises. Ed. by V.A.Shevnin and I.N.Modin. Moscow, RUSSO, 1999, 511 pp. (In Russian)

Bobachev A.A., Bolshakov D.K., Ivanova S.V., Modin I.N., Pervago E.V., Safronov V.S., Shevnin V.A. Pipelines' studies - new problem for geophysics. Proceedings of 4th EEGS-ES Meeting in Barselona, Spain, September 1998. 4 p. (p. 563-566)

Bobachev A.A., Bolshakov D.K., Ivanova S.V., Modin I.N., Pervago E.V., Shevnin V.A. Study of working and projected pipelines with electrical methods. EAGE 60th Conference, Leipzig - 1998. P127. 2 p.

Modin I.N., Shevnin V.A., Bobatchev A.A., Bolshakov D.K., Leonov D.A., Vladov M.L. Investigations of oil pollution with electrical prospecting methods. Proceedings of 3rd Meeting environmental and engineering geophysics. Aarhus, Denmark, 8-11 September 1997. P.267-270.

D.K.Bolshakov, I.N.Modin, B.G.Sapognikov, V.A.Shevnin. Non-contact resistivity measurements. Proceedings of EAGE 58th Conference, June 1996, Amsterdam, The Netherlands. P051.

Bailey N.J.L., Jobson A.M., Rogers M.A. Bacterial degradation of crude oil: comparison of field and experimental data. Chemical geology, N11, 1973.

Dostalek M. The action of microorganism on petroleum hydrocarbons. Microbiology, 1975.

Milner C.W.D., Rogers M.A., Evans C.R. Petroleum transformations in reservoirs. Journal of geochemical exploration, N7, 1977.

Vanhala H. Mapping oil contaminated sand and till with the spectral induced polarization (SIP) method. Geophysical Prospecting, 1997, Vol.45, No. 2, p.303-326.