STUDY OF OIL POLLUTION IN AIRPORTS WITH RESISTIVITY SOUNDING

Vladimir Shevnin, Mexican Petroleum Institute, Mexico, E-mail: vshevnin@imp.mx
Aleksandr Mousatov, Mexican Petroleum Institute, Mexico E-mail: amousat@imp.mx
Edgar Nakamura-Labastida, Mexican Petroleum Institute, Mexico
Omar Delgado-Rodríguez, Mexican Petroleum Institute, Mexico, E-mail: omarito_@excite.com
Abraham Mejía-Aguilar, Mexican Petroleum Institute, Mexico
Jose-Luis Sánchez-Osio, Ecoexel S.A. de C.V., Mexico, E-mail: ecoexel1@rtn.net.mx
Hector Sánchez-Osio, Competitividad Ambiental S.A. de C.V. Mexico

Abstract

In this work we consider the resistivity sounding method based on tomographic technology applied for mapping contamination of geological environment with aviation fuel in two airports in Mexico. Vertical electrical sounding allows to map polluted zone in plan and with depth and to estimate qualitatively the contamination grade. The resistivity survey was supplemented by drilling and chemical analysis of oil concentration. The data of direct and indirect measurements have good correspondence with each other. Oil pollution is marked by anomalies of low resistivity and was traced both in plan and with depth. Inverse correlation between grade of pollution and resistivity is found. To separate contaminated and non contaminated zones, a statistical analysis and petrophysical modeling of rock's electrical properties was applied. In one case we found two contaminated layers with high and low resistivity. The lower conductive layer testifies mature pollution, while upper resistive layer means fresh leakage.

Introduction

Oil pollution can occur at all stages of extraction, transportation, refining and distribution of oil products. The losses of oil products can proceed as single fast accidents, which, as a rule, are rapidly found and their consequences are minimized; and as minor leakages, which are not registered for a long time. This second event resembles the underwater part of an iceberg and exceeds the first part on volume. Detection of oil pollution and cleaning contaminated areas are relevant parts in preservation of a clearness of a surrounding medium, considering that oil pollution constitutes up to 80 % of all pollution cases in industrial countries (Geoecological inspection..., 1999).

Traditional direct methods of pollution analysis (drilling and chemical sampling) are expensive, punctual, and not always provide a complete view of a polluted zone. Oil pollution in ground is subjected to bacteria action: as a result of oil biodegradation some organic and inorganic acids are formed, which in turn react with minerals of rocks and form salts, noticeably rising the total dissolved solids (TDS) in a pore moisture. Soils, contaminated with oil products, have initially very high resistivity, but some months after the pollution event as a result of biodegradation, the pollution place exhibits low resistivity. Such zones can be detected with the help of electrical and electromagnetic methods detecting anomaly of low resistivity. The formation of a low resistivity zone was described in detail by the scientists from West Michigan University (W.Sauck, 1988; E. Atekwana et al., 2001). The electric and electromagnetic methods having high efficiency and low operations cost in comparison with drilling and geochemistry, and also integrated effect, allow obtaining the outline of a polluted zone in plan and with depth, that permits reducing the amount of points for drilling and geochemical sampling and to optimize their position. The preliminary use of electrical and EM methods noticeably reduce the volume and cost of drilling and sampling. Resistivity sounding has equal sensitivity to both high resistivity and low resistivity anomalies and close connection with rock properties that provides better interpretation in a petrophysical sense. The authors have used VES methods for oil pollution study in different geological and hydrogeological situations in Mexico (Shevnin et al., 2002, Delgado and Shevnin, 2002).

In the present work for the study of oil pollution in territory of airports in Mexico, the resistivity method (Electrical Resistivity Tomography - ERT) was applied. The advantage of the ERT technology is in the detailed and accurate anomalies tracing. The evident disadvantage of resistivity method is the necessity of galvanic contacts. In case of the earth surface covered by concrete or asphalt, auxiliary drilling is required.

ERT technology allows characterizing oil pollution on following parameters:

Position of pollution in plan and with depth;
Estimation of pollution grade in different parts of the polluted zone;
Estimation of the direction of pollutants migration;
Probable location of the pollution sources.

General information

Field technology

The electrical soundings in airports were performed in areas, where the essential part of the earth surface was covered with concrete. Thus, concrete drilling was needed for grounding electrodes. To simplify drilling, it was performed in contact zones between concrete plates, and electrode separations depended on the plate size. Length of MN was equal to the spacing interval between current electrodes and equal to the plate size: 4.5 m in the first area and 4 m in the second one. The first sounding spacing AO was equal to 1.5 MN, and others spacings grow up to AO = 30-34 m. The sounding step was equal to 2 MN (8-9 m). The soundings were performed with a four-electrode symmetric array.

The technology of oil pollution study with VES tomography has been developed for different geological noise levels. At high noise level, an AMN+MNB array with filtering geological noise is used (Delgado, Shevnin, 2002; Shevnin et al., 2002), while at low noise level the Schlumberger array application is possible. In our opinion, the geological noise in both airports was low, that is why we used the Schlumberger array.

The areas of study in both airports were: the platform – the area for parking airplanes, boarding passengers, luggage and fuel servicing; and the zone of fuel storage. The system of profiles was located so as to fulfill three requirements:

1 – to intercept the basic supposedly contaminated zones;
2 - to have some measurements certainly outside of pollution zone (as a reference area);
3 - to have profiles allocated in the area, in such a way to allow presenting survey results not only as sections, but also as apparent resistivity maps.

Resistivity instrument

A low-frequency alternating-current (5 Hz) instrument designed in the Mexican Petroleum Institute and consisting of a generator and a meter was used. The current of the generator (10-100 mA) was fixed and stabilized, so it did not require measurement. The meter has high EM noise resistance and sensitivity that allows receiving a consistent signal using small currents. Sensitivity of the instrument (minimal measured value) is 10 microV; maximal signal is 250 mV. The internal noise level of the meter is $3*10^{-7}$ V. The measuring accuracy is 2 %. The low frequency allows neglecting the influence of the induction part of an electromagnetic field. The electromagnetic noise can reach 10^{-2} V/m in industrial areas, and noise suppression should be more than 4 orders. Signal attenuation at industrial frequency (60 Hz) should be 10^{-6}, and more than 10^{-4} for frequencies below 0.1 Hz (self potential variations at measuring electrodes) to cancel their influence.

Airport 1

In the area of the first airport 10 profiles of VES (fig. 1) were performed. The separation between electrodes was 4.5 m and the step along profile - 9 m. In total 158 soundings were made.

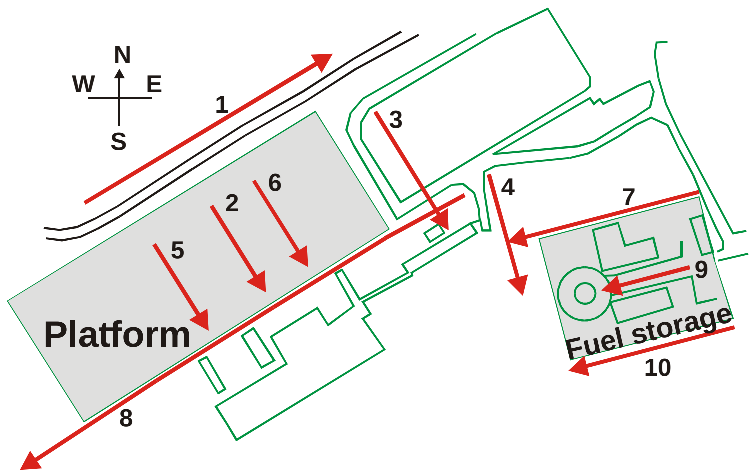

Figure 1.: The scheme of profiles in airport 1.

Geological situation

The groundwater level in this region is at depth of 100 m. The rocks here have high water permeability: On the top there are predominantly sands, and below there are sandstones. In a thick vadose zone the depth position of oil pollution is not clear. It could be concentrated near the surface or deep below.

Criteria of differences between contaminated and non contaminated rocks

For obtaining criterion of differences between contaminated and non contaminated rocks three tools were used: 1 - a statistical VES data analysis; 2 – a preliminary analysis of apparent resistivity maps, pseudo sections and results of quantitative VES interpretation; 3 - petrophysical modeling. In each particular area one of these tools was the most successful. This process was iterative for improving criterion of distinction of the contaminated and non contaminated rocks.

Visualization

The observed data were displayed as apparent resistivity sections, maps, and like different statistical estimations (mean VES curves, curves of dispersions and statistical images). We consider apparent resistivity maps as the most important part of data visualization and field technology aims to receive satisfactory data for this purpose. In ρ_a cross-sections there is frequently some vertical gradient, which makes more difficult to see local anomalies from contamination zone. Pseudo-sections have wider interval of apparent resistivity and this degrade visualizing possibility in the whole interval of ρ_a values. Evident drawback of ρ_a maps is longer distances between measurements for interpolation, than at ρ_a pseudo-sections. The final step of visualization is resistivity section. Frequently in maps and sections we draw additional isolines, separating contaminated and non contaminated areas.

Analysis of results

The first idea of a geoelectrical situation was obtained from apparent resistivity maps. Two pollution zones in apparent resistivity maps (fig. 2 - 3) (for different electrode spacings) are visible, one is located near the fuel storage (to the right) and the other in the platform, where the main pipeline, delivering fuel to airplanes is located. These anomalies are different in amplitude; on the platform these are stronger (and deeper).

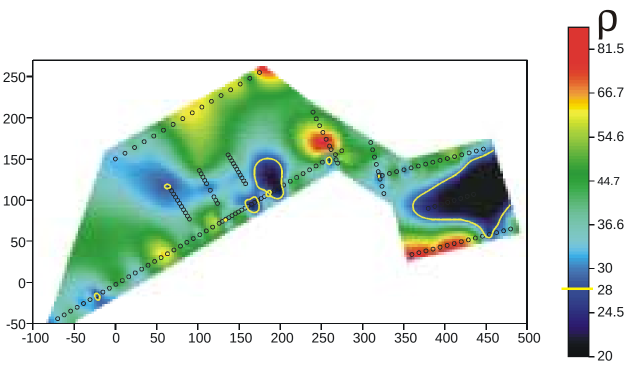

Figure 2.: Apparent resistivity map for AB/2=6.75 m. To the right is the fuel storage area, to the left– the platform.

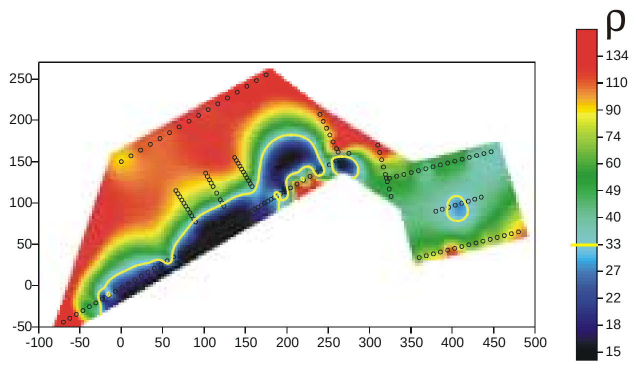

Figure 3.: Apparent resistivity map for AB/2=33.75 m. The zone of low resistivity is near the fuel pipeline.

In general the increase of resistivity with depth is visible in apparent resistivity sections that correspond to a priori geological information. For better visualization and separation contaminated and non contaminated zones on apparent resistivity maps we use different resistivity legends for different maps and different additional iso-resisistivity lines (28 Ohm.m at fig. 2 and 33 Ohm.m at fig. 3). Their values were estimated with statistical data analysis (fig.4).

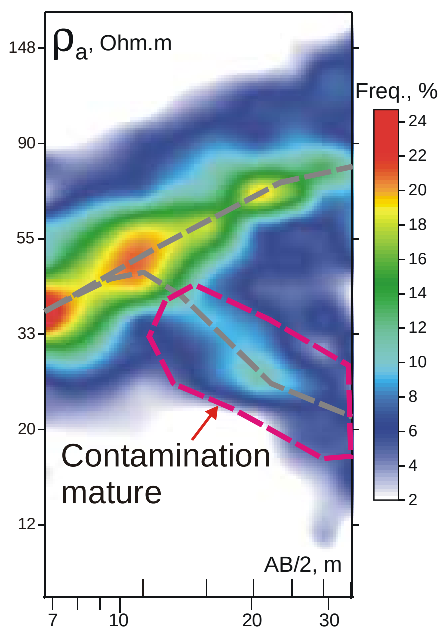

Figure 4.: Statistical ρ_a (AO) image for all profiles.

Statistical data analysis

In fig. 4 the statistical distribution of apparent resistivity values is displayed (in frequencies, in %) for all profiles. Such pictures were used for analysis of both general geoelectrical situation in the area and pollution detection. Additional results of statistical analysis were: mean VES curves for some groups of soundings (fig.5) and graphs of dispersion (standard deviation factor - STDF) for the same groups (fig.6).

In fig. 5 and 6 these graphs are displayed for several groups of data. The mean ρ_a curve for the profile 1 (P1) corresponds to practically non contaminated rocks, the mean curve for profiles 8-2-5-6 corresponds to polluted zone under the platform, where the pollution is clearly noticeable at electrode spacings over 14 m. The graph for profile 9 corresponds to the zone of fuel storage, and curves for profiles 7 - 10 correspond to the area around the same storage. Comparing curves for profiles 9 and 8-2-5-6 it is possible to conclude, that the first case of the pollution is exhibited closer to the earth surface, and the second case starts at some depth, probably because of

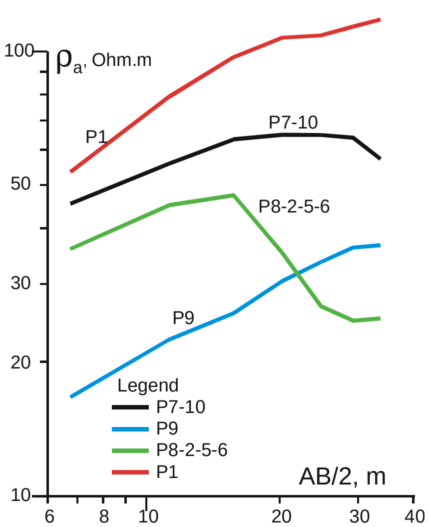

Figure 5.: Mean VES curves for different groups.

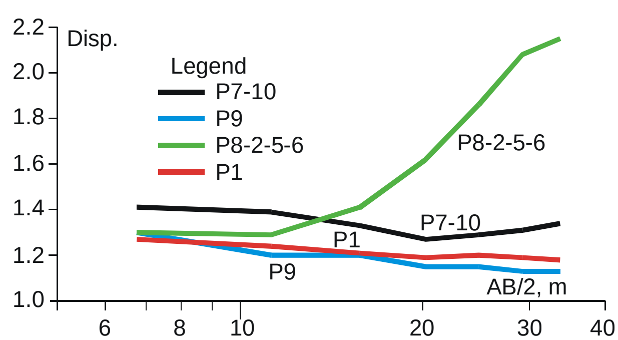

Figure 6.: Dispersion graphs for different groups.

the closer position of profile 9 to the source of leakage and greater remoteness from the source of leakage for profiles 8-2-5-6. Three graphs of dispersions STDF (for profiles 1, 9 and 8-2-5-6) start at the same level of dispersion. Thus the curves of dispersion for profiles 1 and 9 almost coincide. The STDF curve for profiles 7-10 is parallel to curves for profiles 1 and 9, but it is posed a little bit above. As a whole the geologic noise level for these groups is low. The dispersion graph for profiles 8-2-5-6 increases sharply with electrode spacing, this fact is rather typical for the oil pollution zones and reflects the increase of dispersion visible in fig.4.

The quantitative interpretation - was made with the help of the program IPI2Win (designed in Moscow state university with the participation of one of the authors). The advantage of the program is in interpreting each sounding, and forming the result for the profile, the opportunity to control the interpretation process, taking into account additional information, support of constancy or smoothness in variability of resistivities inside each layer and smoothness of layers boundaries.

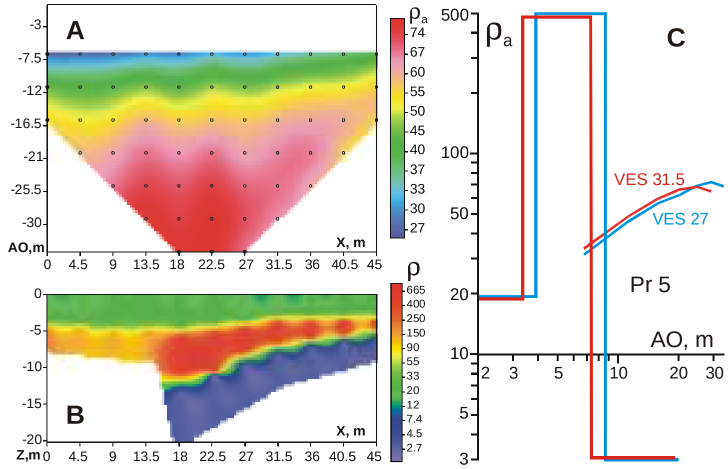

Figure 7.: Pseudo-section (A), vertical section on VES interpretation (B) and typical VES curves (C) for profile 5 crossing the platform. The fuel pipeline is to the right from the end of profile.

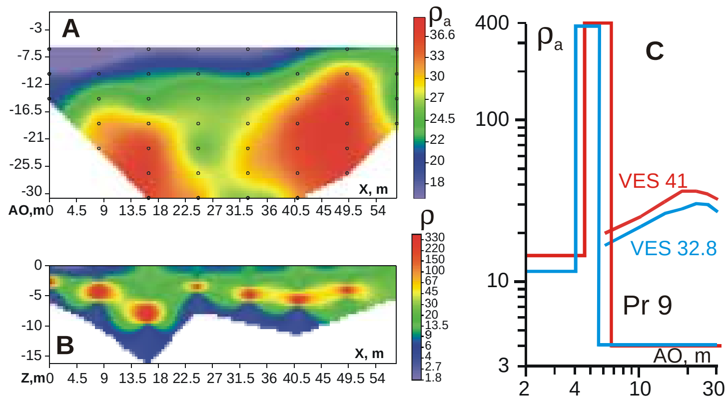

Figure 8.: Pseudo-section (A), vertical section on VES interpretation (B) and typical VES curves (C) for profile 9.

In the vertical section after interpretation (Fig. 7,B) under the platform three layers are detected. The first one is subsoil, below is a high resistivity layer (approximately 500 Ohm.m) and low resistivity layer (less than 10 Ohm.m). In a "normal" section (profile 1) the last two layers are not present. Taking into account all available information, we have decided that the high resistivity layer corresponds to fresh oil pollution, whereas the low resistivity layer corresponds to mature pollution, after bacterial degradation.

A similar vertical section is obtained in the zone of the fuel storage (fig. 8,B). Here there is also a high resistivity layer above and a low resistivity layer under it.

Petrophysical modeling

Petrophysical modeling on our opinion is an essential element of a data analysis (Ryjov and Shevnin, 2002; Shevnin et al., 2002). The calculation of rocks resistivity on the base of underground water resistivity and their comparison with the results of resistivity estimation, received from interpretation, help to understand the geological situation in which the pollution exists, as well as finding differences between contaminated and non contaminated rocks. We managed to extract sample of "water" from "trenches", in which there were pipes with airplanes fuel. The tap water in the area has resistivity of 23 Ohm.m, and that from trenches - 93 Ohm.m, four times higher. The sample had a yellowish color and an oil odor. As a matter of fact it was an emulsion of water with fuel.

To understand rocks resistivity and its changes with porosity, clay content and salinity we calculated (with the help of software Petrofiz (Ryjov, Shevnin, 2002)) resistivity graphs as a function of groundwater salinity for different sandy – clayed rocks presented in fig.9. Because groundwater level is at the depth of 100 m, we suppose that humidity of the upper part is 20% (vadose zone), The legend for this figure is the next:

Line 1 – pure sand with porosity 25%; 2 – pure clay with porosity 50%; 3 – water; 4 – sand-clay mixture with 2% of clay and porosity 24%, 5 - mixture with 4% of clay and porosity 23%, 6 – that with 10% of clay and porosity 20%, 7 – that with 20% of clay and porosity 15%, 8 – that with 30% of clay and porosity 15%, 9 – that with 40% of clay and porosity 20%, 10 – that with 50% of clay and porosity 25%, 11 – that with 70% of clay and porosity 35%, 12 – sand o rock with porosity 10% without clay; 13 - rock with porosity 5% without clay;14 - rock with porosity 2% without clay.

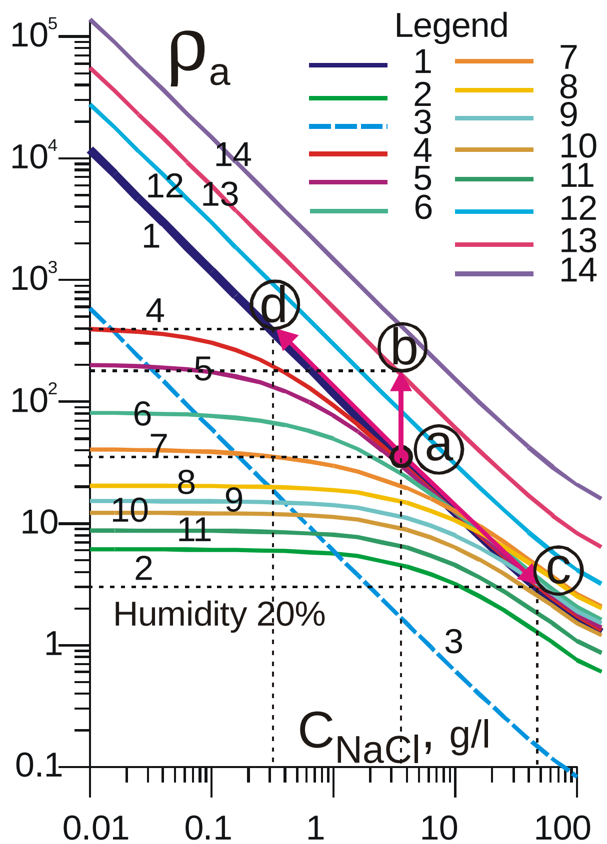

Figure 9.: Petrophysical calculation for different sandy – clayed rocks with 20% humidity.

Base model without contamination for this area (profile 1) has two layers: ρ_1=35 Ohm.m; ρ_2=185 Ohm.m, h_1=3.5 m. For sand (line 1) with porosity 20% and resistivity 35 Ohm.m there is a point "a" in fig.9. At the depth, the porosity becomes smaller (5%) and resistivity grows until 185 Ohm.m (point "b"). Pore water resistivity in this case is 1.7 Ohm.m (arid zone) and salinity (for NaCl) is 3.6 g/l. For the layer with mature contamination (about 3 Ohm.m) salinity grows until 45 g/l (point "c"). Layer with fresh contamination has resistivity of 400 Ohm.m (point "d") and pore water resistivity of 18 Ohm.m.

There is no contradiction between resistivity of water, contaminated with oil fuel from the trench (93 Ohm.m) and this estimation; in pores of rock water change its salinity in comparison with open space for water (in the trench).

Comparison of geochemical and resistivity data

After the resistivity survey the drilling and sampling (only on the territory of the fuel storage) with chemical analysis was made. In fig. 10 the map of oil pollution in plan and the correlation graph between grade of contamination (on chemical data) and ρ_a values are displayed. The map of pollution at a qualitative level coincides well with the low resistivity anomaly in this area. The correlation graph demonstrates that smaller resistivity corresponds to the greater pollution. In the fuel storage area the pollution above the limit of 2000 ppm is not found. The resistivity anomalies on the platform area

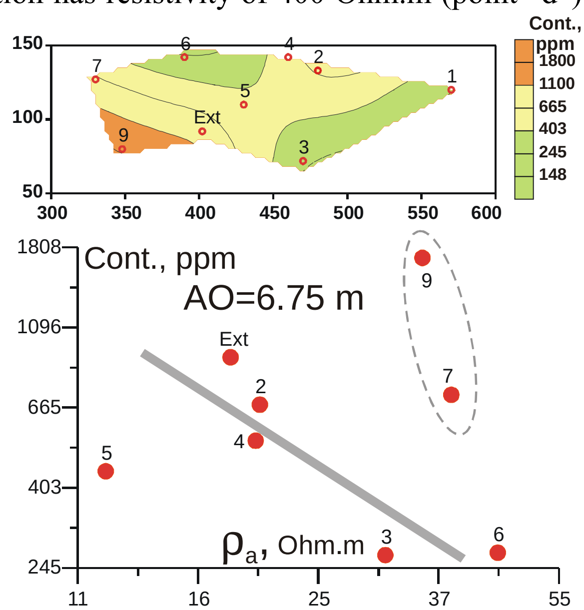

Figure 10.: The map of contamination in fuel storage (above); and correlation graph between contamination and apparent resistivity for AO=6.75 m (below).

are much higher, but drilling and chemical sampling was not performed here.

Airport 2

The technology of field measurement was similar. 296 VES along 15 profiles marked by letters A-O were performed (fig.11). Electrode spacings AO were from 6 up to 30 m, MN=4 m. The profiles are aggregated in several groups: A, K, N, J (interior fuel storage), B, C, D, L - (exterior fuel storage), E, F, G, H, I, O (platform), profile M (road).

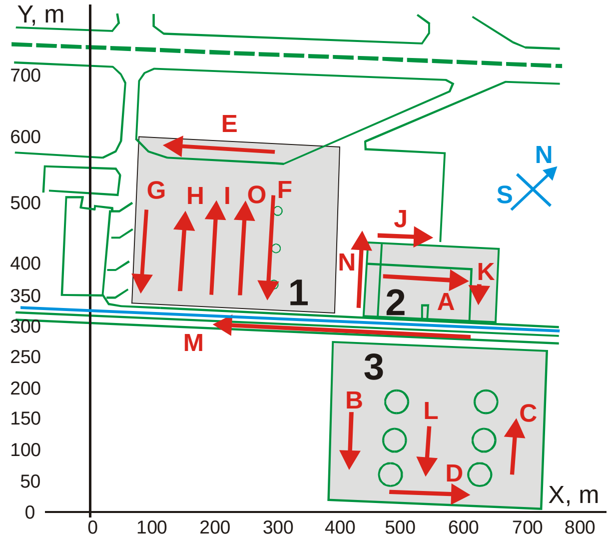

Figure 11.: The scheme of profiles in airport 2. Profiles are marked with arrows and letters A-O. 1-Platform, 2- interior and 3 exterior fuel storages.

We had not enough geological information. We did not know underground water resistivity and rock lithology, therefore our deductions were based more on some estimations, than on the actual facts.

1. In the upper part of earth there is loose material (most probably - the sand), and below there is rocky ground (sandstone, limestone, magmatic rocks).
2. It was very probable to find oil pollution in this area. Most evidently the low resistivity oil pollution was detected under the platform, and also under interior fuel storage (fig. 12-13).
3. There is no evidence (on geophysical data) of the presence of clay or clay materials in this area. The boundary between the contaminated and non contaminated rocks was built under the assumption of the absence of clay component in rocks.

The statistical data analysis of the resistivity data (fig. 14) has shown, that on electrode spacings 6-30 m (AB/2) apparent resistivity values are in interval 40 - 120 Ohm.m. The mean VES curve for the total area looks like a two-layer ascending curve (yellow broken line in fig. 14, B, C, D). The zones marked by a red broken line (fig.14, B, C) probably correspond to oil-contaminated rocks. Such zones are mostly evident in the area of the platform.

Supposing that resistivity value of non contaminated sand was equal to 50 Ohm.m, it would

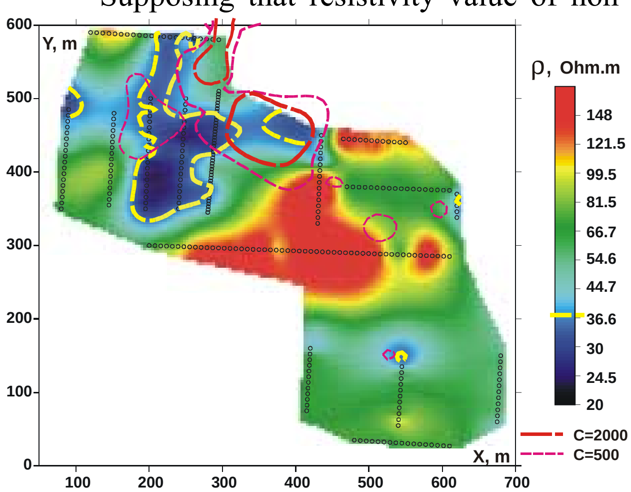

Figure 12.: Apparent resistivity map for AB/2=10 m. To the right are fuel storage areas, to the left is platform area.

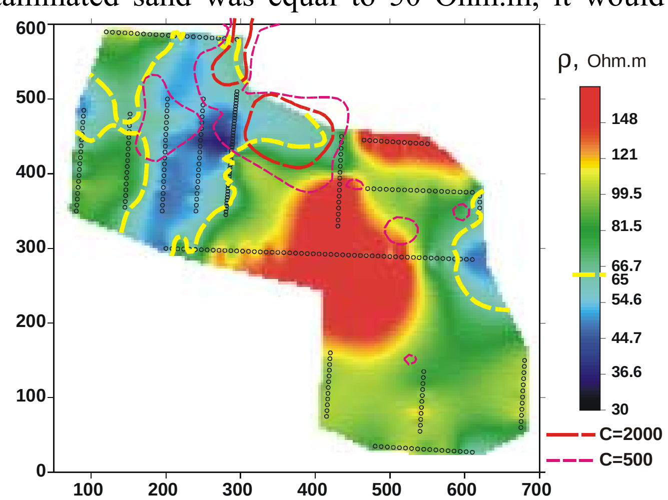

Figure 13.: Apparent resistivity map for AB/2=22 m. Red lines show contamination on chemical data.

mean that ground water has resistivity of 16 Ohm.m and salinity of 0.4 g/l (for NaCl). The porosity of sand was accepted as 25 %. In such situation the contaminated sands should have 10 Ohm.m or below.

This situation becomes more complicated due to variations of apparent resistivity depending on electrode spacing. For mapping areas of pollution on apparent resistivity maps we have added on these ρ_a maps some isolines separating contaminated and non contaminated areas (fig.12-13), different for each electrode spacing (AO): AO=6 - ρ_a 30 Ohm.m, AO=10 - ρ_a 35, AO=14 - ρ_a 48, AO=18 - ρ_a 60, AO=22 - ρ_a 65, AO=26 - ρ_a 70, AO=30 - ρ_a 80 Ohm.m. Examples of apparent resistivity maps for electrode spacings of 10 and 22 m are displayed in fig. 12 and 13. On these maps one resistivity minimum is found under the platform. A small area of low resistivity is found in the interior fuel storage area.

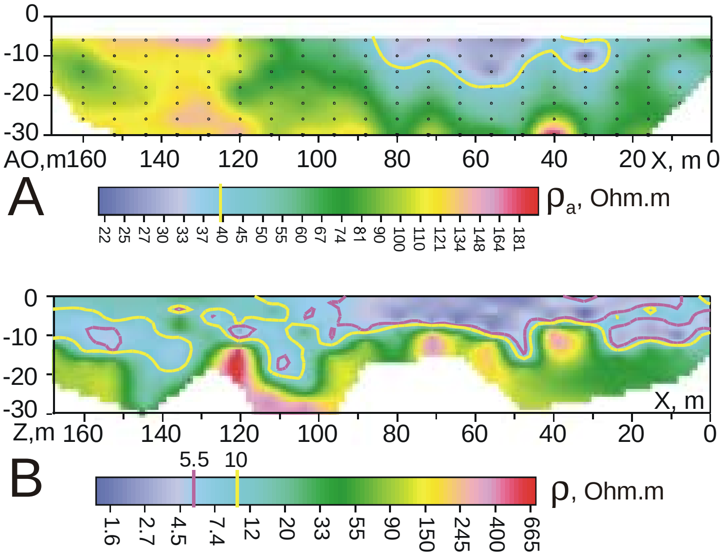

Figure 15.: Pseudo-section (A) and vertical section (B) for profile E.

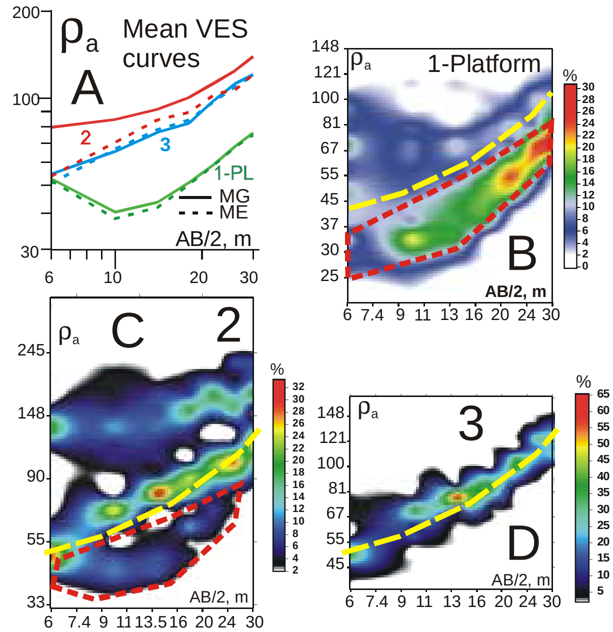

Figure 14.: Mean VES graphs (A) and statistical ρ_a (AO) images for different zones (B,C,D).

Vertical pseudo-section on VES data

As the true resistivity of rocks (on results of VES interpretation) differs from apparent resistivity, also boundary values separating contaminated and non contaminated rocks differ from accepted on apparent resistivity maps. For true resistivity we have considered 10 and 5.5 Ohm.m as such boundary values (fig.15, B).

Petrophysical modeling

As for the case of the airport 1 for airport 2 we also calculated resistivity graphs as a function of

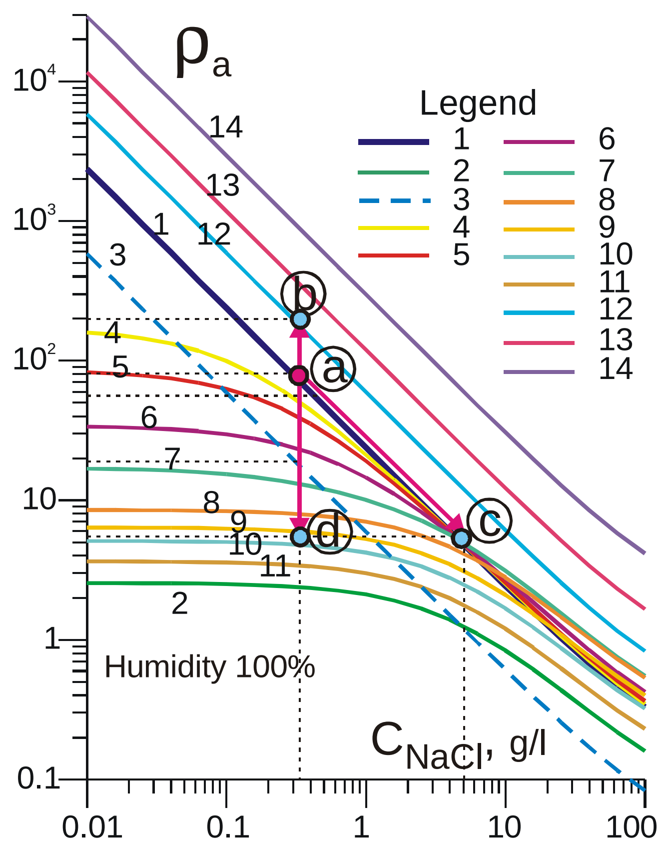

Figure 16.: Petrophysical calculation for different sandy – clayed rocks with 100% humidity.

groundwater salinity for different sandy – clayish rocks presented in fig.16. Because groundwater level is at the depth of 3 m and the first separation AO=6 m, we suppose that humidity of the upper part is 100% (below GWL), The legend for this figure is the same as for fig.9.

Base model without contamination for this area has two layers: ρ_1=55-80 Ohm.m; ρ_2=200 – 250 Ohm.m, h_1=8-10 m. For the first layer - sand (line 1) with porosity 25% and resistivity 55-80 Ohm.m there is a point "a" in fig. At the depth 8-10 m the porosity becomes smaller (8-10%) and resistivity grows until 200 - 250 Ohm.m (point "b"). Water resistivity is this case is 20 Ohm.m (humid zone) and salinity (for NaCl) is 0.33 g/l. For the layer with mature contamination (about 5.5 Ohm.m) salinity grows until 5 g/l (point "c"). Our conclusion about contamination in this area can be true or wrong, because the increase of clay content in the sand until 45% (point "d") can give the same effect as contamination (point "c"). That is why our conclusion needs to be checked with direct methods (chemical analysis).

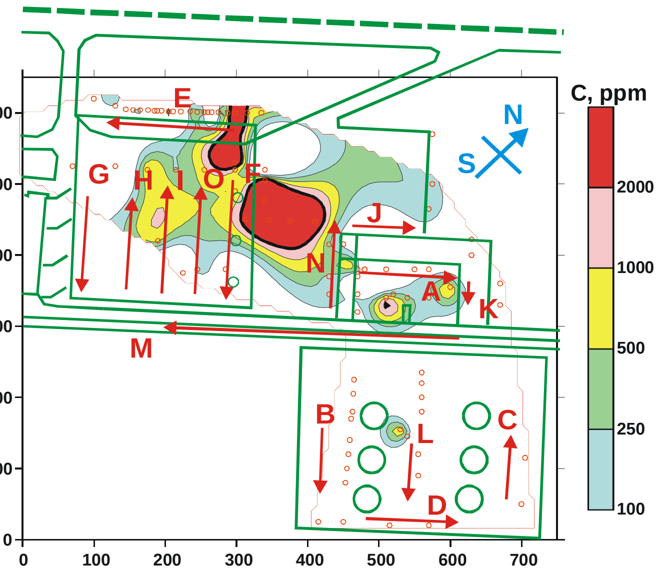

Figure 17.: Map of contamination on geochemical data.

Comparison of geochemical and resistivity data

To estimate pollution by direct methods in the airport territory about 90 wells with chemical analyses of samples were drilled. The map of oil pollution anomalies is displayed in fig.17. On the same figure the position of resistivity profiles is shown. Only after completion of all operations the positions of VES profiles and points of chemical sampling were compared. The basic polluted zone is outside VES profiles. The resistivity profiles cross pollution zone on its flanks, not in epicenter. Nevertheless, the resistivity anomalies marked zones near the basic outline of pollution in the platform, and also marked minor zones of pollution in the interior and exterior fuel storage.

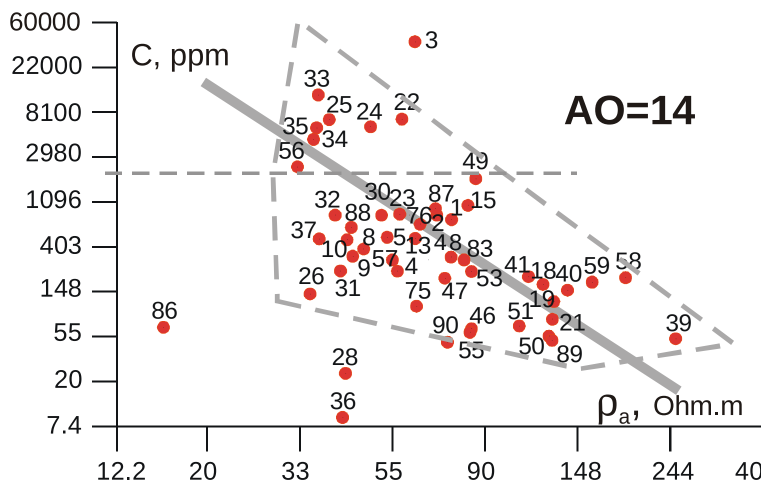

Figure 18.: The correlation graph between apparent resistivity values (for AO=14 m) and the grade of pollution.

In fig.18 the correlation graph between apparent resistivity values (for electrode spacing 14 m) and the pollution grade is displayed. An inverse correlation between values C (ppm) and ρ_a is visible.

Conclusions

The resistivity method on tomographic sounding technology was successfully applied for mapping pollution zones from aviation fuel in two airports of Mexico.

The electrical survey was supplemented by drilling and chemical analysis of oil concentration. The direct data and indirect measurements are well correlated.

Oil pollution is marked by anomalies of low resistivity and has inverse correlation between a pollution grade and resistivity. Such correlation is detected as for areas of a high grade of pollution (above maximum concentration limit), and for minor pollution, that speaks about sufficiently high sensitivity of electrical survey to pollution (in interval between 50 and 20000 ppm).

In polluted areas it is possible to predict the position of source and migration paths.

For the first time a two-layer structure of polluted zone (high resistivity layer above a low resistivity layer) was detected. It is believed, that here we found two zones: one of mature pollution below and another one of fresh pollution above. The presence of resistive zone may indicate, that the source of pollution is still active. In the case of highly resistive layer resistivity sounding has better sensitivity to it in comparison with inductive methods.

References

1. Atekwana E.A., Cassidy D.P., Magnuson C., Endres A.L., Werkema D.D., Jr., Sauck W.A. Changes in geoelectrical properties accompanying microbial degradation of LNAPL. SAGEEP proceedings, 2001. OCS_1.
2. Delgado O., Shevnin V. Application of resistivity sounding method for oil pollution study in urban and rural areas. SAGEEP Proceedings, 2002. 10 p.
3. Cassidy, D.P., Werkema, D.D., Sauck, W.A., Atekwana, E.A., Rossbach, S., and Duris, J. 2001, The effects of LNAPL biodegradation products on electrical conductivity measurements, Journal of Environmental and Engineering Geophysics, vol., 6, p. 47-52.
4. Geoecological inspection of oil industrial enterprises. Ed. - V.A.Shevnin and I.N.Modin. Moscow, RUSSO, 1999, 511 pp. (In Russian).
5. Modin I.N., Shevnin V.A. et al., 1997 Investigations of oil pollution with electrical prospecting methods. Proceedings of the 3rd EEGS-ES Meeting. Aarhus, Denmark, 8-11 September 1997. P.267-270.
6. Ryjov, A. and Shevnin, V., 2002: Theoretical calculation of rocks electrical resistivity and some examples of algorithm's application. SAGEEP Proceedings, 2002. 10 p.
7. Ryjov A.A., Sudoplatov A.D. The calculation of specific electrical conductivity for sandy-clayed rocks and the usage of functional cross-plots for the decision of hydro-geological problems. // In book "Scientific and technical achievements and advanced experience in the field of geology and mineral deposits research. Moscow, 1990, pp. 27-41. (In Russian).
8. Sauck W. A. A conceptual model for the geoelectrical response of LNAPL plumes in granular sediments. SAGEEP Proceedings. 1998, pp. 805-817.
9. Sauck, W.A., 2000 A Conceptual Model for the Geoelectrical Response of LNAPL Plumes in Granulated Sediments, Journal of Applied Geophysics 44/2-3, 151-165.
10. Shevnin, V., Ryjov, A., Nakamura E., Sanchez A., Korolev V., Mousatov A., 2002: Study of oil pollution in Mexico with resistivity sounding. SAGEEP Proceedings, 2002. 10 p.
11. Werkema D. D., Jr., Atekwana E., Sauck W., Rossbach S., and Duris J. Vertical distribution of microbial abundances and apparent resistivity at an LNAPL spill site. SAGEEP Proceedings, 2000.