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USING GROUND PENETRATING RADAR AND PHOTOGRAMMETRY FOR HYDROCARBON POLLUTION ASSESSMENT IN CONTAMINATED AREAS: AN INTEGRATED APPROACH FOR ENVIRONMENTAL MONITORING

Sorin ANGHEL

National Institute for Research and Development on Marine Geology and Geoecology -GeoEcoMar, 23-25 Dimitrie Onciul, District 2, Bucharest, Romania

Corresponding author email: soanghel@geoecomar.ro

Abstract

This paper presents the use of ground-penetrating radar (GPR) and photogrammetry in the assessment and monitoring of hydrocarbon contamination in polluted areas. The integrated approach combines the advantages of both techniques to provide a detailed image of pollution distribution in the soil and potential migration pathways of contaminants. The GPR, used to detect underground anomalies, was complemented by photogrammetry to obtain accurate mapping of the microrelief and terrain structure. The studies were conducted through electrical resistivity measurements and field surveys, with the collected data being integrated into a detailed geophysical model. This combined method allowed for the identification of hydrocarbon accumulation zones and their migration according to the geological structure and infiltration conditions. The results obtained are essential for understanding the impact of pollution on the surrounding environment and for developing efficient solutions for monitoring and rehabilitating affected lands.

Key words*: contamination, hydrocarbon, monitoring, photogrammetry, soil.*

INTRODUCTION

The detection and monitoring of hydrocarbon contamination in the geological environment (soil, geological formations, and groundwater) represent key objectives of geophysical investigations in areas adjacent to refineries. Investigations were carried out in zones neighboring refineries with industrial activity exceeding five decades, located near the city of Năvodari, particularly around the Petromidia refinery. Both “classical” geophysical techniques (VES – vertical electrical sounding) and recently introduced methods on a global scale (GPR – ground-penetrating radar and photogrammetry) were used. Electrical and electromagnetic measurements were accompanied by magnetic investigations, drilling works, as well as geological and hydrogeological observations. Among all methods, the most effective geophysical measurements for both detection and monitoring of subsurface hydrocarbon contamination were the geoelectrical resistivity surveys, due to the significant electrical resistivity contrast between the highly resistive pollutants and the more conductive geological medium consisting of rocks and fluids (Popescu et al., 2019). Geological and hydrogeological data from shallow boreholes were used to correctly interpret geophysical anomalies, while the results of magnetic measurements indicated the path of buried pipelines - potential sources of pollution - and, in some cases, the presence of unexploded military ordnance, buried remnants of the intense bombings refineries were subjected to during the last world war. Hydrocarbon contamination of soils and groundwater in the vicinity of refineries, fuel depots, oil extraction sites, and even transport pipelines represents one of the major challenges in environmental protection. Currently, the localization and determination of the spatio-temporal distribution of contamination rely almost exclusively on direct biochemical analyses of soil and water samples taken from the surface or from boreholes. However, such information is point-based and, therefore, cannot provide a comprehensive picture of land and groundwater contamination. Moreover, these analyses are costly and time-consuming. The integration of point-based information into

a three-dimensional spatio-temporal image of hydrocarbon-contaminated areas and residual water becomes possible through the appropriate use of geophysical methods supported by hydrogeological data.
Implementing a geophysical research program for the spatio-temporal monitoring of hydrocarbon contamination resulting from refining, storage, and transportation activities near the refinery located in the Năvodari area represents the only viable solution for assessing the degree of soil contamination. The development of such a program requires simultaneous geophysical and hydrogeological investigations over different time intervals (time-lapse investigations), both in areas with a high contamination potential and in uncontaminated zones, in order to validate the hydro-geophysical research approach.

MATERIALS AND METHODS

Field data acquisition was carried out in the industrial area of the Petromidia refinery, using an integrated approach that combined ground-penetrating radar (GPR), aerial photogrammetry, and vertical electrical soundings (VES).
Areas with a high potential for contamination were investigated through vertical electrical sounding measurements using AGI MINISTING equipment. The GPR system used was a NOGGIN model produced by Sensors & Software, equipped with a set of antennas operating at frequencies between 100 and 500 MHz, which provided good resolution and penetration depending on the local geological conditions.
For photogrammetry, a DJI Phantom IV Pro drone equipped with a high-resolution camera was used. The flight missions were planned and executed using DJI Terra software, which enabled precise coverage of the investigated area.
Data georeferencing and high-accuracy positioning in the field were carried out using a TRIMBLE RTK GPS system.
The data processing was performed using specialized software packages (Res2DInv, EarthImager, and EKKO-Project) and integrated into a three-dimensional geophysical model that reflects the 3D spatial distribution of the contaminants.

Geophysical measurements for the detection of hydrocarbon contamination

For the geophysical detection of subsurface hydrocarbon pollution, various geoelectrical techniques (VES) and GPR were used.
The most effective proved to be the vertical electrical soundings (VES). VES measurements were carried out using AGI MINISTING-type instruments along profiles crossing areas affected by hydrocarbon pollution. The observation data were processed and interpreted using specialized software programs (Res2DInv, EarthImager, IP2WIN – Figure 1).
The analysis of vertical electrical sounding curves performed in the area of the Petromidia refinery confirmed that, from a geoelectrical point of view, two main patterns of electrical resistivity distribution in depth can be identified in the investigated region:

- Representative H-type VES curves in the northeastern area of the Petromidia refinery;
- Representative K-type VES curves in the southwestern area, adjacent to the Danube–Black Sea Canal.

The main difference between these two sectors, characterized by distinct variations in electrical resistivity, lies in the presence of a conductive clay layer at the upper part of the geological structure in the north-eastern area - a layer that is absent in the south-eastern zone (with K-type VES curves).
This clay layer, also intercepted in shallow boreholes, provides substantial protection to the northeastern zone, resulting in significantly reduced hydrocarbon contamination compared to the south-western area.
The rapid increase in electrical resistivity observed in the VES measurements conducted in the south-western zone is due to the presence at shallow depth (1–2 meters) of a resistive layer that includes a film of pollutants and geological formations impregnated with petroleum products. The processing and quantitative interpretation of VES data led to the generation of resistivity sections down to a depth of 10 meters along the profile directions in the investigated areas.

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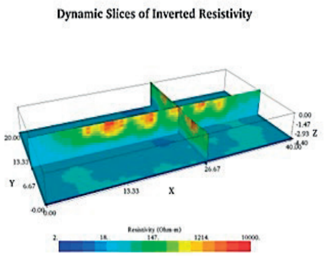

Figure 1. 3D electrical resistivity section obtained within a perimeter located in the immediate vicinity of the refinery

The outlined high-resistivity anomalies illustrate the presence of hydrocarbon contamination plumes at depth. Geoelectrical resistivity measurements using the vertical electrical sounding (VES) method were continued to detect hydrocarbon and industrial wastewater pollution in the geological environment, allowing for a more detailed delineation of previously identified anomalies (Marin et al., 2020). On profiles arranged in parallel with 5-meter spacing, clear benefits were observed in terms of the resolution with which geophysical anomalies could be identified. As an example, we present the 3D electrical resistivity section obtained within a perimeter located in the immediate proximity of the refinery (Figure 1).

In the field of geophysical detection of subsurface hydrocarbon contamination, electrical resistivity measurements were continued using the vertical electrical sounding (VES) method with the Schlumberger array, resulting in improvements in both the processing and graphical presentation of the data obtained.

RESULTS AND DISCUSSIONS

The high potential of Vertical Electrical Sounding (VES) and Ground Penetrating Radar (GPR) in detecting subsurface hydrocarbon contamination was demonstrated through the geophysical measurements carried out in this study. Among the applied geophysical methods, VES proved to be the most effective, using AGI MINISTING-type instruments along profiles located in areas known to be affected by hydrocarbon pollution.

The identification of two distinct patterns of vertical electrical resistivity distribution in the VES curves allowed for their classification into:

- H-type curves, representative of the northeastern sector of the refinery. The "H" symbol reflects the curve shape, suggesting a sequence of high resistivity (dry or sandy layer) – low resistivity (wet clay, mud, or saturated material) – high resistivity (sands or compact rocks) in the vertical profile;
- K-type curves, corresponding to the southwestern area, near the Danube–Black Sea Canal. The "K" symbol refers to a curve shape that suggests a low resistivity layer (clay or wet soil) – high resistivity (dry sand or hydrocarbon-contaminated material) – low resistivity sequence.

There are essential differences between these two sectors in terms of contamination risk assessment. The presence of a conductive clay layer near the surface in the northeastern zone, also confirmed through shallow boreholes, highlights the existence of natural protection against pollutant migration, resulting in significantly reduced contamination. In contrast, the southwestern zone lacks this protective layer. High-resistivity anomalies at shallow depths (1–2 meters) in this area may indicate the presence of a layer contaminated with hydrocarbons.

Through the quantitative interpretation of the VES data, 3D resistivity sections were generated (Figure 1), highlighting resistivity anomalies associated with subsurface contamination plumes. The resolution and accuracy in delineating the affected zones were significantly improved by conducting measurements along profiles spaced at 5-meter intervals.

Photogrammetry data were integrated with the geophysical results, adding a precise spatial component to the analysis. This integration enabled a direct correlation between surface conditions and subsurface structures. The integrated approach represents a valuable tool for planning remediation strategies at contaminated sites and provides a solid foundation for long-term environmental monitoring.

GPR (GROUND PENETRATING RADAR) MEASUREMENTS

Given the significant scientific interest presented by the perimeter located in the northeastern area, Ground Penetrating Radar (GPR) measurements were carried out using a 500 MHz antenna (Figure 3). During the data processing (Figure 2) phase, horizontal sections corresponding to depths of 0.5 m, 1 m, and 2 m were generated.

The study of amplitude variations and stratigraphic discontinuities was conducted as part of the data interpretation process. The results, presented in Figure 2 as a radargram, can be interpreted both in terms of shallow geological structure - highlighting the presence of local tectonic features - and in terms of the boundary between hydrocarbon-saturated and unsaturated zones.

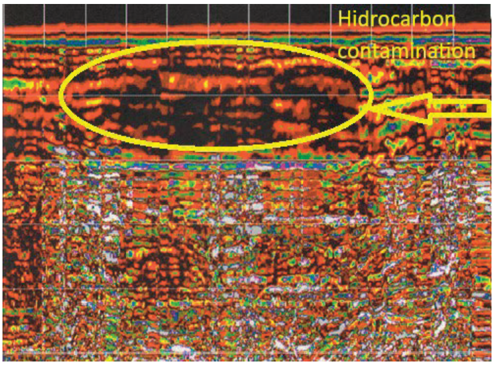

Figure 2 Radargram showing the boundary between the hydrocarbon-saturated and unsaturated zones

The hydrocarbon contamination front, resulting from the overlap of historical and current contamination, is largely influenced by the regional dynamics of the aquifer (Dobre et al., 2017).

Figure 3. Data acquisition using GPR NOGGIN

MAGNETOMETRIC MEASUREMENTS

Magnetometric measurements were continued by creating panels in the investigated area to identify potential damaged underground pipelines from which pollutants may be leaking into the subsurface.

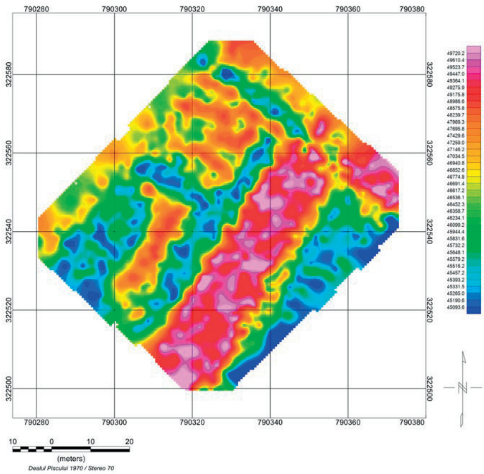

Figure 4. Map of horizontal magnetic field variation measured using a G864 cesium magnetometer with real-time GPS positioning

The magnetometric measurements were performed with an accuracy of 0.1 nT, using a proton precision magnetometer (Geometrics 856) to measure diurnal variations, and a cesium magnetometer (G864) for continuous measurement and real-time positioning of the measurements. Total horizontal magnetic field measurements were conducted with the sensor placed 0.8 meters above the topographic surface. Magnetometric measurements for the diurnal variation correction were conducted at specific stations for each investigated area, with the magnetic sensor positioned 1.3 meters above the ground and a sampling interval of 10 minutes. Detailed magnetometric measurements were executed continuously, with real-time positioning. Magnetometric measurements were carried out in a network of parallel profiles spaced 2 meters apart. The profile network in the Petromidia refinery area was positioned considering its proximity to the railway and the electrical line built along it.

Significant magnetic disturbances were observed along the investigated profile routes, caused by the presence of buried metal structures or pipelines at shallow depths (figure 4 – red-coloured zones). The modelling of magnetic high anomalies using the PotentQ software allows the determination of the shape, inclination, and position of the body that generated the anomaly (Georgescu et al., 2022).

PHOTOGRAMMETRIC INVESTIGATION AND CREATION OF THE DIGITAL TERRAIN MODEL

This results in the creation of a Digital Terrain Model (DTM) for multiple critical areas (with high pollution levels), including the geophysically investigated perimeters. The detection of fine topographic details, such as microrelief or anthropogenic structures that may influence the pollution dynamics, is closely related to high spatial resolution. The extensive coverage allows for the rapid mapping of large areas, reducing time and costs compared to traditional methods (Tudor et al., 2021). The photogrammetric method involves identifying changes in the terrain and highlights areas where industrial activities or accidental hydrocarbon spills have caused visible disturbances to the soil.

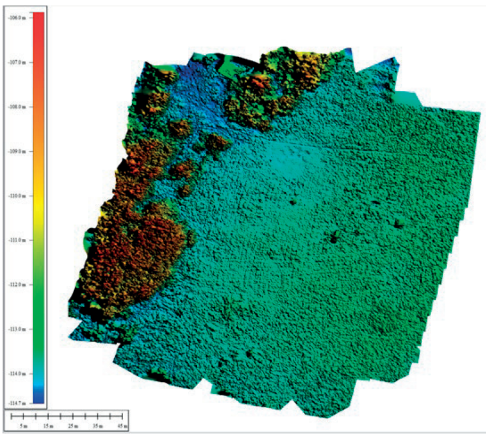

Figure 5. Digital Terrain Model (DTM)

This method plays a crucial role in identifying polluted areas by creating the Digital Terrain Model (DTM), which provides essential information for investigating hydrocarbon contamination, such as:

- Identifying areas without vegetation, which may indicate soil contamination with hydrocarbons, especially in areas where the alternation between vegetation and barren zones has been observed.;
- The identification of potential hydrocarbon spill paths, especially on gently sloping terrains that facilitate surface migration, can be determined using 3D models. The local relief obtained from the DTM allows for the delineation of areas at risk of contamination.

Digital models enable the correlation of the topography of the investigated area with the measured resistivity, so that even minor elevation variations can influence the distribution of sandy stratification.

The optimal positioning of Vertical Electrical Soundings (VES) and GPR profiles in areas susceptible to pollution depends on the accuracy of the Digital Terrain Model (DTM-Figure 5). Topographic features identified through photogrammetry can be used to confirm the correctness of interpretations and can be compared with resistivity anomalies during the geophysical data verification process.

For the creation of the Digital Terrain Model (Figure 5) corresponding to the area adjacent to the Petromidia refinery, photogrammetric targets were placed in the field. A DJI Phantom 4 drone was used to carry out the mission at an altitude of 30 meters.

CONCLUSION

The electrometric methods (VES) and GPR revealed resistivity anomalies and subsurface structures associated with the presence of hydrocarbons. In these areas, 2D and 3D maps confirmed the existence of localized contaminant concentrations, without evidence of large-scale spreading (Figure 1).

The drillings carried out allowed the identification of the groundwater table at a depth of 1.7 meters and of the sand layers contaminated below this level (Ionescu et al., 2018). These results confirmed the geophysical data and validated the interpretations regarding the presence of hydrocarbons in areas with high resistivity. The collected data were integrated into a detailed hydrogeophysical model that highlighted low-intensity contamination, without regional migration of hydrocarbons. The model enabled the identification of possible directions of local migration, as well as a clear delineation of areas of interest. Geophysical, hydrogeological, and photogrammetric methods were integrated to provide a multidisciplinary approach and accuracy in the interpretation of results, contributing to the reduction of uncertainties associated with the investigations.

Figure 6. Hydrocarbon contamination of the geological formation located above the water table, due to seasonal variations

Geophysical methods represent an indispensable tool in identifying soil areas contaminated with hydrocarbons, allowing for rapid and detailed detection of anomalies without destructive interventions on the ground. Essential information about the internal structure of the soil and the presence of pollutants (Figure.6) can be obtained through the use of vertical electrical soundings (VES) and GPR measurements, contributing to the assessment of soil quality and the precise delineation of affected areas.

A correct interpretation of soil contamination, achieved by integrating geophysical methods with topographic and hydrogeological data, can support informed decisions for long-term remediation and monitoring. The generation of the digital terrain model using drone technology enabled not only the detailed mapping of microrelief features but also the accurate correlation of geophysical data with surface conditions. This approach proved useful in identifying vegetation-free zones and depressions, which are susceptible to hydrocarbon accumulation.

The direction of migration is influenced by the sandy structures and the presence of the groundwater table, while areas of maximum resistivity correspond to local hydrocarbon accumulations.

The integration of data from various sources enhances the robustness of the hydrogeophysical model, so that the correlation of geophysical, photogrammetric, and hydrogeological data allowed for a deeper understanding of pollution distribution, providing a solid model for future risk management.

Preventing the deterioration of soil quality and ensuring a safe growing environment for plants depends on continuous soil monitoring using geophysical methods. The impact of pollution on soil structure and fertility, through the integration of geophysical, hydrogeological, and photogrammetric data, is essential for the effective management of agricultural lands. Implementing appropriate solutions for soil rehabilitation and maintaining an ecological balance favourable to agricultural crops depends on identifying areas with high contamination risks using the ground-penetrating radar (GPR) method.

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