Applied Geophysical Challenges for Environmental Engineering in the Baltic Sea Region

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Abstract: - Landfills and dumps mark the end of a product's life cycle but often contain valuable secondary raw materials, posing both environmental risks and untapped resource potential. This study highlights the use of near-surface geophysical methods to map and characterize buried waste without excavation. These methods, including active/passive and invasive/non-destructive techniques, can explore depths from decimeters to tens of meters and are applied via both static setups and mobile platforms. Case studies performed in Latvia and Sweden demonstrate the effectiveness of geophysical surveys applying specifically proton magnetometry, induced polarization, and electrical resistivity in identifying hidden dumpsites and analyzing their contents. These techniques help assess the physical properties of buried waste materials, offering spatial insights into waste distribution and site structure. The findings underscore the role of geophysics in locating secondary raw materials and support advanced landfill mining strategies, contributing to environmental management and resource recovery.

Key-Words: - Abandoned dumpsites, geophysical methods, environmental assessment, hidden waste, landfill mining, secondary raw materials, subsurface mapping, waste characterization.

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1 Introduction

Geophysical investigation methods are easily accessible for application but often challenging to interpret within complex environmental issues, such as those attributed to landfills and dumps. Various shallow exploration techniques are applicable, including ground-penetrating radar (GPR) tomography, magnetic, gravimetric, and electromagnetic (EM) surveys, as well as microseismic surveys. The induced polarization (IP) method provides insights into near-subsurface properties, offering information on structure, texture, underground fluids, and cracks, [1].

While geophysical methods are primarily used for mineral exploration, their application is expanding to address environmental, hydrological, and other challenges related to urban and industrial sites, often in conjunction with the application of geographic information systems (GIS) techniques, [2], [3], [4], [5]. Electrical resistivity has been utilized in studies related, for example, to environmental contamination detection, geotechnical investigations, hydrogeology, pollution flow, and leachate research, [6], [7], [8].

If municipal waste in landfills or dumpsites is not appropriately managed, it can become a source of contamination at moderate to heavy levels. Older landfills, often referred to as dumps, are frequently concealed from passersby's view, and their location may even be unknown to the public, [9], [10], [11]. These abandoned areas of dumps can negatively impact the quality of the surrounding environment and contaminate food chains in the long term, [12]. Understanding precipitation and analyzing the waste mass matrices are essential for assessing hydraulic flows and considering geomorphological features. The structure and location of such sites are crucial for effective and sustainable landfill and dumpsite closure projects, [13].

EM and GPR methods have been used to examine soil and sediment matrices, including those contaminated with pollutants, [14]. This paper focuses on applying EM and proton magnetometer studies. The goal was to propose an efficient approach for screening and mapping the sites with concealed waste material, where even the basic information on their location is often lacking. The issue of hidden dumpsites is of high topicality in terms of long-term environmental safety and material recovery; furthermore, the waste management industry seeks efficient and reliable solutions.

2 Insight into Case Studies

2.1 Ground Magnetic Proton Magnetometer Survey

Earth's magnetic field fluctuates over all time scales; however, fast changes, with time-spans of seconds to years, result from solar-driven currents in the ionosphere and magnetosphere. Slower, but long-term variations stem from the Earth's internal geodynamo. To separate these effects, continuous and precise magnetic field measurements are necessary. Therefore, geomagnetic observatories worldwide provide such data, often supported by repeat stations, [15], [16].

Secular variation studies are limited by the sparse distribution of magnetic observatories, which restricts regional analysis and interpretation. While regional magnetic surveys, conducted by most European countries since the early 20th century, offer higher spatial resolution, they provide less accurate and continuous data. Two types of surveys exist: (a) ground vector surveys, which map the internal geomagnetic field with dense networks but are rarely repeated, and (b) repeat station surveys, which track secular variation at fixed points every few years with higher accuracy. Repeat station data are ideal for studying secular variation; however, many countries conduct only one type of survey. The surveys vary widely in terms of spatial and temporal coverage, which affects data consistency. Accuracy issues emerge less from instruments and more from "reduction errors" due to temporal differences in measurements and assumptions about uniform external field effects. Using observatory data to standardize measurements can introduce errors. Ideally, variometers at repeat stations should be used to correct and avoid errors, as recommended by the International Association of Geomagnetism and Aeronomy (IAGA), [17], [18].

Absolute geomagnetic measurements are crucial not only for navigation and targeted detection but also for calibrating relative measurements. The problematic aspects involve integrating data from different magnetometers, which is challenging due to varying operating principles and difficulties in implementing simulations. For absolute secular variation data, the time-span is centuries, and it depends on global-scale changes in the Earth's entrails. In Latvia, a country in northeastern Europe, the expedition aimed to survey various areas to identify the best location for a future undisturbed presence of a stationary variometer station, thereby enhancing the global measurement network.

Expeditions utilizing profiling measurements using a PHP-5 proton magnetometer were conducted along specific routes, ensuring consistent and relevant adjustment of geomagnetic data. The primary aim of the research was to establish a location for a variometer to support geophysical and geodetic network purposes. The sessions of repeated measurements and mapping were conducted across Latvia, adhering to a predefined model.

The region surveyed was located in eastern Latvia, in a forested, moraine-hilly area with complex mobility and infrastructure challenges. A significant part of the surveyed area was situated in a swampy depression near the coordinates N56º06'22'', E27º24'58''. The gradiometer survey routes were designed to align with normal ionospheric conditions. Both distant and near gradiometer networks were measured, with orientations selected along the NS and WE profiling directions. The step length for the long gradiometer network profile was approximately 80-100 m, while the detailed gradiometer network had a step size of about 1-2 m. Additionally, the gradient of vertical changes in the geomagnetic field was determined.

The relative heights chosen for the survey were 3.0 m, 2.5 m, 1.65 m, 0.7 m, and 0.1 m.

During the survey, the long gradiometer network profiling points unexpectedly revealed an anomaly, with an amplitude ranging from hundreds to thousands of nT (nanotesla). This anomaly was associated with a closed (possibly illegally filled) dumpsite located to the west of the survey area; see grey spot on the west of point No. 10.0 (Figure 1).

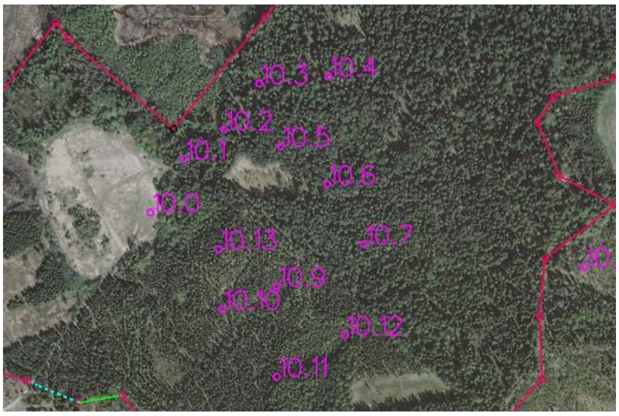

Fig. 1: Profiling points of the gradiometer survey and detected anomaly near point No. 10.0 at a hidden dumpsite in Latvia
Source: created by the authors

This anomaly was not recognized in remote mode, but proton-magnetometer measurements enabled contouring of intense disturbances from a dump. The anomaly was mapped, and the surrounding area was excluded from the planning of the geomagnetic variometer station.

The geomagnetic field at points No. 10.1 to 10.12 was uniform, with variations ranging from 0.1 to 0.5 nT. However, at point No. 10.0 and in the grey area, respectively, the dumpsite, where detailed studies were conducted, the variations increased significantly, reaching numbers of several hundred up to 4000 nT. During the investigation, the average background of the Earth's magnetic field, measured with the PMP-5 proton magnetometer, was found to be between 50,000 and 51,000 nT in this region, [19].

2.2 Integration of Geological-Geophysical Methods at Industrial Dumpsite

A comprehensive set of geological, environmental, and geophysical studies was conducted in southern Sweden (Figure 2) to support the prospective excavation of disposed waste masses as a secondary raw material source combined with remediation efforts in the area contaminated by the glass production industry. The aim was to gather information on the quantity and characteristics of buried waste, which consisted of a mix of industrial glass and construction waste, [11]. The geophysical part of the study was carried out using EM and induced polarization (IP) methods.

Fig. 2: Dumped construction and glass waste heap buried under forest soil and vegetation at Älghult landfill in Sweden
Source: created by the authors

Electrodes were profiled and connected to a series of multielectrode cables arranged along three lines, each 100 m apart, with 300 m long profiles covering the disposed of waste masses buried under vegetation (Figure 3). Electric current was passed through various pairs of electrodes to measure potential differences. Direct current pulses with alternating polarity and IP measurements were carried out using an electrode selector and multi-core electrode cables. Stainless steel electrodes were spaced 1 m apart, and the land masses were moistened to ensure good horizontal and vertical resolution. The resistivity values for the dumpsite ranged from 1,000 to 3,000 Ωm, typical for densely packed construction and demolition waste. However, areas with glass waste were identified where resistivity exceeded 6,000-7,000 Ωm.

Several challenges for future investigation of similar waste disposal dumpsites can be highlighted as follows: (a) historical archive data on landfill and dump areas and preliminary assumptions are essential for identifying site-specific anthropogenic geomorphological features when setting up profiling for EM, IP studies, and magnetometry; (b) EM and IP studies face limitations in data acquisition when dealing with excessive porosity and underground voids; (c) magnetometry is more effective when background anomaly data are known; (d) the remediation of the Älghult and Flerohopp sites in Sweden is approximated to be complex, as 50-80% of the estimated waste consists of construction and demolition waste; furthermore, glass waste recycling in general is complicated; (e) while magnetometry is a faster screening method than EM profiling, IP data can provide better recognition compared to basic electric profiling.

Fig. 3: Setting the instrument for geophysical screening at an industrial dumpsite in Sweden for measurements of conductivity and electric resistivity with the induced polarization system
Source: created by the authors

Geophysical methods provide non-invasive tools for assessing landfills and dumpsites, where low resistivity values are observed. For example, at the Weidenpesch landfill in Germany, EM surveys were combined to map the boundaries of the landfill area and to assess the level of contamination. Low resistivity values (1-50 Ωm) indicated the main waste masses, contrasting with the high-resistivity surrounding soils, [20]. Variations in conductivity and magnetic susceptibility reflect material heterogeneity. Repeated surveys may reveal temporal changes, emphasizing the value of ongoing monitoring. This integrated approach has proven its efficiency in landfill characterization and sustainable environmental planning.

2.3 GPR Study of Buried Technogenic Soil

The origin of technogenic (human-made) sediments is primarily linked to industrial anthropogenic activities such as mining, construction, and waste disposal. A case study was conducted at the Jaunmilgravis site in Riga Freeport, Latvia, on technogenic buried soil by applying GPR research.

In three selected areas of the site, the enhanced concentration of heavy metal-containing sediments was determined during excavation works, primarily originating from rusted parts of former industrial infrastructure. However, advanced profiling is always necessary in technogenic (filled soil) sediments, as they are heterogeneous and exhibit unpredictable characteristics.

The GPR data correlated well with geological data obtained from borehole measurements. A high-pass frequency filter was used at 81 soundings per second, and noise reduction was performed using Prism2.5 software (Figure 4).

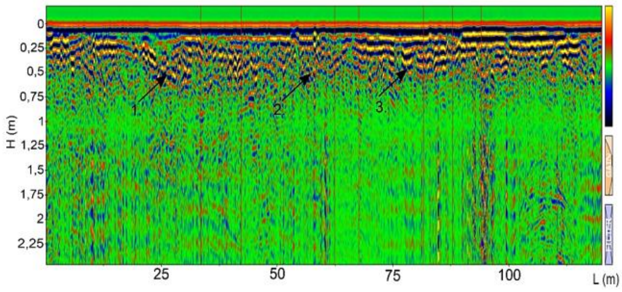

Fig. 4: Output of dual-channel GPR (Zond-12e) radar profiling using a 900 MHz antenna system at the Jaunmilgravis site in Latvia (created by the authors)

According to calculations, the industrial technogenic soils at the Jaunmilgravis site were estimated to be 1,264 tons or 15 kg/m² within the superphosphate slag area. The amount of particular metals and metalloids was estimated at 755 t for copper, 85 t for lead, 358 t for zinc, and 66 t for arsenic, while iron and manganese were present in hundreds of thousands of tons, representing a significant economically usable volume. In some locations, the target concentration of metals and metalloids exceeded 30 g/kg.

Several signals associated with soil heterogeneities can be identified in the obtained radar profiles. The composition and structure of technogenic sediments vary and depend on the waste management technologies employed. Usually, these sediments are outlined in detailed geological engineering maps and can be identified in industrial site plans; however, historically contaminated areas may remain hidden in the long term.

3 Conclusion

Municipal and industrial landfills and dumpsites require remediation to maintain environmental sustainability, as a significant portion of the disposed waste can be recycled into valuable secondary raw materials, and the abandoned areas can be repurposed to meet society's needs. To implement targeted remediation, geophysical research methods complement geotechnical and geological investigations by offering a comprehensive view to link anthropogenic layers beneath the surface.

Magnetometry and electromagnetic methods are effective for mapping and identifying geomorphological features of various types of dumps. These techniques allowed for identifying boundaries for old, buried municipal and construction-demolition waste mixed with glass. Using a proton magnetometer is a quick and valuable approach for assessing the magnetic properties of the background. Furthermore, when combined with data from remote sensing or geology, it simplifies the planning of contours for anthropogenic dumps and urban mining sites.

Electromagnetic studies revealed that resistivity values vary depending on the composition of construction and demolition waste, such as waste fines, concrete, glass, and organic materials with higher moisture content. In this case, geophysical methods, particularly magnetometry and electromagnetic studies, serve as cost-effective tools for preliminary investigations and mapping of landfills for remediation and recycling projects.

Combining magnetic, electrical resistivity, and ground-penetrating radar (GPR) methods provides a more accurate and comprehensive understanding of subsurface conditions. Each method detects different soil and material properties, e.g., magnetic surveys reveal ferrous materials, resistivity highlights moisture and layering, and GPR provides high-resolution imaging of buried structures and waste or sediment masses. This multi-method approach reduces uncertainty and improves the reliability of geotechnical assessments. It helps identify potential hazards, such as voids, buried waste, or unstable ground, before construction begins. Ultimately, integrating these methods supports safer, more cost-effective project planning and sustainable design.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

The authors wrote, reviewed, and edited the content as needed, and they did not utilize artificial intelligence (AI) tools. The authors take full responsibility for the content of the publication.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- Juris Burlakovs: conceptualization, investigation, writing – original draft, resources.
- Martins Vilnitis: data curation, investigation, writing – original draft, validation.
- Maris Krievans: methodology, formal analysis, data curation, visualization, software.
- Zane Vincevica-Gaile: writing – review and editing, visualization.
- Yahya Jani: conceptualization, methodology, investigation, data curation, validation.

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Conflict of Interest

The authors have no conflicts of interest to declare.