Adıyaman University
Journal of Engineering Sciences
Adyü J Eng Sci 2026;13:e260119
Adıyaman Üniversitesi
Mühendislik Bilimleri Dergisi
Adyü Müh Bil Derg 2026;13:e260119
https://doi.org/10.54365/adyumbd.1807473

Research Article / Araştırma Makalesi

Determination of Waste Thickness of the Closed Solid Waste Site, Halkalı,Istanbul, Türkiye

Halkalı, İstanbul, Türkiye'deki Kapalı Katı Atık Sahasının Atık Kalınlığının Belirlenmesi

Fethi Ahmet Yüksel [1], **Nihan Hoşkan** [2*]

[1] L.N. Gumilyov Eurasian National University, Faculty of Economics, Department of Tourism, Astana,Kazakhstan
[2] İstanbul Üniversitesi-Cerrahpaşa, Mühendislik Fakültesi, Jeofizik Mühendisliği Bölümü, Büyükçekmece, İstanbul,Türkiye

Abstract

The aim of this study is to analyze the closed Halkalı solid waste landfill in Istanbul using Ground Penetrating Radar (GPR) in order to evaluate the depth and spatial distribution of accumulated waste. The landfill, which operated between 1983 and 1994, has raised concerns regarding its future usability due to potential environmental risks. The research focuses on Menekşe Valley, located between the Menekşe and Hasanoğlu streams, and aims to determine whether the remaining waste thickness at the site poses a potential contamination threat, particularly in the context of increasing urban development interest. GPR surveys conducted with 38 MHz and 75 MHz antennas revealed waste layers at depths ranging from 5 to 15 meters, indicating significant heterogeneity within the study area. These findings may suggest a potential environmental risk associated with leachate generation due to rainwater infiltration; however, a more reliable assessment would require detailed characterization of the leachate and/or systematic monitoring of groundwater quality. The results of this study are of great importance for assessing the site's suitability for development, shaping environmental policies, and providing scientific data to support land-use planning.

Keywords: *: GPR, Halkalı,Istanbul, Leachate, Solid Waste Site, Waste Thickness.*

Öz

Bu çalışmanın amacı, atık birikimlerinin derinliğini ve yayılımını değerlendirmek amacıyla Yer Radarı (GPR) kullanarak İstanbul'daki kapatılmış Halkalı katı atık sahasını analiz etmektir. 1983 ile 1994 yılları arasında faaliyette olan bu çöp sahası, çevresel riskler açısından gelecekteki kullanılabilirliği konusunda çeşitli endişelere yol açmıştır. Araştırma, Menekşe ve Hasanoğlu dereleri arasında yer alan Menekşe Vadisi'ne odaklanmakta ve özellikle artan kentsel gelişimi bağlamında, sahada kalan atıkların kalınlığının tespit edilmesiyle potansiyel bir kirlilik tehdidi oluşturup oluşturmadığını belirlemeyi amaçlamaktadır. 38 MHz ve 75 MHz antenlerle gerçekleştirilen GPR araştırmaları sonucunda, 5 ila 15 metre derinlikte atık tabakaları tespit edilmesi, çalışma alanında önemli heterojenite bulunduğunu göstermiştir. Bu bulgular, yağmur suyunun yeraltına sızması sonucu oluşan sızıntı sularıyla ilişkili potansiyel bir çevresel riski işaret ediyor olabilir; ancak daha güvenilir bir değerlendirme için sızıntı sularının ayrıntılı bir şekilde karakterize edilmesi ve/veya yeraltı suyu kalitesinin sistematik olarak izlenmesi gerekmektedir. Çalışmanın sonuçları, sahanın imara uygunluğunun değerlendirilmesi, çevre politikalarının şekillendirilmesi ve arazi kullanım planlamasına bilimsel veri sağlanması açısından büyük önem taşımaktadır.

Anahtar Kelimeler: *GPR, Halkalı, İstanbul, Sızıntı Suyu, Katı Atık Sahası, Atık Kalınlığı.*

* Corresponding e-mail (Sorumlu yazar e-posta): nihan@iuc.edu.tr
Received (Geliş Tarihi):20.10.2025, **Accepted (Kabul Tarihi):** 06.05.2026

1. Introduction

The rapid pace of industrial development and uncontrolled urban population growth have placed significant strain on environmental resources, resulting in pollution emerging as a critical global issue. Among the various environmental challenges, solid waste mismanagement has become especially severe in densely populated urban centers. Improperly managed landfills pose serious threats to soil and water quality, public health, and regional biodiversity. As cities expand, the pressure to repurpose old landfill sites for new development further complicates efforts to manage their environmental impact. Accordingly, earth and environmental scientists have increasingly focused on understanding and mitigating pollution risks associated with closed landfill sites, employing a variety of geophysical methods to assess subsurface contamination and its potential spread. In this context, for example, electromagnetic terrain conductivity surveys have primarily yielded successful results in delineating the boundaries of landfill sites [1–2] and in detecting contaminant plumes within leachate [3]. Similarly, investigations of groundwater contamination in solid waste disposal areas using the electrical resistivity method have been conducted, providing comprehensive insights into the depth, volume, and moisture distribution of the waste within the study area [4-6]. In addition to these approaches, more advanced techniques are frequently employed to determine the base of abandoned landfill sites, including high-resolution seismic reflection and refraction methods, as well as passive surface wave analysis and horizontal-to-vertical spectral ratio (HVSR) measurements. These methods are particularly effective in landfill environments where wave velocities are likely to be lower than those of the surrounding soil or underlying bedrock [7–9].

In recent years, GPR has emerged as a particularly effective tool for investigating subsurface conditions within landfill sites, alongside other commonly used geophysical methods such as electrical resistivity tomography (ERT), electromagnetic (EM) surveys, and seismic techniques. Compared to these methods, GPR stands out due to its high-resolution imaging capability, rapid data acquisition, and effectiveness in detecting shallow subsurface heterogeneities, making it especially suitable for delineating waste stratigraphy and identifying zones affected by leachate. By using high-frequency electromagnetic waves, GPR can detect variations in material properties, enabling the identification of waste thickness and the presence of leachate within landfills. In solid waste disposal sites, GPR surveys are employed alongside the electrical resistivity method to determine waste thickness [10–12]. Furthermore, GPR has also been used in studies investigating the contamination of groundwater by landfill leachate [13–16].

The utility of GPR in providing rapid, non-invasive, and cost-effective data has led to its widespread application in landfill studies, where it helps to map contamination zones, evaluate site stability, and assess environmental hazards before further land use.

This study focuses on the Halkalı Wild Solid Waste landfill in Istanbul, Türkiye-a site spanning approximately 1.5 million square meters, which was operational from 1983 until its closure in 1994. Positioned north of the Marmara Sea, west of Istanbul's urban center, and adjacent to Küçükçekmece Lake (Fig. 1), the landfill area represents a significant environmental legacy, shaped by decades of rapid urban expansion and insufficient waste management planning [17].

In 1994, following a methane explosion at Istanbul's Ümraniye landfill, local authorities closed the Halkalı landfill due to its high risk of methane buildup and other pollution hazards. Mitigation efforts following the closure included the installation of temporary methane venting pipes and the application of a soil cover to stabilize the site and reduce leachate exposure. Initial plans considered converting the area into an Olympic park, but after further review, the site was ultimately earmarked for residential development. Historical studies have underscored the environmental impact of the Halkalı landfill, particularly concerning its effects on local water quality. Avcı et al. [18] conducted early analyses on groundwater contamination by sampling from nearby observation wells, revealing the infiltration of landfill leachate into aquifers. Building on this, Kayabalı et al. [4, 17] employed hydrochemical and resistivity techniques to delineate contamination zones and identify specific pollutants affecting groundwater quality. They

identified localized contamination plumes near the seepage points in the Menekşe Valley, exhibiting minimal dispersion and limited impact on groundwater, and recommended ongoing monitoring and remediation efforts to mitigate further pollution. In 2006, Demirci et al. [19] utilized remote sensing and GIS data to evaluate the impact of landfill activities on Küçükçekmece Lake, uncovering pronounced patterns of water pollution, while Yüksel [14] investigated the extent of water pollution relative to waste depth at the site.

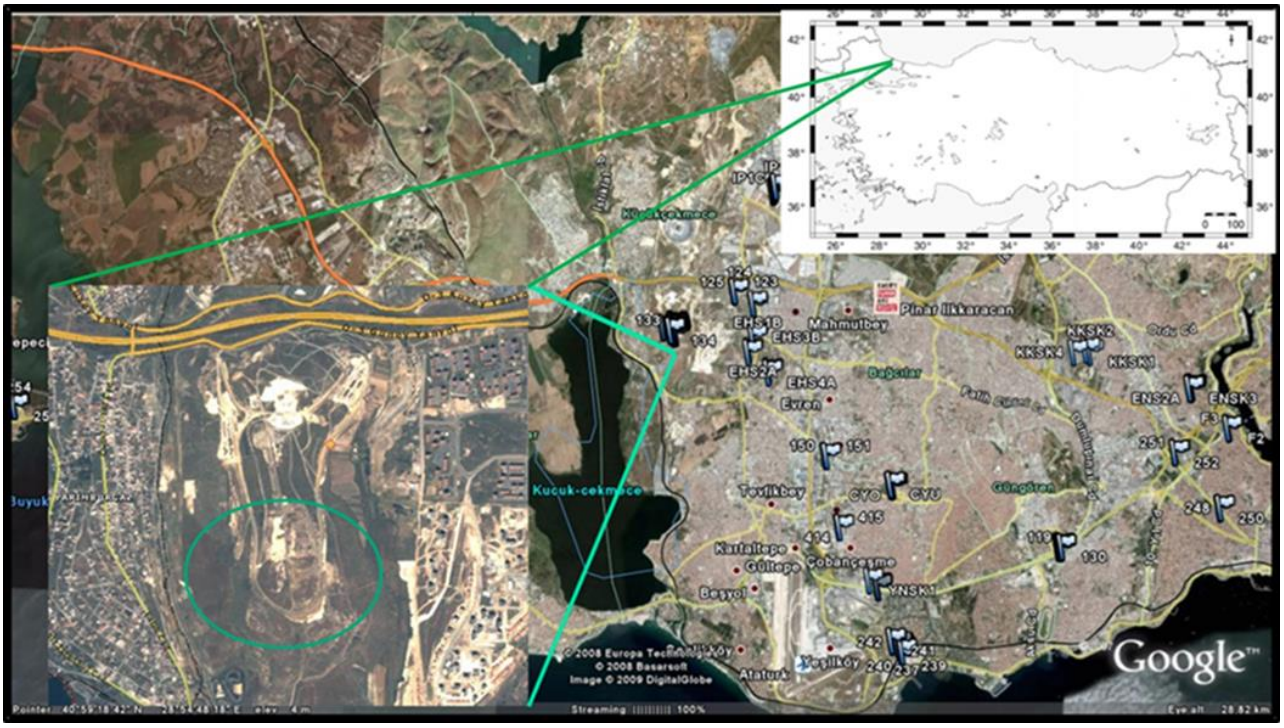


Figure 1. The location of the study area (www.googleearth.com).

The objective of this study is to utilize GPR data obtained from profiles to characterize the thickness and spatial variability of waste deposits across the Halkalı landfill. While previous studies on landfill sites have predominantly focused on groundwater contamination and gas emissions[4, 17-19], relatively limited attention has been given to the assessment of subsurface conditions in the context of post-closure land use, particularly for residential development. In this regard, the present study aims to address this gap by providing a detailed geophysical characterization of waste distribution and heterogeneity to evaluate the site's suitability for safe urban expansion.

Given the designation of the landfill area for residential development, this research offers site-specific insights that are directly relevant to land-use planning and risk assessment. Furthermore, the findings contribute to the broader environmental geoscience literature on urban land reclamation by integrating geophysical data into decision-making processes. They also provide a foundation for future policymaking and sustainable site management in areas where former landfill sites are being reconsidered for development.

2. Material and Method

The closed Halkalı solid waste site is situated west of Istanbul and north of Küçükçekmece Lake, positioned on a ridge that lies between the Menekşe and Hasanoğlu creeks (Fig. 1). Geologically, the site comprises two distinct formations. The bedrock is characterized by interbedded layers of moderately hard, fractured clayey limestone and marl of the Eocene epoch, the latter being relatively soft and weakly cemented [20]. Additionally, an alluvial formation occupies the valleys of the Menekşe, Hasanoğlu, and Nakkaş creeks, where sediments have accumulated over time [4, 17] (Fig. 2, Fig. 3(a)).

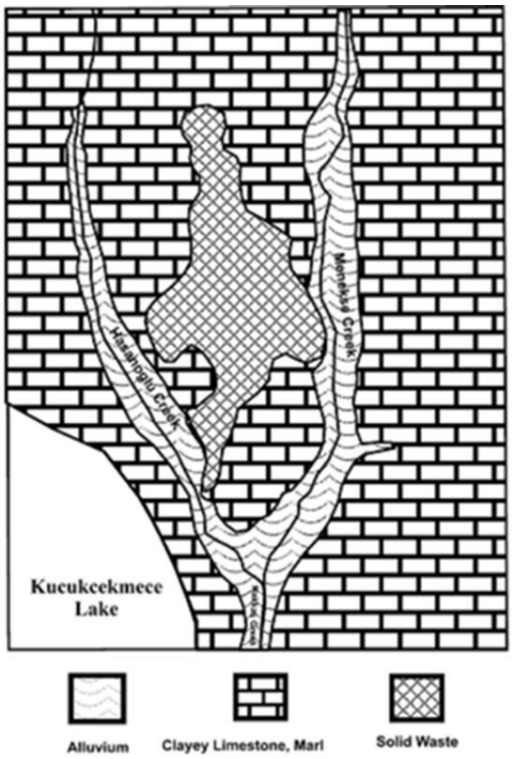


Figure 2. Geological map of the study area (modified from Kayabali et al. [4, 17]).

The bedrock strata exhibit an east to southeast dip, with an inclination of approximately 10 degrees. As reported by Kayabalı et al. [4, 17] , the thickness of the alluvial deposits within the Hasanoğlu and Nakkaş creek valleys ranges from 0.2 to 2 meters. A satellite image from 1999, provided by Istanbul's local authorities, illustrates the state of the area before extensive reclamation efforts (Fig. 3(b)). Subsequent reclamation activities persisted until 2009, as depicted in a satellite image from that year (Fig. 3(c)). Comparative analysis of these two images reveals substantial reclamation undertakings aimed at reducing the risk of methane explosions and securing waste deposits with sufficient cover. Figure 3(d) presents a map showing changes in the cover layer between the two periods, where white areas denote excavated zones, and black areas indicate regions designated as landfill sites.

One of the principal advantages of the GPR method lies in its capacity to generate high-resolution subsurface images, with a resolution ranging from a few centimeters to several meters [21-23]. GPR, typically employed for detecting subsurface structures or landfill boundaries, achieves spatial mapping by transmitting electromagnetic waves in the frequency range of 1–1000 MHz [23]. These waves are reflected in accordance with the dielectric properties of the subsurface materials and are captured by receiver antennas. The recorded data undergo processing to enhance image clarity and improve resolution.

The GPR method has been extensively utilized for the detection of underground pipes and cables [24], in archaeological investigations [25-29], in mineral exploration [30], and for addressing environmental challenges associated with landfill sites [31-32].

In Fig. 4 landfill site and methane venting pipe are shown. The southeastern section of the Halkalı waste disposal site was surveyed along three GPR profiles (Fig. 5). The starting and ending points of each profile were established via GPS measurements and subsequently mapped onto a Google Earth overlay to maintain spatial accuracy.

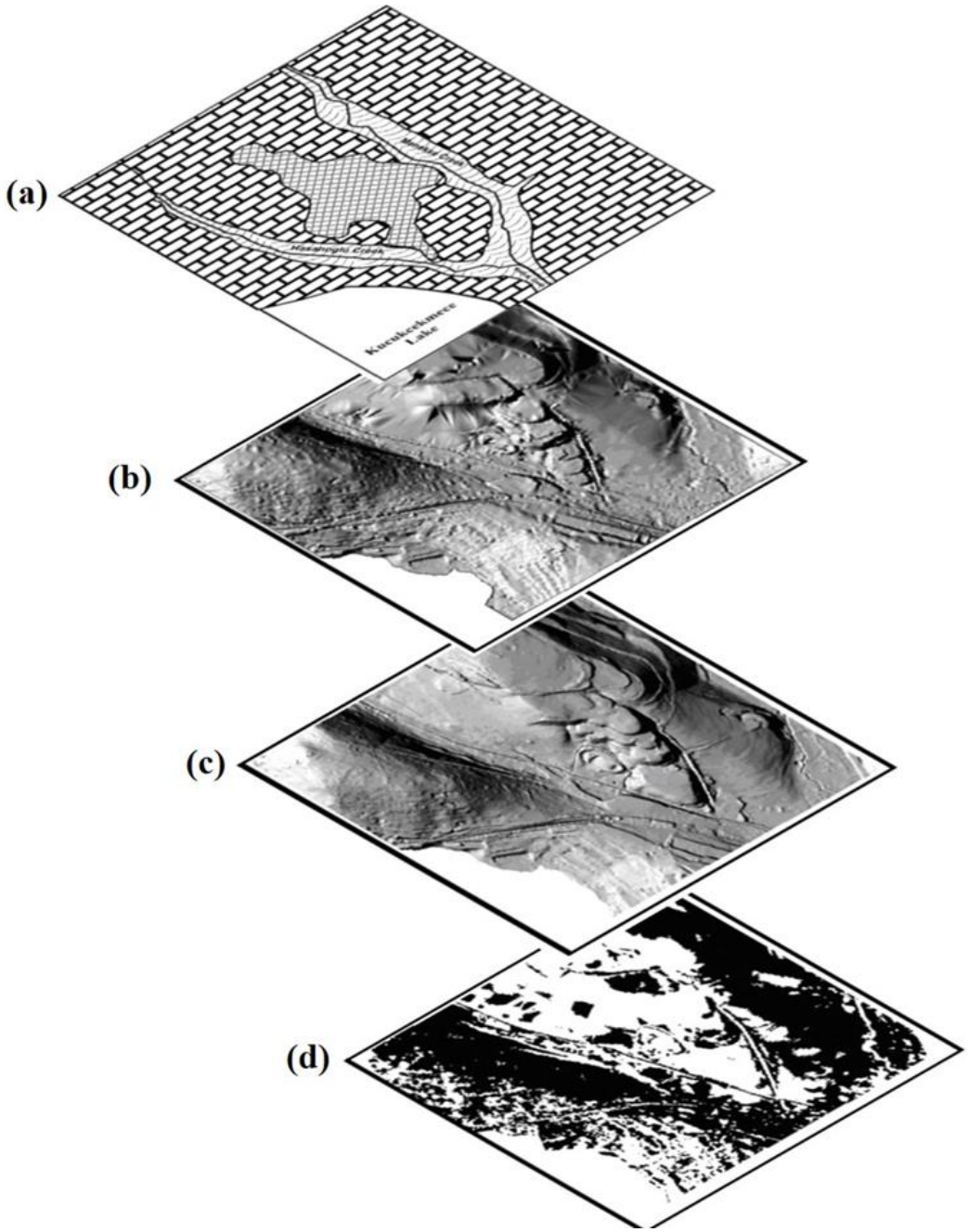


Figure 3. (a) Geological map of the study area (b) Satellite image of the study site obtained in 1999 (www.googleearth.com) (c) Satellite image of the study site obtained in 2009 (www.googleearth.com) (d) The map showing the difference between satellite image 1999 and satellite image 2009 (the white colored part shows the area that was excavated by the local government, the black colored part demonstrates landfills areas).

At Lirung Glacier, Nepal, debris thickness was successfully measured using GPR, and the authors concluded that the method is highly effective for mapping the spatial distribution of debris cover [33]. They further emphasized a three-way trade-off among penetration depth, measurable thickness range, and uncertainty. In the present study, data acquisition was performed using a ZOND-12E system equipped with 38 MHz and 75 MHz antennas, since this antenna configuration provides an optimal compromise between penetration depth and resolution [21–23]. Lower-frequency antennas, such as 38 MHz, provide greater penetration, allowing the detection of deeper waste layers within the landfill (up to 30 meters in this study), but with lower resolution. Conversely, higher-frequency antennas, like 75 MHz, offer higher resolution, which improves the ability to identify finer details, such as buried infrastructure and localized leachate zones, but with a more limited penetration depth. By using both frequencies, the

study was able to capture both the overall waste distribution at depth and the detailed subsurface features, providing a comprehensive characterization of the landfill site. This dual-frequency approach is a common practice in GPR studies of heterogeneous sites, such as landfills, where both depth and detail are important for environmental and land-use assessments.

Data processing was conducted with Prism 2.5 software. A pulsar voltage of 200 volts was applied. Noise reduction involved horizontal low-pass, de-noising, and band-pass filtering. Signal enhancement was achieved using amplitude gain adjustments, and the scan rate was set to 56.



Figure 4. A view of the landfill area (temporary methane venting pipe is shown).



Figure 5. GPR profiles location obtained from GPS measurements (www.googleearth.com).

3. Results and Discussion

The study area is characterized as an uncontrolled solid waste landfill containing a considerable amount of metallic and heterogeneous waste materials. Such uncontrolled disposal sites typically exhibit irregular internal stratification, variable compaction, and complex moisture conditions, which strongly influence geophysical responses. GPR surveys were therefore conducted to evaluate waste thickness, internal heterogeneity, and possible leachate-related anomalies within the closed landfill area. Figure 6 presents the radargram obtained from Profile Line-1, oriented southeast and extending 95 m in length, acquired using a 38 MHz antenna. The interpreted waste thickness along this profile varies between approximately 5 and 7.5 m. In addition, zones of signal attenuation and disrupted reflector continuity suggest active leachate production or moisture-enriched waste materials. Similar radar responses have been widely reported in previous landfill investigations, where conductive leachate reduces signal penetration and causes chaotic or weak reflections [9–13].

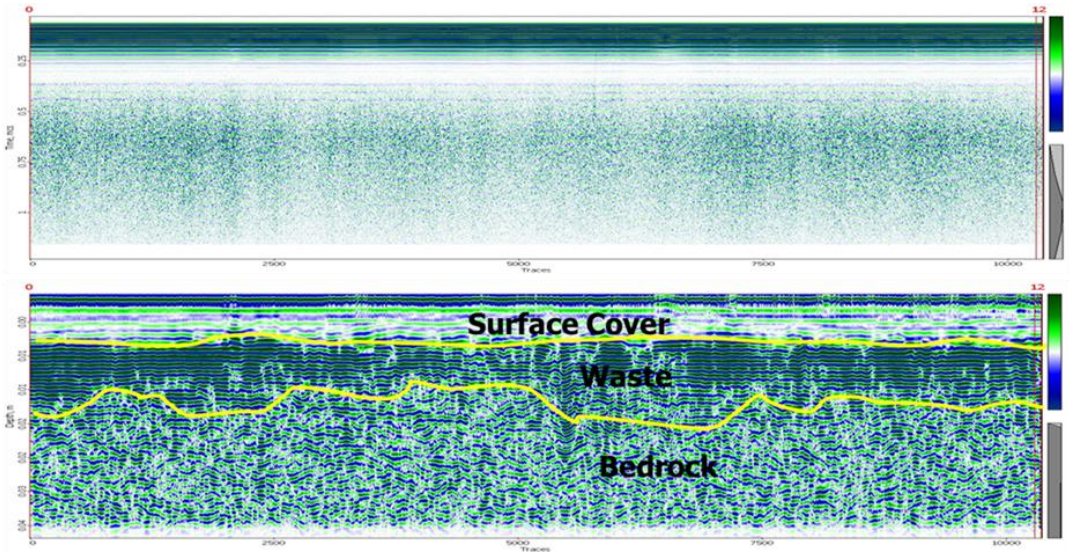


Figure 6. (a) Raw data (b) Radargram obtained from Line-1 profile.

The radargram from Profile Line-2, also oriented southeast and measuring 73 m, indicates a thicker waste body ranging from approximately 8 to 10 m. Prominent anomalous zones interpreted as leachate accumulations were identified between 23–28 m and 60–70 m along the profile. These localized anomalies likely correspond to preferential fluid accumulation zones controlled by waste heterogeneity, permeability contrasts, settlement depressions, or irregular compaction. Comparable findings have been reported in older uncontrolled landfill sites lacking engineered liners and drainage systems, where irregular moisture migration commonly develops within the waste mass [10,14,16–18]. In contrast, modern sanitary landfills generally display more organized internal layering and more controlled leachate movement due to the presence of basal liners and leachate collection systems [4,17–19].

Profile Line-3, oriented southeast and extending 125 m, was surveyed using a 75 MHz antenna. The resulting radargram indicates heterogeneous subsurface distribution to depths of approximately 15 m, suggesting deeper waste accumulation or complex buried materials (Fig. 8). However, portions of the profile exhibit reduced data quality and poor reflector continuity. This is most likely related to site-specific conditions such as high moisture content, metallic debris, signal scattering, and electromagnetic attenuation. These limitations are consistent with previous studies emphasizing that landfill environments are among the most challenging settings for GPR interpretation due to strong contrasts in dielectric properties and the abundance of conductive materials [11,13,18, 33].

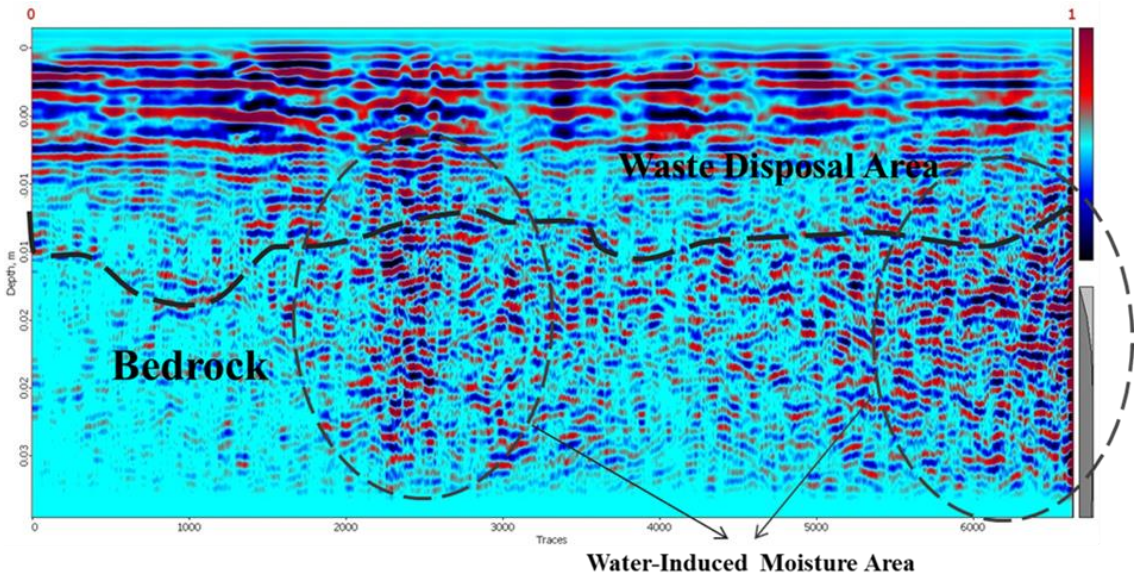


Figure 7. Radargram obtained from Line-2 profile.

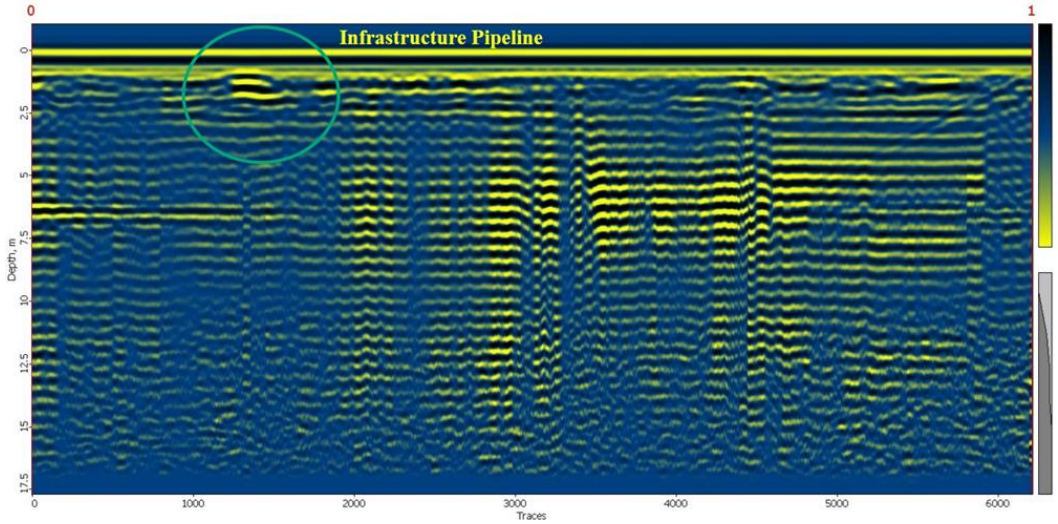


Figure 8. Radargram obtained from Line-3 profile.

Utilizing the thickness measurements derived from all radargrams, the overall waste thickness of the region was calculated, and a thickness map was subsequently generated (Fig. 9).

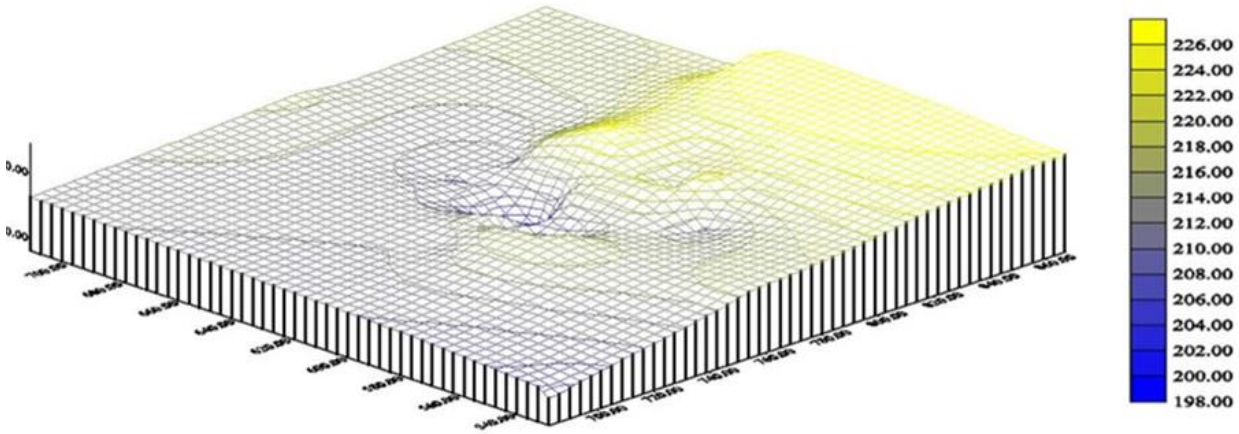


Figure 9. 3D topographic map of the solid waste area.

The integrated GPR results provide important insights into the subsurface characteristics of the closed Halkalı landfill. The radargrams clearly demonstrate that the landfill consists of highly heterogeneous waste deposits with variable thicknesses, which is typical of uncontrolled disposal areas where waste emplacement was not systematically managed. This heterogeneity reflects irregular dumping practices during the operational period, resulting in discontinuous layering and uneven waste accumulation throughout the site. Similar structural complexity has been reported in abandoned or informal landfill areas worldwide, where historical waste placement was largely uncontrolled [9–18].

The thickness map further confirms substantial spatial variability in waste thickness across the study area. This finding is particularly significant for engineering and land-use planning purposes, as thicker waste zones may be more susceptible to long-term settlement, landfill gas accumulation, elevated pore pressures, and leachate generation [14]. Differential settlement is a common post-closure issue in former landfill sites and may create risks for any future construction or redevelopment activities. Accordingly, the identification of thicker waste sectors through GPR provides valuable baseline information for zoning decisions, foundation design, and post-closure monitoring programs.

From an environmental perspective, the identification of active leachate zones indicates that the landfill remains hydrogeologically active despite its closure. The interpreted leachate anomalies are characterized by signal attenuation, disturbed reflector continuity, and reduced penetration depth, which collectively suggest elevated electrical conductivity associated with contaminated pore fluids. Their presence implies that the waste body continues to interact with infiltrating precipitation and subsurface flow systems, thereby maintaining the potential for contaminant generation and migration. This is especially important considering the proximity of Menekşe and Hasanoğlu streams, where surface water quality may be vulnerable to leachate discharge or runoff-related transport.

The findings are also highly relevant in an urban context such as İstanbul, where formerly peripheral landfill sites may now be surrounded by expanding residential, commercial, and transportation infrastructure. Potential downward migration of contaminants into underlying soils and groundwater, together with lateral movement through preferential pathways, should therefore be considered in future environmental risk assessments. Similar concerns have been emphasized in studies of closed landfills located within rapidly urbanizing metropolitan areas [14,17,19].

Methodologically, the study confirms that GPR is an efficient and non-invasive technique for landfill characterization, capable of rapidly delineating waste thickness, internal heterogeneity, and moisture-related anomalies without excavation. However, survey performance depends strongly on antenna frequency selection and local site conditions. Lower-frequency antennas, such as the 38 MHz system used in this study, provide greater penetration depth but lower resolution, whereas higher-frequency systems offer improved imaging of shallow features at the expense of penetration. Similar penetration depth–resolution trade-offs have been widely documented in previous GPR studies [21-23,33]. In addition, metallic waste, conductive leachate, and rough ground conditions may complicate data interpretation and reduce signal quality.

4. Conclusions

This study demonstrated the effectiveness of GPR for the characterization of the closed Halkalı landfill in İstanbul. The results showed that waste thickness varies significantly across the site, generally between 5 and 15 m, reflecting the irregular disposal practices of the former uncontrolled landfill. The resulting waste-thickness map provides valuable information for understanding the spatial geometry of the landfill. It also helps identify areas that may be more vulnerable to settlement, landfill gas accumulation, or continued leachate generation. In addition, the interpreted leachate-related anomalies indicate that the site remains hydrogeologically active despite its closure and may still pose environmental risks to surrounding soil and water systems.

These results highlight the usefulness of GPR for supporting land-use planning, environmental monitoring, and redevelopment decisions at former waste disposal sites. In addition, the study confirms that the site continues to present environmental risks, emphasizing the need to re-evaluate current land-use practices. It also supports the integration of GPR with complementary methods in future studies to improve the reliability of landfill assessments.

Acknowledgement

Authors thank to Mehmet Şafi YILMAZ for their supports.

Contribution Statement

Research design, literature review and evaluation, data collection, data analysis, validation of data and analyses, interpretation of findings: Fethi Ahmet Yüksel; Literature review and evaluation, data analysis: Nihan Hoşkan; Writing of the article: All authors.

Declaration of Competing Interest

The authors of the article declare that they have no personal or financial conflicts of interest with any institution, organisation or individual.

References

[1] McQuown MS, Becker SR, Miller PT. Subsurface characterization of a landfill using integrated geophysical techniques. In: Proceedings of the Fifth National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, ed. Water Well Journal Publishing Co., pp. 933-946, May 13-16; Las Vegas, Nevada, Amerika; 1991.

[2] Scaife JE. Using geophysical techniques in environmental site assessments. Municipal & Industrial Water & Pollution Control 1990; CXXVIII(4): 4-5.

[3] Hall DW, Pasicznyk DL. Application of seismic refraction and terrain conductivity methods at a ground water pollution site in North-Central New Jersey. In: Graves B, Lehr JH, Butcher K, Alcorn P, Ammerman L, Williams P, Renz M, Shelton V (eds) 1st national outdoor action conference on aquifer restoration, groundwater monitoring and geophysical methods. National Water Well Association, pp 505–524, Las Vegas, Nevada, Amerka; 1997.

[4] Kayabalı K, Yüksel FA, Yeken T. Integrated use of hydrochemistry and resistivity in groundwater contamination caused by a recently closed solid waste site. Environ. Geol. 1998; 36:227–234.

[5] Aristodemou E, Thomas-Betts A. DC resistivity and induced polarization investigations at a waste disposal site and its environments. Journal of Applied Geophysics 2000; (2-3):275-302.

[6] Sauck WA. A model for the resistivity structure of LNAPL plumes and their environs in sandy sediments. Journal of Applied Geophysics 2000; 44:151–165.

[7] Abidin MHZ, Saad R, Ahmad F, Wijeyesekera DC, Baharuddin MFT. Seismic refraction investigation on near surface landslides at the Kundasang area in Sabah, Malaysia. Procedia Eng. 2012; 50:516–531.

[8] Konstantaki LA, Ghose R, Draganov D, Diaferia G, Heimovaara T. Characterization of a heterogeneous landfill using seismic and electrical resistivity data. Geophysics 2015; 80:EN13–EN25.

[9] Dumont G, Robert T, Marck N, Nguyen F. Assessment of multiple geophysical techniques for the characterization of municipal waste deposit sites. J. Appl. Geophys. 2017; 145:74–83.

[10] Orlando L, Marchesi E. Georadar as a tool to identify and characterize solid waste dump deposits. Journal of Applied Geophysics 2001; 48:163–174.

[11] Porsani JL, Filho WM, Elis VR, Shimeless F, Dourado JC, Moura HP. The use of GPR and VES in delineating a contamination plume in a landfill site: A case study in SE Brazil. Journal of Applied Geophysics 2004; V55, Issues 3–4, 55:199–209.

[12] Pujari PR, Pardhi P, Muduli P, Harkare P and Nanoti MV. Assessment of pollution near landfill site in Nagpur, India by resistivity imaging and GPR. Environmental Monitoring and Assessment 2007; 131:489–500.

[13] Reyes-Lopez JA, Ramirez-Hernandez J, Lazaro-Mancilla O, Carreon-Diazconti C, Garrido MML. Assessment of groundwater contamination by landfill leachate: A case in México. Waste Management. 2008; 28:(S33-S39).

[14] Yüksel FA. Geophysical works for opening the area which for rest solid material, International Symposium on Environment, 20-23 May, Manas University, Kyrgyzstan; 2009.
[15] Araruna JT, Pires PJM, Domingues DLP, Pereira de Campos TM. The Use of Ground Penetrating Radar in Municipal Solid Waste Landfill Geotechnical Investigation, Journal of Civil Engineering and Architecture 2016; 10:822-827.
[16] Wijewardana YNS, Shilpadi AT, Mowjood MIM. et al. Ground-penetrating radar (GPR) responses for sub-surface salt contamination and solid waste: modeling and controlled lysimeter studies. Environ Monit Assess. 2017; 189(2):57.
[17] Kayabalı K, Yüksel FA, Yeken T. Katı atık sahalarının neden olduğu yeraltı suyu kirlenmesini belirlemede rezistivite ve hidrokimya metodlarının kullanılması. 1997, Proje No: YDABÇAĞ-302, TÜBİTAK.
[18] Avcı CB, Guler E, Togrol E, Karpuzcu M, Kılanç B. The influence of wild solid waste disposal sites on groundwater quality; case-study on Istanbul Halkalı Solid Waste Disposal Site (in Turkish). IMO Teknik Dergisi 1995; 65:885–881.
[19] Demirci A, McAdams MA, Alagha O, Karakuyu M. The relationship between land use change and water quality in Kucukcekmece Lake watershed, 4th GIS Days in Turkey, Fatih University, September 13-16, İstanbul, Türkiye; 2006.
[20] Arıcı C. 1955. Haliç- Küçükçekmece Gölü arasındaki bölgenin jeolojik hatları. [Doktora Tezi]. İstanbul, İstanbul Teknik Üniversitesi; 1955.
[21] Annan AP and Cosway SW. Ground penetrating radar survey design. In: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP '92), Apr. 26–29, pp. 329–352, Oakbrook, IL, USA; 1992.
[22] Knight R. Ground penetrating radar for environmental applications. Annual Review of Earth and Planetary Sciences 2001; 29:229–255.
[23] Annan AP. Ground Penetrating Radar Workshop Notes. San Diego, CA, USA; 1992.
[24] Yilmaz Y, Soycan A. The Detection of the Buried Pipes Using GPR in Utility Works: A Case Study. International Journal of Environment and Geoinformatics (IJEGEO); 2022, 9(4):124-137.
[25] Imai T, Sakayama T, Kanemori T. Use of ground probing radar and resistivity surveys for archaeological investigation. Geophysics 1987; 52 (2):137- 150.
[26] Bevan BW. The search for graves. Geophysics 1991; 56 (9):1310-1319.
[27] Yüksel, FA. Orta Aras Havzasında Arkeolojik Mirasin Korunması Çalışmalarında Arkeojeofizik Araştırmaların Önemi. Amisos 1 (Özel Sayı-The Special Issue (Orta Aras Havzası/The Middle Aras Basin) 2022; 95-106.
[28] Kwan RL, Lai WWL. Archaeological investigation of burials preluded by ground penetrating radar and geospatial technologies. Journal of Archaeological Science 2024; V.170:106058.
[29] Damiata BN, Steinberg JM, Bolender DJ, Zoëga G. Imaging skeletal remains with ground-penetrating radar: comparative results over two graves from Viking Age and Medieval churchyards on the Stóra-Seyla farm, northern Iceland, J. Archaeol. Sci. 2013; 40 (1):268-278.
[30] Patterson JE, Cook FA. Successful application of ground-penetrating radar in the exploration of gem tourmaline pegmatites of southern California. Geophysical Prospecting 2001; 50(2):107-117.
[31] Doolittle JA. Characteristics and monitoring the vadose zone with ground penetrating radar. Advanced Ground Penetrating Radar: Technologies and Applications pp. 105-119, 26-28 Oct., Ohio State University, Columbus, Ohio, USA; 1993.
[32] Doolittle JA, Collins ME. Use of soil information to determine application of ground penetrating radar. Journal of Applied Geophysics 1995; 33:101-108.
[33] Mccarthy M, Pritchard H, Willis I, King E. Ground-penetrating radar measurements of debris thickness on Lirung Glacier, Nepal. Journal of Glaciology 2017; 63(239) 543–555.