Assessment of landfill leachate in Nam Son, Hanoi using 3D electrical imaging and self-potential data

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Abstract:

The main objective of this study was to assess the environmental impact of the Nam Son landfill on the subsurface geological structure studied using 3D electrical imaging and self-potential investigations. The map of the equipotential was based on self-potential data and was indicative of concentrations of redox-active components, and the map of the electrical conductivity provided information about the mineralization of the groundwater. The electrical conductivity of the subsurface was obtained from 3D-electrical imaging analysis conducted using a Wenner-based array configuration. An inversion of the data was carried out using 3D regularized least-squares optimization methods with robust model constraints. Three profiles of 3D electrical imaging and 180 self-potential data points, scattered within the study area near the disposal site, were implemented. The self-potential method supports the results of the geoelectrical method relating to a contaminated zone in the survey area with a large negative self-potential anomaly of ~-260 mV with respect to the reference of a contaminant plume. Interpretations of geophysical data showed a low resistivity zone (<10 Ω m), which appeared to be a fully saturated zone with leachate from the Nam Son open dumpsite. The correlation between geophysical investigations and hydrochemical analysis proved to show high conductivity zones related with landfill leachate.

Keywords: contaminant plume, electrical imaging, fluid conductivity, landfill leachate, self-potential.

Classification number: 4.3

Introduction

One of the major causes of the pollution problem for municipal solid waste landfills is landfill leachate, which is generated from precipitation, surface run-off, and the infiltration or intrusion of groundwater percolating through a landfill, biochemical processes in waste cells and the inherent water content of wastes themselves [1].

The landfill leachate has the potential to contaminate groundwater and surface water supplies, and threaten human health as it migrates from landfills and contaminates surrounding lands and water. As the population grows and industries develop, the landfill leachate problem becomes increasingly serious [2, 3].

Landfill leachate consists of a number of complex factors, including the composition of the solid waste composition, the age of the waste, the operation of the landfill, the hydrogeological conditions in the vicinity of the landfill site, the rate of water movement through the waste, the temperature of the landfill, the moisture content, the pH, the landfill chemical and biological activities, and the seasonal variations in weather [4].

Nam Son is the biggest landfill in Hanoi and receives more than 4,000 tons of domestic waste per day. landfill leachate is a serious problem there. During the last decade, some research projects have been conducted to compare landfill leachate treatment systems which have been used across Vietnam and in the world at large, including at the Nam Son landfill site in Hanoi [5], and studies investigating the recovery ability of N, P in leachate from the Nam Son landfill, Hanoi for pretreatment of ammonium have also been carried out [6].

During the past 20 years, geophysical methods have proven to be efficient and effective means for characterizing the subsurface geology and hydrology associated with landfills [7-9]. As a result, the geophysical characterization of landfills is now routine practice. Even so, due to the inherent uniqueness of each site, it is necessary to carefully select a method and appropriately design survey parameters in order to derive adequate benefits. In many cases, particularly when multiple objectives are desired, it is best to use complimentary geophysical methods [1, 2, 10]. A variety of techniques can be applied to define landfill properties, leachate circulation, or regional contamination from offsite seepage [11]. A combination of various geophysical methods, as well as 3D electrical imaging and self-potential, were used for shallow geological structure investigation in the north of the Nam Son landfill. These techniques were applied in the lowest altitude

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terrain around the landfill to monitor the volatility of the soil and water environment; that may be caused by the landfill operation.

Geological features of the study area

The terrain of the study area is hilly, but the typography is fairly simple. The general form terrain is a very soft transition from 10 to 20 m. The study area is located within a region of moist, tropical monsoon heat. Average annual rainfall is 1,670 mm and average air humidity is 84%. The aquifers are deposits of Holocene (qh) and Pleistocene (qp) [11, 12]. The water layer deposit of the Triassic Rift (t), is exposed in the north of the Soc Son district, and is characterized by slightly better water quality in the quaternary sediments. The silver-coloured soil in some parts of the research area is the result of the ancient alluvial ferralitic products. According to a geological-mineral map (scale 1:50,000) published in 2015 by the Hanoi Institute of geology and environment, the structure of Soc Son district is mainly in the upper Triassic system and the Jura conglomerate [13]. There are two stratigraphic formations: the Khon Lang (T_{2a} kl) and the Na Khuat (T_2 nk). There are three boreholes at 30 m of depth there, where, in general, the stratigraphic column consists of:

- From the ground surface to 1.5/2 m - the class covered ruins in a sepia-brown golden colour, the composition of clay and gravel in a semi-hard state.
- From 1.5/2 m to 14/15 m - lightning weathered siltstone rock was made perfectly golden brown, semi-hard hard status.
- From 14/15 m to 30 m: grey-black shale weathering to soft weathering, medium to the hard state.

Methodology of research

The research area covers 180 x 300 m (Fig. 1) which allowed for the convenient use of many geophysical methods, e.g. 3D electrical imaging and self-potential (SP) methods to assess subsurface environmental contamination.

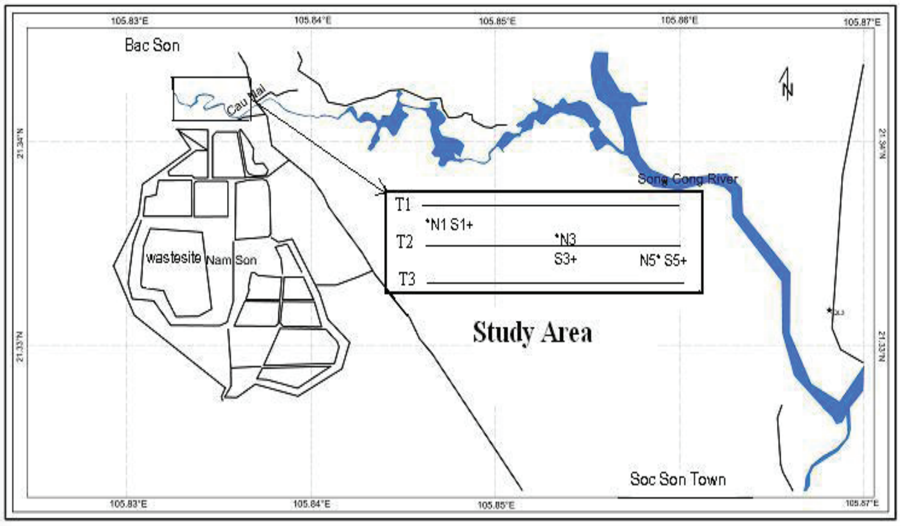

Fig. 1. The location of the Nam Son landfill and study area of the measurements profiles: T1, T2, T3, and samples surface water sites: N1, N3, N5, and samples groundwater sites: S1, S3, and S5.

3D electrical imaging surveys method

Overview of electrical surveys:

The purpose of the electrical surveys was to determine the subsurface resistivity distribution by making measurements of the ground surface. From these measurements, the true resistivity of the subsurface was estimated. Ground resistivity is related to various geological parameters such as the mineral and fluid content, porosity and degree of water saturation in the rock [10, 14].

Resistivity measurements were normally made by injecting current into the ground through two current electrodes and measuring the resulting voltage difference at two potential electrodes. From the current (I) and voltage (V) values, an apparent resistivity (ρa) value was calculated [10].

$$\rho_a = k\, V / I \qquad (1)$$

where k is the geometric factor which depends on the arrangement of the four electrodes.

Resistivity meters normally gives a resistance value of R = V/I, so in practice, the apparent resistivity value was calculated by:

$$\rho_a = k\, R \qquad (2)$$

To interpret the data from such a survey, it is normally assumed that the subsurface consists of horizontal layers. However, in this case, the subsurface resistivity changed only with depth, but did not change towards the horizontal direction. It was a one-dimensional model (1D) of the subsurface structure. Another classical survey technique is the profiling method. However, in this case, the spacing between the electrodes remained fixed, and the entire array was moved along a straight line. This gave some information about lateral changes in the subsurface resistivity, but it did not detect vertical changes in the resistivity. An interpretation of the data from profiling surveys was mainly qualitative. Nowadays, however, 3D electrical surveys are practical commercial techniques with the relatively recent development of multi-electrode resistivity surveying instruments [3] and fast computer inversion software [15].

Before dealing with the 2D and 3D resistivity surveys, we will briefly look at the resistivity values of some common rocks, soils, and other materials. Resistivity surveys give a picture of the subsurface resistivity distribution. To convert the resistivity picture into a geological picture, some knowledge of typical resistivity values for different types of subsurface materials and the geology of the surveyed area, is important.

3D electrical imaging surveys:

Since all geological structures are 3D in nature, a fully 3D resistivity survey using a 3D interpretation model gives the most accurate results [16]. At the present time, 3D surveys are a subject of active research. Many of the early 2D surveys were carried out using the Wenner Array because the sensitivity plot of the Wenner Array had nearly horizontal contours beneath the centre of the array. As well, the Wenner Array was relatively sensitive to vertical changes in the subsurface resistivity below the centre of the array. In general, the Wenner is good for resolving vertical changes (i.e. horizontal structures). Compared to other arrays, the Wenner Array has a moderate depth of investigation. With the Wenner Array, the geometric factor is 2πa, ('a' is for the electrode spacing) which is smaller than the geometric factors of other arrays. Among the most common arrays is the Wenner Array as it has the strongest signal strength. This can be an important factor if the survey is carried out in areas with high background noise. One disadvantage of this array, however, is that 2D surveys have relatively poor horizontal coverage because the electrode spacing is increased. This could be a problem if you use a system with a relatively small number of electrodes.

Figure 2 shows one possible arrangement of the electrodes from a 3D survey using a 25 electrodes system. For convenience the electrodes were usually arranged in a square grid with the same unit electrode spacing in the *x*- and *y*-directions. To map slightly elongated bodies, a rectangular grid with different numbers of electrodes and spacing in the X- and Y- directions was used. In this case, each electrode was, in turn, used as a current electrode, and the potential of all the other electrodes was measured.

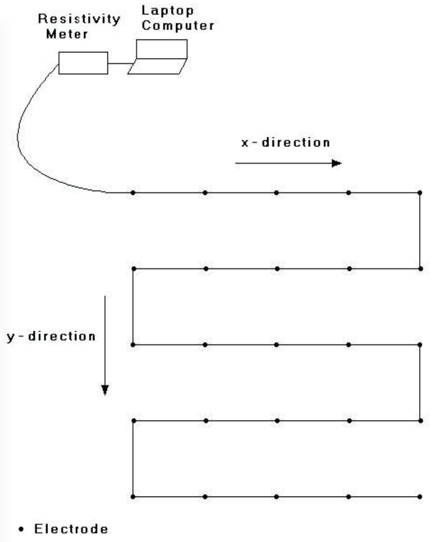

Fig. 2. The arrangement of the electrodes for a 3D survey [16].

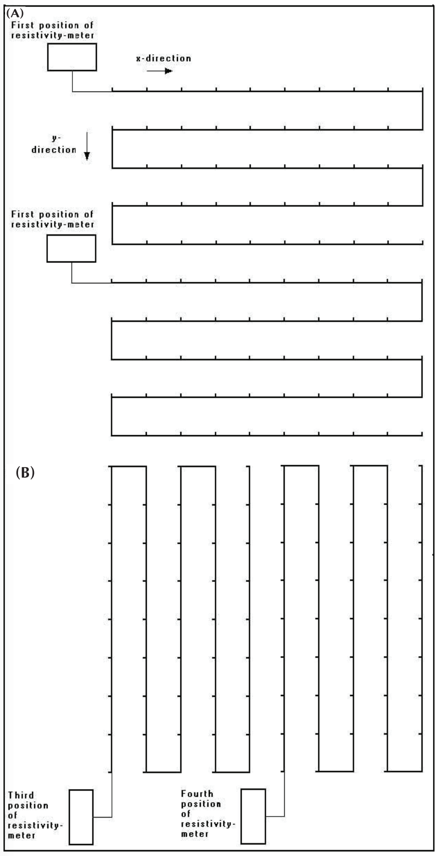

Fig. 3. Using the roll-along method to survey a 10 by 10 grid with a resistivity meter system with 50 electrodes. (A) Survey using a 10 by 5 grid with lines orientated in the x-direction. **(B)** Surveys with lines orientated in the y-direction [16].

3D roll-along techniques: The nearly 3D surveys involved grids of at least 16 by 16 in order to cover a reasonably large area. A 16 by 16 grid required 256 electrodes, which was more than what was available on many multi-electrode resistivity meter systems. A method used to survey such large grids with a limited number of electrodes was to extend the roll-along technique used in 3D surveys [4, 16]. The traditional survey showed an example of a survey using a multi-electrode resistivity-meter system with 50 electrodes to survey a 10 by 10 grid. Initially, the electrodes were arranged in a 10 by 5 grid with the longer lines orientated in the x-direction (Fig. 3). Measurements were then made primarily in the x-direction, with some possible measurements made diagonally. Next, the entire grid was moved in the y-direction so that the 10 by 5 grid then covered the second half of the 10 by 10 grid area. The 10 by 5 grid of electrodes was then orientated to the y-direction (Fig. 3).

The 3D forward modeling program: The free 3D resistivity forward modeling program, RES3DMOD.EXE, enables user to calculate the apparent resistivity values for a survey of a rectangular grid of electrodes over a 3D structure. We calculated resistivity values using the resistivity model, we also calculated the apparent resistivity values using the Calculate option. The RES3DMOD program also has an option to save the apparent resistivity values into a format that can be accepted by the RES3DINV inversion program. For our case, to save the apparent resistivity values as a RES3DINV data file for one of the models, and later carry out an inversion of this synthetic data set [16].

Data inversion: A model used to interpret the 3D data set is shown in Fig. 4. The subsurface is divided into several layers and each layer is further subdivided into a number of rectangular blocks. A 3D resistivity inversion program, RES3DINV, was used to interpret the data from 3D surveys. This program attempted to determine the resistivity of the blocks in the inversion model that most closely reproduced the measurements' apparent resistivity values from the field survey. Within the RES3DINV program, the thickness of the layers was modified by the user [4, 16].

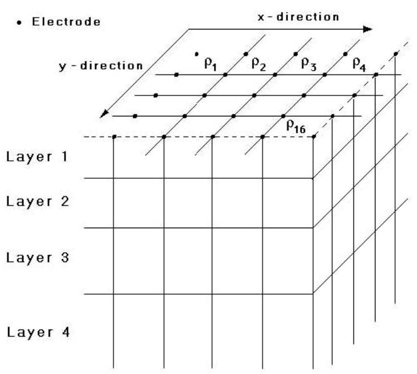

Fig. 4. The model used in 3D inversion where the widths of the rectangular blocks are equal to the unit electrode spacing in the x- and y-directions [16].

Self-potential (SP) method:

The basic concept: Various potentials are produced in native ground and within the subsurface which is altered by our actions. Natural potentials occur in dissimilar materials, at near varying concentrations of electrolytic solutions, and are due to the flow of fluids which may be mapped to determine information about the subsurface. SP can be produced using mineralization differences, electro-chemical action, geothermal activity, and bioelectric generation of vegetation. Four different electrical potentials are also recognized. Electrokinetic potential, or the streaming potential, is caused by the flow of fluids with certain electrical properties that passes through pipes or porous mediums with different electrical properties [17]. Liquid-junction potential, or diffusion potential, is caused by the displacement of ionic solutions of dissimilar concentrations. Mineralization potential, or electrolytic contact potential, is produced at the surface of conductors with other media. Shale potential occurs when similar conductors have solutions that are of differing concentrations about them. Telford, Geldart, and Sheriff (1990) provided equations for these differing potentials [10]. Recognition of different SP sources is important in order to eliminate noise and lower background voltages. Some engineering and environmental occurrences may be mapped by contouring surficial voltages between base electrodes and mobile electrodes.

Data acquisition: A simple SP survey consists of a base electrode position and a roving electrode to determine potential differences on a gridded survey or along profile lines. The required equipment merely includes electrodes, wires, and a precise millivolt meter. The electrodes are in contact with the ground surface and should be of the nonpolarizing type, which are also called porous pots. Millivolt Meters are used to read the potentials in the millivolt range using a resolution from 0.1 to 1.0 mV [18]. Measurements using the electrodes may require systems to reverse the electrode position to resolve contact potentials at the electrodes. Previously measured locations may need to be remeasured on a systematic or periodic basis. Reoccupation of stations is necessary when very accurate surveys are being conducted and for sites with temporal potential changes or spatial variations of electrode potential. Changes are temporally in the electrodes and are due to the self-potential of the field require the survey to be conducted in a gridded or looped array [19].

Data interpretation: Most SP investigations use a qualitative evaluation of the profile amplitudes, or grid contours, to evaluate self- and streaming-potential anomalies. Flow sources produce potentials in the direction of the flow. Fluid inflow produces negative relative potentials, as would greater distance from the flow tube; outflow of the fluid results in positive potentials [20]. The self-potential due to water flow is a direct parameter for a grouting remediation of reservoir leakage. SP methods can be very useful for karst groundwater regimes identified in quick surveys of sites or in long-term surveys during rainy seasons. There can also be a qualitative evaluation of the flow volume in different subsurface routes if the ground surface may be assumed parallel to the surface through the irregular flow paths.

Results of investigations

3D electrical imaging surveys

We used Terrameter SAS 4000 (four channel) Resistivity and IP instrument, with an integrated PC for full control of the data acquisition process and storage of data, and 64 electrodes [21]. The data collection was carried out along three profiles T1, T2, and T3 using the Wenner Array with 5 m electrode spacing and using integrated roll-along surveys. (Fig. 2). The raw data was interpreted using the software RES3DINV to build 3D inversion models. The RMS error for iterations of resistivity data varied by 9.46% in the inverse resistivity models. The results suggest delineation of geological formations such as various sub-surface lenses like clays and in situ-saturated sands and clays, which were up to the depth of several meters. The principal aquifer was formed in the unconsolidated alluvial formations, deposited under various sedimentary environments. The 3D electrical imaging showed resistivity values that varied laterally with the depth; two levels were distinguished in accordance with their obtained resistivity values.

Figure 5 shows the distribution of resistivity values. In the resistivity value less than 10 Wm for a majority on the surface, in the position of a 50 meter to 190 meter, with a width of about 20 m and a depth of about 5 m, which tended to penetrate deep down at nearly 10 m and spread out towards the N-canal Lai Son. Meanwhile, the resistivity value block > 30 Wm occupied most of the lower portion of the model that corresponded with the medium grain sand and clay

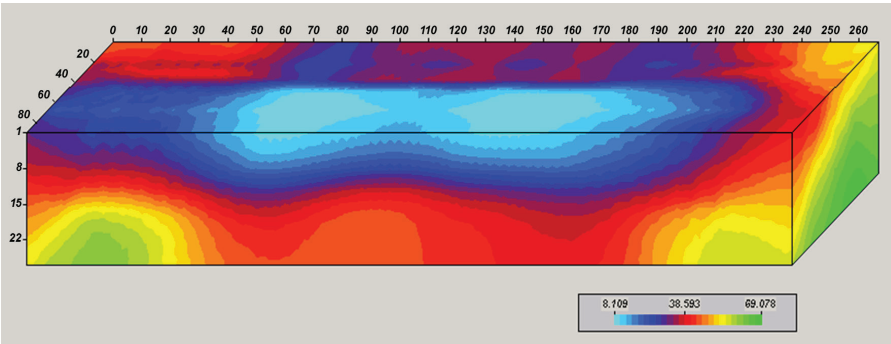

Fig. 5. The distribution of resistivity values by 3D model inversion for the study area.

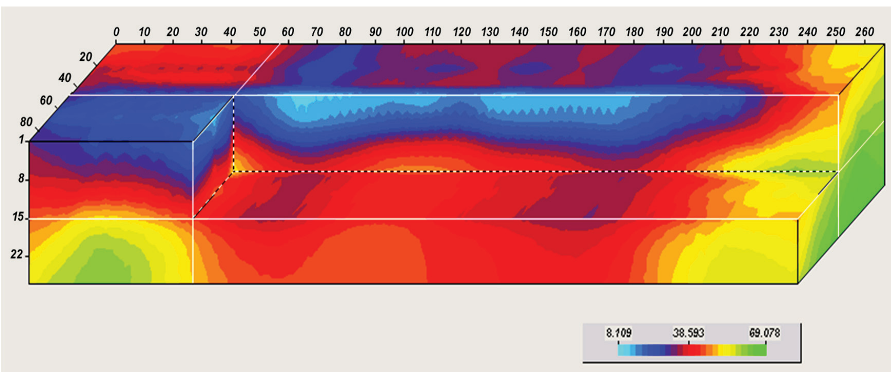

Fig. 6. The distribution of resistivity values by 3D model inversion after cutting a part of structures.

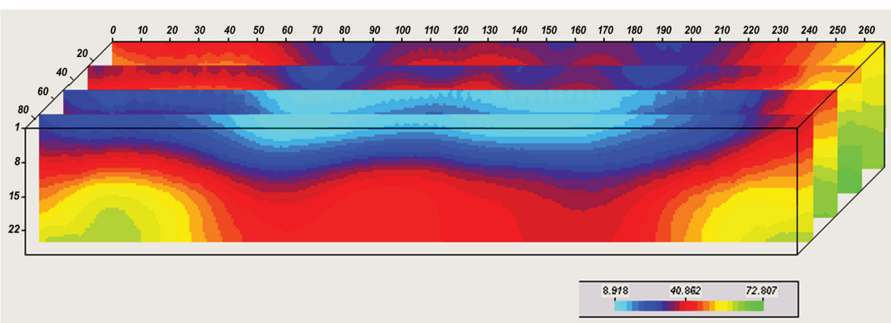

Fig. 7. The distribution of resistivity values by 3D model inversion by y-direction.

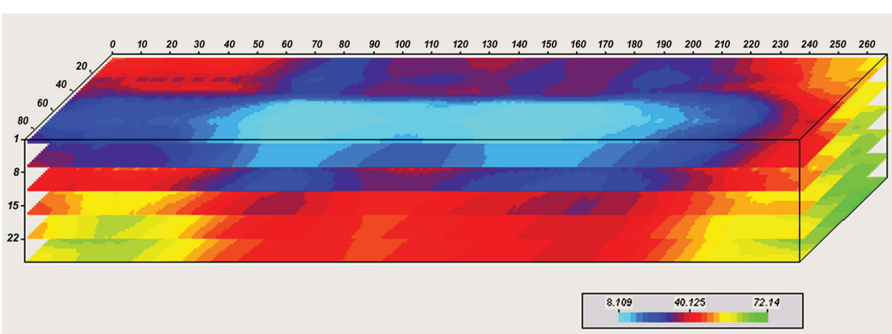

Fig. 8. The distribution of resistivity values by 3D model inversion by z-direction.

shale lithology.

To more clearly observe the distribution of blocks down to a deep resistivity was low, and we had to cut off parts in places from 60 to 270 metres according to the x-direction, from 50 to 90 metres according to y-direction, and from the ground down the 15 meter according to the z-direction (Fig. 6). We can see the block of low resistivity distribution only down about 10 m deep, which tends to expand at the N-canal of Lai Son. Below a depth greater than 10 m, the resistivity values were from 30 to 70 Wm corresponding to the lithology and are medium sand and clay shale (water layer).

To review the distribution of resistivity value according to the y-direction, we divide the model into the sections along the local y-direction; each cut was from 10 m, resulting in showing the resistivity zone at less than 10 Wm (blue colour) on the surface to the depth of 10 m (Fig. 7).

We can divide the blocks into six sections and vertical sections, each separated by 5 m. In Fig. 8, resistivity values less than 10 Wm appear on the surface quite broadly and as deep down as this value is possible, shrinking to a depth of about 10 m, then disappearing. Meanwhile, high resistivity values of over 30 Wm rise when more down deep.

The 3D electrical imaging shows the spatial distribution of waste and leachate concentrations within the study area of the landfill. Accordingly, a 3D survey was undertaken to determine the pattern of leachate drainage within the waste so that a more refined contaminant transport model could be developed. A full 3D survey was undertaken by sub-dividing the landfill into a number of discrete rectangular blocks and acquiring data on multiple parallel lines. The line data were merged into a single x-y matrix file and then inverted using a 3D finite element algorithm. The results were then presented as a 3D volumetric tomograms in order to show the inferred waste distribution and leachate flow. The resistivity model indicated that leachate had accumulated at several discrete localities within the landfill at high conductivities. A narrow leachate plume was indicated in one part of the landfill, migrating down-gradient to the north. The inferred leachate concentrations in the study area were subsequently confirmed by drilling down and making hydrochemical samples which showed elevated solute levels that are coincident with distinct resistivity lows of <10 Ωm.

This survey shows that surface electrical resistivity imaging can be a suitable method to study resistivity distribution (3D) at a large scale (ten to several tens of meters wide and down to 30 m deep). 3D electrical imaging is becoming a common tool to study recirculation experiments in landfills, as well as focusing on electrical resistivity changes in the subsurface by pollution of groundwater or location of shallow or deep infiltration/recharge zones or delineation of leachate plume in landfills.

Self-potential survey

The data collected by the SP method was processed to eliminate noise exemplified by low background voltages for recognition of different spontaneous-potential sources. After processing, the SP data was in the range of -260 to +30 mV for three measured profiles (T1, T2, and T3). We aimed to assess the relationship of the near-surface geological formation with environmental occurrences, and we used the processed SP data to map the contouring surficial voltages between base/reference electrode(s) and the mobile electrodes. On the map made from an equipotential based on SP data collected in March 2016 (Fig. 9), one can distinguish three positive anomalies (marked in red/brown) and two zones of negative anomaly (in dark blue). The values of the positive SP anomalies were within the range +10 to +25 mV

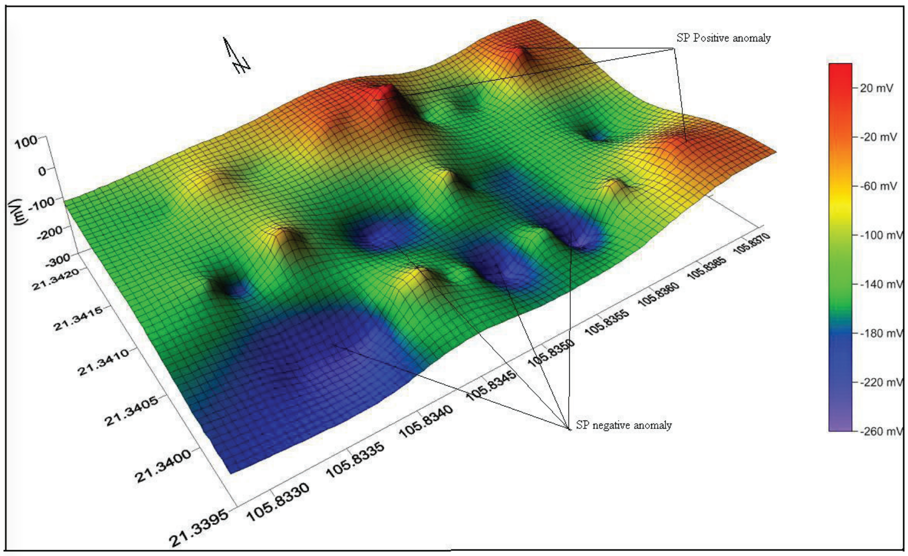

Fig. 9. A map of equipotential based on self-potential (SP) data carried out in March 2016.

and negative was in the range from -150 to -260 mV. The SP anomalies were positive (resurgence) where the hydrostatic pressure decreased (i.e. in the direction of the water flux), and the SP anomaly was negative for the infiltration case. Other occurrences produce spontaneous potentials, which were mapped to determine information about the subsurface. Spontaneous potentials can be produced by differences in the mineralization of the ground, electro-chemical actions, geothermal activities, and bioelectric generation of vegetation.

The notable thing here are the SP positive anomalies at three points (Fig. 9 -red/brown colour), and the SP negative anomaly at the back which expands out into two distinct zones that the position of the two zones on the measured profile, T3, located near the Nam Son landfill. So, we much ask if it was due to the landfill leachate that caused this effect? As a blanket statement, this phenomenon has the related zone with the high electrical conductivity in the structure according to 3D electrical imaging stated above.

There is an increasing interest in the use of the SP method for non-invasive characterizing of subsurface groundwater flow and contamination. The interpretation of SP signals is underlined by the understanding of the main physical process involved in their origin. The equipotential map based on the SP data demonstrates the direction of the water.

Hydrochemical analysis

There are many sources of water in the landfill, for example, precipitation, groundwater infiltration, surface run-off, and the disposal of liquids or sludges. The amount of water entering the landfill depends on such factors as the seasonal distribution of the water balance, the topography, the geology, and the hydrogeological properties of the site, soil type, land cover, human activity, and other similar factors. [1]. Water plays three major roles in land filling: first, as a medium essential for bacterial activity; second, as a medium for chemical reactions in organic matter; and third, as a medium for the movement of contaminants and solvents.

In this research project, to conduct analysis, we sampled surface water in three locations (N1, N3, and N5) on the Lai Son canal and groundwater in three boreholes, drilled in the area of research

Table 1. Hydro-geochemical analysis of surface water (N1, N3, and N5) and groundwater (S1, S3, and S5) samples affected by the Nam Son Landfill for the 2016 year by Institute of Chemistry and Institute of Geophysics, VAST.

Parameter	Surface water name of samples and content for date			Groundwater name of samples and content for date			Standard values QCVN-08/09-MT(B1-2015)
	N1	*N3*	*N5*	*S1*	*S3*	*S5*	
pH	7.86	7.71	7.52	7.22	7.14	7.08	5.5÷8.5
EC (µS/cm)	2,507	2,646	2,659	1,645	1,778	1,601	1,000
Water level (m)				4.2	4.7	5.5	
Temperature (^{0}C)	21.3	22.5	22.8	24.8	25.0	25.1	
TDS (ppm)	1,630	1,720	1,702	1,051	1,156	1,025	1,500
DO (mg/l)	2.1	2.7	2.2	3.7	3.4	3.3	≥4
COD (mg/l)	156	162	157	44	56	53	40
BOD_5 (mg/l)	112	124	105	28	26	33	25

Legend: COD: chemical oxygen demand; EC: electrical conductivity; TDS: total dissolved solids; DO: dissolved oxygen; BOD_5: Biochemical or Biological Oxygen Demand during 5 days at 20^{0}C; QCVN-08/09-MT (B1-2015): Vietnam Technical Regulation on surface water or groundwater quality by Ministry of Natural Resources and Environment (MONRE).

(S1, S3, and S5) (Fig. 1). The water samples were collected and analyzed in March 2016. The results of the analysis are presented in Table 1 for surface water and groundwater, respectively.

The environmental indicators of water quality can be roughly divided into the physical indicators of temperature, EC, and TDS; and the chemical indicators of pH, BOD, COD, and DO. Because direct measurements of water quality can be expensive, we used on-site test kits and water samples analyzed at laboratories using real-time monitoring. The values of the parameters are presented in Table 1. The data shows that the values of most parameters in 2016 are of a higher concentration by comparison of their standard values. Most of the water samples indicated a slightly alkaline nature with pH 7.08/7.86. The values of DO, for all sites, are lower than regular, but the values of COD and BOD_5 exceed permissible limits. High concentration of TDS and EC were observed in all sites along Lai Son canal and all wells, which means that the surface water and groundwater in the landfill areas are of very poor quality. The results of the hydrochemical analysis show that the values of TDS and EC for surface and groundwater are very high. Although generally TDS is not considered a primary pollutant, it is used as an indication of aesthetic characteristics of domestic water and as an aggregated indicator of the presence of a number of chemical contaminants [2]. Primary sources of the TDS in waters are soil contaminants and polluted water from the landfill. Bear in mind, however, that the concentration of some naturally occurring dissolved solids increases as a result of weathering and dissolution of rocks and soils and influences the results of analyses.

The BOD is widely used as an indicator of water quality. In this case, BOD values ranged from 26 to 33 mg/l for groundwater and from 105 to 124 mg/l for surface water. These values are too high for natural water to acceptable.

Conclusions

Integrated, geophysical surveys methods, as well as 3D electrical imaging and self-potential (SP) were employed to determine the subsurface geological structure, and assess the effect of landfill leachate at the Nam Son waste site. The case study area was generally close to the ground surface and was characterized by the non-homogenous formations which were largely responsible for the transfer of contaminated water into the underlying aquifers.

Interpretations of 3D resistivity geoelectrical data showed a low resistivity zone (<10 Ωm), which appeared to be a zone that is fully saturated with leachate from an open dumpsite. The SP method supported the results of the geoelectrical method relating to a contaminated zone in the survey area from a largely negative SP anomaly of ~-260 mV with respect to the reference with the contaminant plume. These electrical anomalies could be the signature of oxido-reduction phenomena which occur at various depths in the contaminated groundwater. A comparison with the available hydrochemical data suggests that this SP anomaly could be attributed to high redox potential gradients in this area.

The results of our research clearly indicate the need for regular monitoring of groundwater and surface water quality in the vicinity of the Nam Son landfill. Also, we recommend installing a waste water treatment plant that could diminish pollution from seeping waters flowing directly from the Lai Son canal. The management of the landfill should also pay more attention to the environmental protection of groundwater resources from domestic wells in the areas around the landfill area.

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