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Original Research

Evaluation of the Proper Electrode Spacing for ERI Surveys in Open Dumpsites Using Forward Modeling

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Abstract

Electrical resistivity imaging surveys are widely conducted in waste disposal sites due to their ease of operation and accurate results; however, some essential measurement parameters, such as optimal electrode spacing, have not been thoroughly evaluated. Accordingly, this study aims to identify the optimal electrode spacing for electrical resistivity surveys in open dumpsites. An electrical resistivity survey was conducted at the Nonthaburi disposal site, Thailand, and the results were compared to synthetic cases simulated using the forward modeling technique. Electrode spacing values of 2, 2.5, 4, and 5 m were used. The models were evaluated using the Nash–Sutcliffe model efficiency coefficient, model sensitivity, and root mean square error. The real case survey results illustrate that small electrode spacings of 2 and 2.5 m provide a realistic model, however, the root mean square error is higher due to the use of more outlier electrodes during measurement. Consistent with the synthetic case studies, electrode spacing values of 2 and 2.5 m yielded accurate inverted models. Overall, this study illustrates the benefits of using a forward modeling technique for selecting the optimal electrode spacing for open dumpsite surveys.

Keywords: electrical resistivity imaging, forward modeling, electrode spacing, open dumpsite

Introduction

The principal municipal solid waste (MSW) management methods are waste disposal on land (i.e., landfilling and open dumping), recycling, and incineration. Landfilling and incineration methods are usually conducted in developed countries [1], whereas open dumping is typically performed in developing countries [2]. As of 2019, of the 2,246 disposal sites in Thailand, 2,004 were open dumpsites (89.23%) with improper waste disposal management [3]. These dumpsites are responsible for a range of environmental

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issues, including waste leakage, greenhouse gas emissions, and groundwater contamination. However, waste mining is an efficient process to mitigate these problems and reduce environmental contamination; in addition, this method yields recycled materials and energy from processed waste [4].

The waste mining process begins with the excavation of material from stabilized waste, which is then sorted by size and composition [5]. The waste mining site's characteristics, economic potential, safety regulations, and associated project costs will be assessed before the implementation phase [6]. The site characteristics include the waste composition, waste stability, groundwater level, and geological structure, which are also studied during the initial setup of the site. Direct investigation methods such as test pits and borehole drilling are generally used for site studies; however, these investigation methods typically heavily spatially restricted due to costs and time-consuming, whereas geophysical surveying allows a much larger area to be investigated. Moreover, direct investigation can be high-risk [7].

Geophysical techniques are increasingly being used to examine disposal areas and waste characteristics. Examples of the use of geophysical surveys for disposal work management purposes include evaluating solid fuel in dumpsites, pre-scanning before mining decisions, defining heterogeneous features in landfills, delineating leachate plumes, studying leachate migration, investigating water pollution from dumpsites, detecting soil contamination, and constraining the geometry of landfill [8-17]. These approaches have the advantage of not causing damage to the area under investigation and taking less time than direct investigation methods [7]. The typical geophysical methods used for field studies are seismic, electromagnetic (EM), ground-penetrating radar (GPR), and electrical resistivity imaging (ERI) surveys. However, seismic, EM, and GPR techniques have notable limitations such as operational difficulty, shallow subsurface penetration, and decreasing imaging depth when surveying through clay layers [18]. The ERI method is popular due to its convenience, low cost, accurate results, and lack of site disturbance [19]. The ERI technique is used to analyze the electrical behavior of the subsurface [20]. This method's surveying process initially involves passing electricity through a pair of metal electrodes and measuring the potential difference at another pair of electrodes [21]. The apparent resistivity (ρ_a) can be calculated as follows:

$$\rho a = K \frac{\Delta V}{I} \tag{1}$$

where I is the electrical current, ΔV is the voltage drop between the electrodes, and K is a geometric factor [22]. The collected data are processed using computer software to generate a subsurface electrical resistivity model that represents the characteristics of the surveyed waste materials. The electrode spacing in ERI surveys is fixed, however, differences in electrode spacing affect the survey results, where wider electrode spacing values generally allow a greater subsurface investigation depth [23]. However, the electrode spacing can significantly impact the entirety of the ERI model [24].

Improper selection of electrode spacing values may lead to an incomplete electrical resistivity model, and preliminary models may provide an inaccurate or misleading interpretation of the subsurface. To address these issues, the electrical resistivity forward modeling method can be used to identify the optimal electrode spacing and determine which electrode spacing values are unsuitable [23]. Thus, in this study, we aim to evaluate the correct electrode spacing for ERI surveys in open dumpsites using a forward modeling approach. Optimizing electrode spacing is crucial for providing reliable survey results and improving the accuracy of waste characteristic interpretations in disposal sites prior to waste mining operations.

Materials and Methods

Study Site

This study's investigation was conducted at the Nonthaburi waste disposal site, located in Thailand's Nonthaburi province. This site has received MSW from the local administration since 1983. The study area is a dumpsite situated over a clay base with no liner and daily cover. The disposed waste is typically around 17-19 years in age; the thickness of the waste ranges from 12 to 20 m. This waste has suitable characteristics for recovery as it is already stabilized. The disposed waste primarily consists of plastic and soil-like materials, accounting for 40.08% and 38.48% of the total waste, respectively. Other disposed waste components include wood, leather, textiles, ceramics, glass, and metals (5.48%, 0.59%, 0.74%, 6.00%, 1.86%, 3.00%, and 3.76%, respectively) [25]. Differences in the site's waste composition cause spatial variability in the subsurface resistivity of waste in the disposal area. The Nonthaburi disposal site has a refuse-derived fuel plant, leachate treatment plant, and infectious waste kiln within its boundary, as shown in Fig. 1.

The overall study workflow is shown in Fig. 2. The ERI survey was conducted with variable electrode spacing and the synthetic apparent resistivity model was then created using the forward modeling method; a comparison was then performed between the synthetic model and real survey data. The synthetic models were designed to have the same geometry as the field data collected using different electrode spacings. Typically, the forward modeling method is used before ERI surveying when the target subsurface feature is approximately known. However, the subsurface structure of the dumpsite is complex, therefore, in this study, synthetic models were generated after the survey.

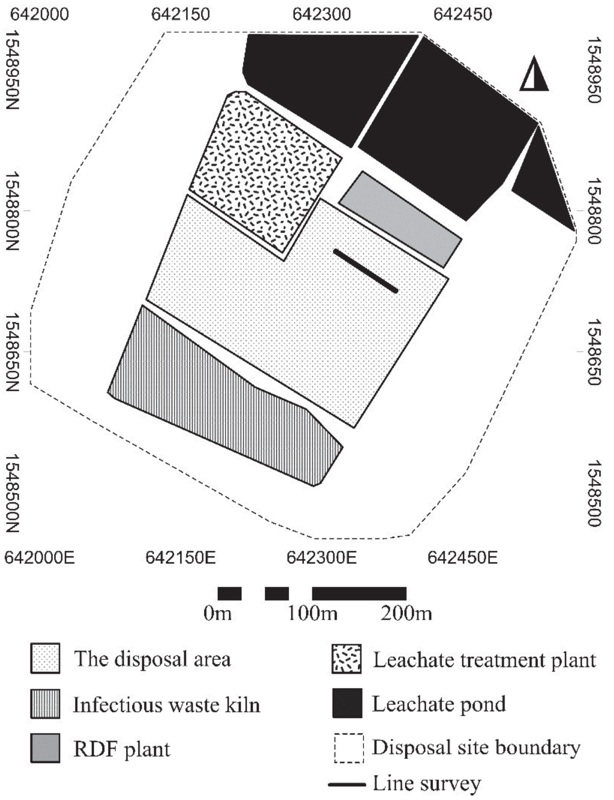

Fig. 1. Nonthaburi disposal site plan view.

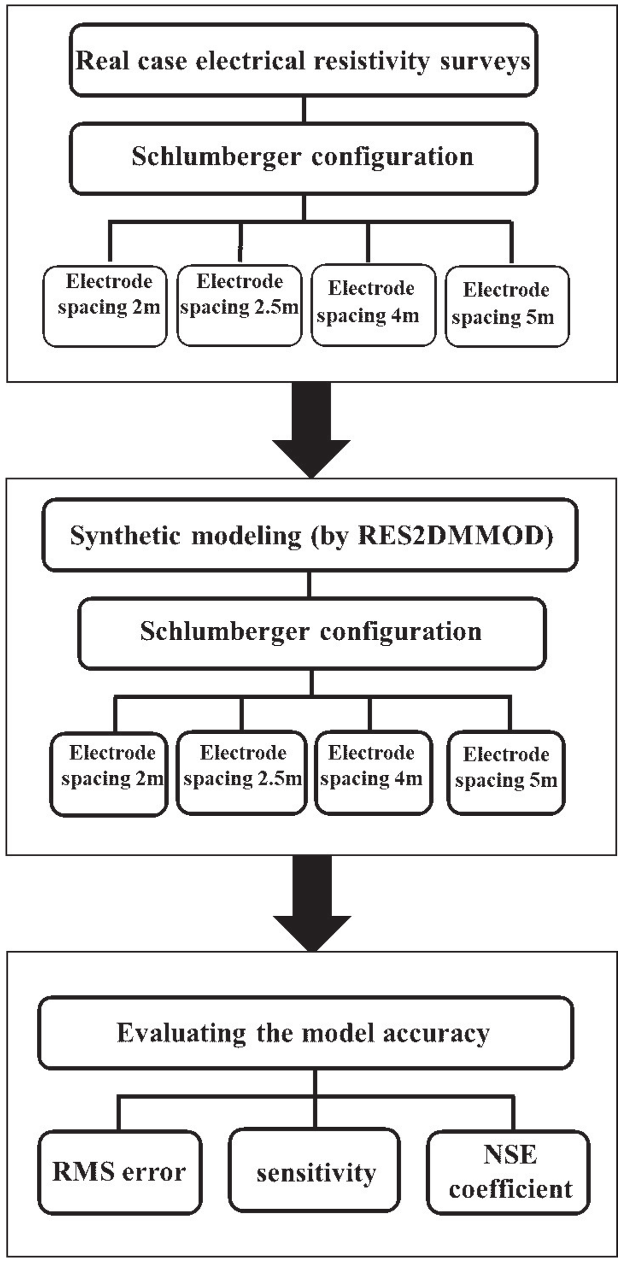

Fig. 2. Research workflow.

Electrical Resistivity 2D Survey

In this study, a GD-10 resistivity meter system with multi-electrodes (ST Geomative Co., Ltd, Shenzhen, China) was used to measure the electrical resistivity of waste strata at the disposal site. First, the electrical resistivity was measured by passing an electrical current through a pair of electrodes; the electrical potential was then measured using another electrode pair, as shown in Fig. 3. The electrodes were made of copper, with a diameter of 10 mm and a length of 280 mm. Of the three traditional ERI configurations (i.e., Wenner, Schlumberger, and dipole-dipole), the Schlumberger array was used in this study due to its moderate sensitivity to horizontal and vertical structures [23], which is suitable for the dramatic changes in subsurface conditions present at the studied disposal site. Furthermore, this configuration also requires minimal time for data collection [26] compared to the dipole-dipole configuration and provides similarly accurate results. The electrode spacings were set to 2, 2.5, 4, and 5 m for each measurement, with a total survey line length of approximately 100 m. The apparent resistivity data from measurements were processed using RES2DINV ver. 4.03 software – this program generates a true resistivity model from apparent resistivity data using the least squares optimization method with five iterations.

Electrical Resistivity 2D with Forward Modeling

After the resistivity measurements were conducted, forward modeling was also performed to simulate the study site's apparent subsurface resistivity; the synthetic models in this study were created using the finite element technique in RES2DMOD software. This approach is suitable for creating complex models representative of the heterogeneous nature of open dumpsites. The subsurface features are divided into many rectangular blocks, as shown in Fig 4. The M nodes and N nodes represent the vertical and horizontal directions of the rectangular mesh, respectively. These rectangular elements can contain different resistivity values; thus, complex subsurface features can be resolved using a sufficiently fine mesh in this method.

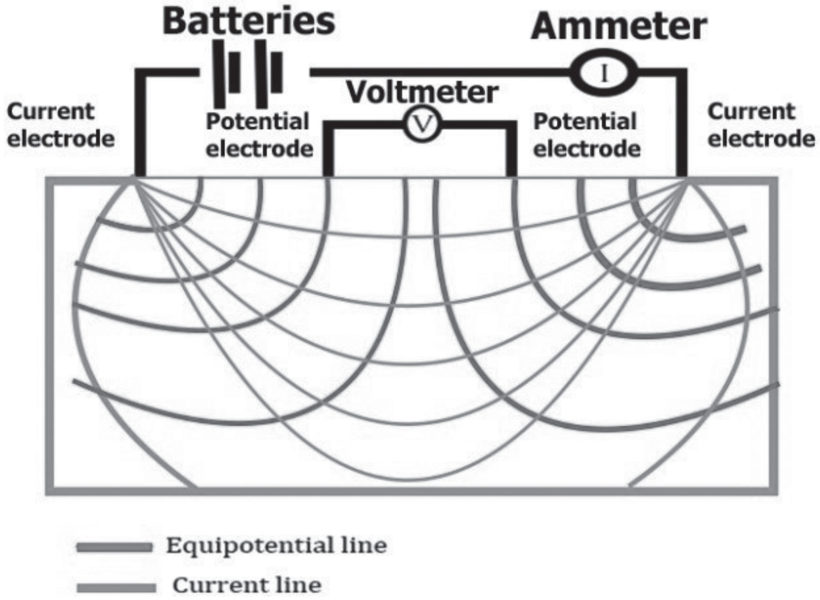

Fig. 3. Electrical resistivity measurement method.

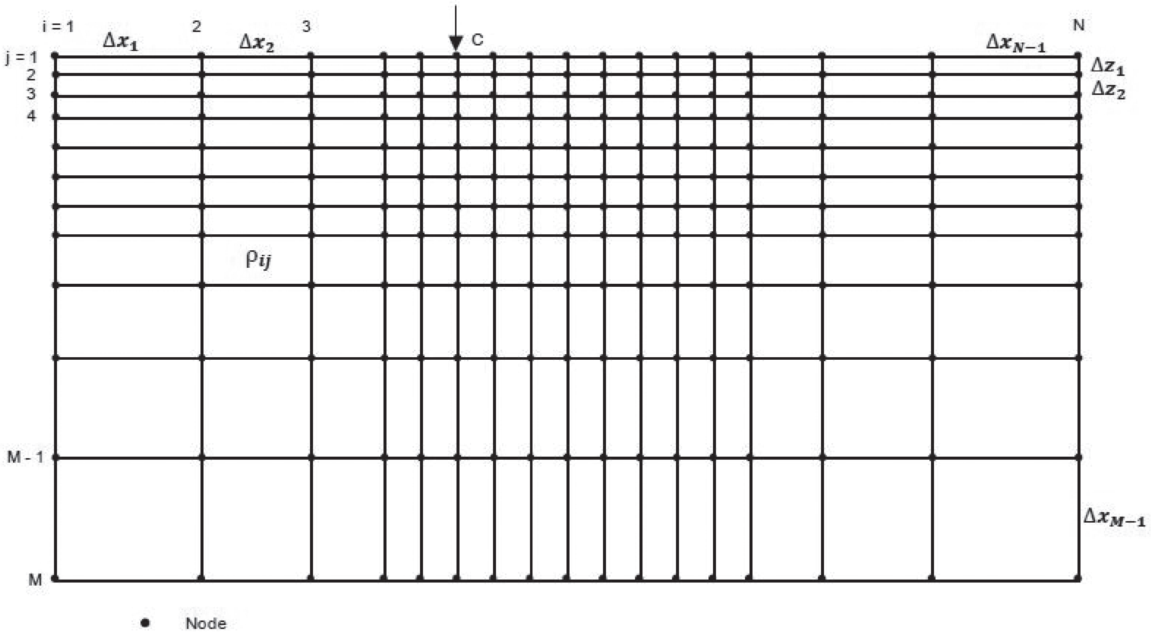

Fig. 4. Schematic diagram of the finite-difference or finite-element mesh (Modified from [27]).

The numbers of rectangular blocks used in the models in this study vary according to the electrode spacing. For example, the models with spacings of 2, 2.5, 4, and 5 m contain 188, 152, 96, and 76 rectangular blocks, respectively. The number of blocks is calculated using Equation (2):

$$\textit{Number of blocks} = (N_E - 1) \text{ x } \textit{number of nodes per unit electrode spacing} \quad (2)$$

where N_E is the number of electrodes [27], and the number of nodes per spacing used in this study is four. The model parameters, such as electrode spacing, were generated for different distance values. The synthetic apparent resistivity model was a total of 31 m thick, consisting of a low resistivity layer (12 Ω·m) representing the clay basement at the base of the site (depth values of 17-31 m). The layer overlying the clay base, i.e., the compacted waste layer with high moisture (depth values of 4.4-17 m), was assigned a higher resistivity (25 Ω·m). This was overlain by a simulated layer of compacted waste with low moisture (depth values of 0-4.4 m). In addition, other anomalies were simulated in the synthetic model, including

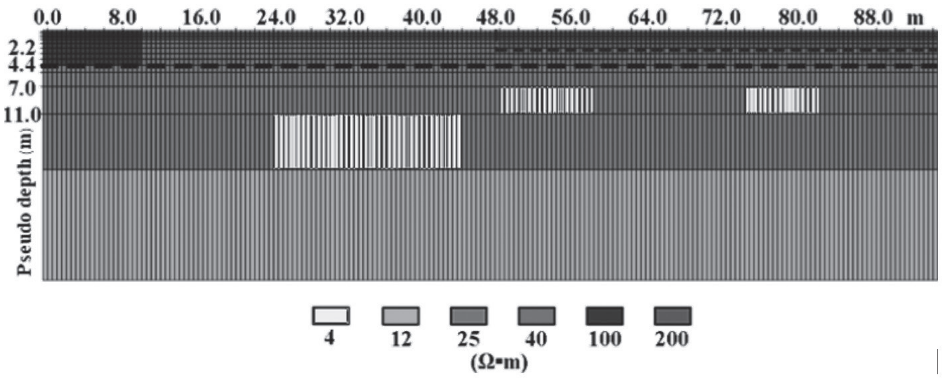

Fig. 5. A complex synthetic apparent resistivity model created by RES2DMOD.

the resistive layer (100-200 Ω·m), representing dry waste or material with high plastic content, and conductive plumes (4 Ω·m) corresponding to leachate zones. The synthetic model is shown in Fig. 5.

The synthetic apparent resistivity model was saved in the. DAT file format. These data were also processed using RES2DINV ver. 4.03 to calculate the true resistivity model. The synthetic model was simulated consistently with the data collected using the Schlumberger configuration. The electrode spacing values in the synthetic model were set at 2, 2.5, 4, and 5 m, i.e., the same spacings as the field survey measurements.

Model Accuracy Evaluation

In this study, the Nash-Sutcliffe model efficiency coefficient (NSE) was used to evaluate the model accuracy in each case. The NSE coefficient can be calculated using Equation (3):

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)}{\sum_{i=1}^{n}(Y_i - \bar{Y}_i)} \tag{3}$$

where the actual data, mean of the actual data, calculated data, and the number of data points are represented by Y_i, $\bar{Y}$, $\hat{Y}$, and n, respectively. The NSE coefficient is generally used to evaluate the accuracy of hydraulic or environmental models, including geophysical models [26]. The sensitivity of each model was also assessed to evaluate the model accuracy. This parameter was derived from the average sensitivity calculation for each model; the higher the value of the sensitivity function, the greater the subsurface region's influence on the measurement [23]. The root mean square (RMS) error for each model was also considered in this study. The RMS error describes the difference between the actual measurements and calculated data, following equation (4):

$$RMS\ error = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \hat{x}_i^2)^2}{N}} \tag{4}$$

where x_i, $\hat{x}_i$, and N are the measured apparent resistivity, the calculated apparent resistivity, and the number of data values, respectively.

Results and Discussion

Resistivity Models from Forward Modeling

The resistivity models calculated from the synthetic data (Fig. 5) are shown in Fig. 6. The RMS errors for the simulated resistivity models were 1.24%, 1.32%, 2.4%, and 3% for electrode spacings of 2 m, 2.5 m, 4 m, and 5 m, respectively (Fig. 7). The investigation depth of these models was approximately 16-19 m (Fig. 6). From these results, the conductive layer, representing the clay base at the bottom of the site below depths of 17 m, cannot be detected in all cases, although the maximum investigation depth of the model was 19.2 m for an electrode spacing of 4 m. Interference caused by the shallower anomalies can cause difficulty in detecting the deeper anomalies [28]. In the inversion model, the waste layer with high moisture and compaction is shown as a conductive layer (20-25 Ω·m). The compacted waste layer with low moisture in the synthetic model appears as a moderate resistivity layer (40-50 Ω·m) in the inversion models. The size and position of both layers in the inversion model were close to those of the original geometry in the synthetic model. The calculated anomalies show different magnitudes after the inversion process. The resistive layers representing the dry waste or waste with high plastic content can be observed in the inversion models for electrode spacing values of 2, 2.5, and 4 m; the size and position of these resistive layers in the models using electrode spacings of 2 and 2.5 m were almost precisely the same as those in the input synthetic model.

The inversion model using a spacing of 5 m did not exhibit clear resistive anomalies. The conductive zone representing the leachate plume was poorly resolved in the inversion models with electrode spacing values of 4 and 5 m (Fig. 6). In the models using electrode

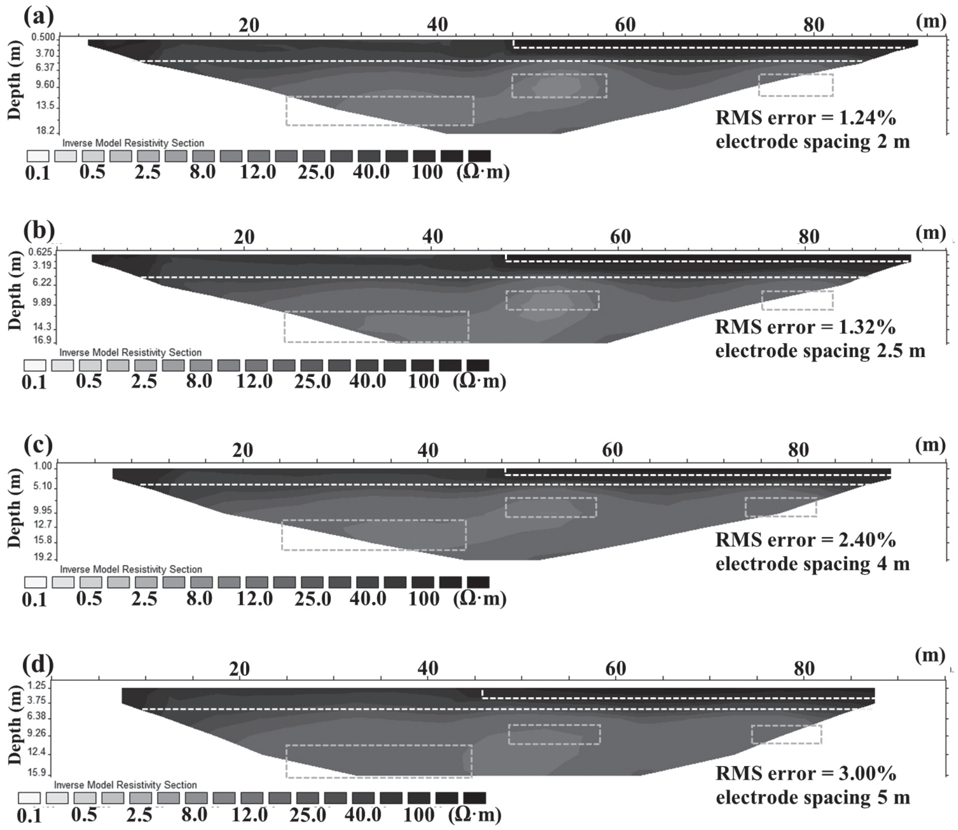

Fig. 6. Inversion models of the synthetic apparent resistivity data with spacings of 2 m, 2.5 m, 4 m, and 5 m (plots a, b, c, and d, respectively). The dashed boxes represent the exact positions of the anomalies that were generated in the synthetic models.

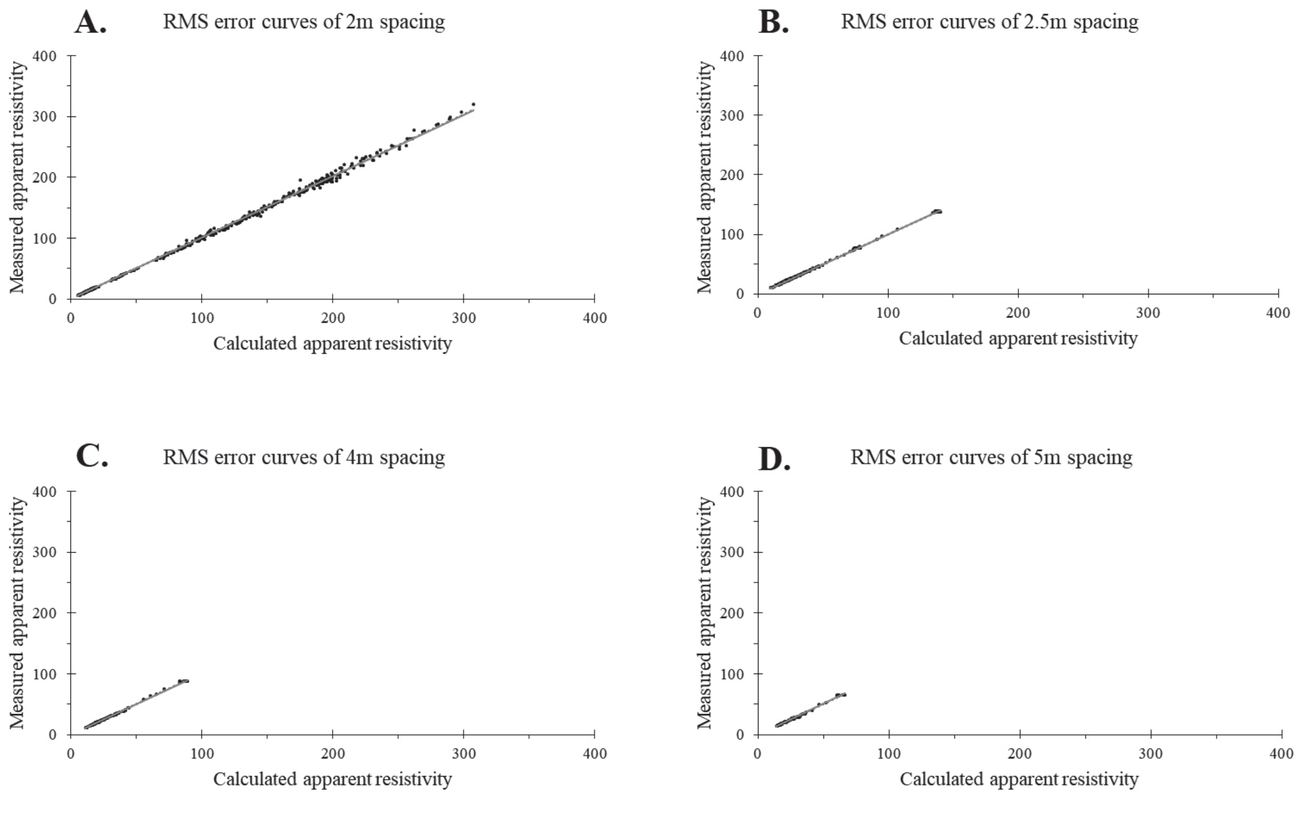

Fig. 7. RMS error curves for electrode spacing 2 m, 2.5 m, 4 m, and 5 m (A, B, C, and D, respectively).

spacings of 2 and 2.5 m, the conductive plumes (10 Ω·m zones) were not fully resolved, with only one of the upper plumes present in the inversion model (Fig. 6). Furthermore, the positions of these zones and their resistivity values differed from those in the synthetic model. These observations are consistent with the study of Nordiana and Sadd [29], who found that some features from the input synthetic model can be changed during the inversion process. Furthermore, the fact that some anomalies were not resolved in the models using 4- and 5-meter electrode spacings demonstrates that these spacing values are not suitable for use in open dumpsites. This finding is similar to observations by Abdul-Nafiu et al. [24], who reported that improper electrode spacing causes the disappearance of some subsurface features. From this study's results, the inversion models with narrower electrode spacing tend to describe the complexity of the model better than the wider spacings. This is due to the greater number of model blocks in the models with short electrode spacing than those with larger electrode spacing, a finding consistent with the study of Zhang et al., [30]. Overall, the greater the mesh density, the higher the inversion resolution.

Resistivity Models from Real-World Surveying

Fig. 8 shows the true resistivity models based on ERI surveying at the Nonthaburi disposal site. These models exhibit heterogeneous features due to the variable material characteristics within the dumpsite. The identified resistivity zones can be classified into three principal types. The first is the high resistivity layer (100-200 Ω·m), representing dry waste with low compaction or resistive material such as plastic or rubber. The resistivity characteristics of a plastic layer were examined in the study of Chungam et al. [17], in which the low density of the plastic layer was found to cause high electrical resistivity (100-300 Ω·m). In addition, this finding is in agreement with the study by Yannah et al. [31], who identified the high resistivity layer in the dumpsite as household waste which consists of plastic and rubber. The resistivity of materials from municipal activity (i.e., rubber, plastic, or glass) is typically high (around 80 to 200 Ω·m) and resistive layers are usually located near the surface. The second zone type is the moderate resistivity zone (20-40 Ω·m). This characteristic can be interpreted as resulting from high subsurface organic content or material with high water retention, such as soil-like materials. The latter interpretation is consistent with the study by Kusuyama

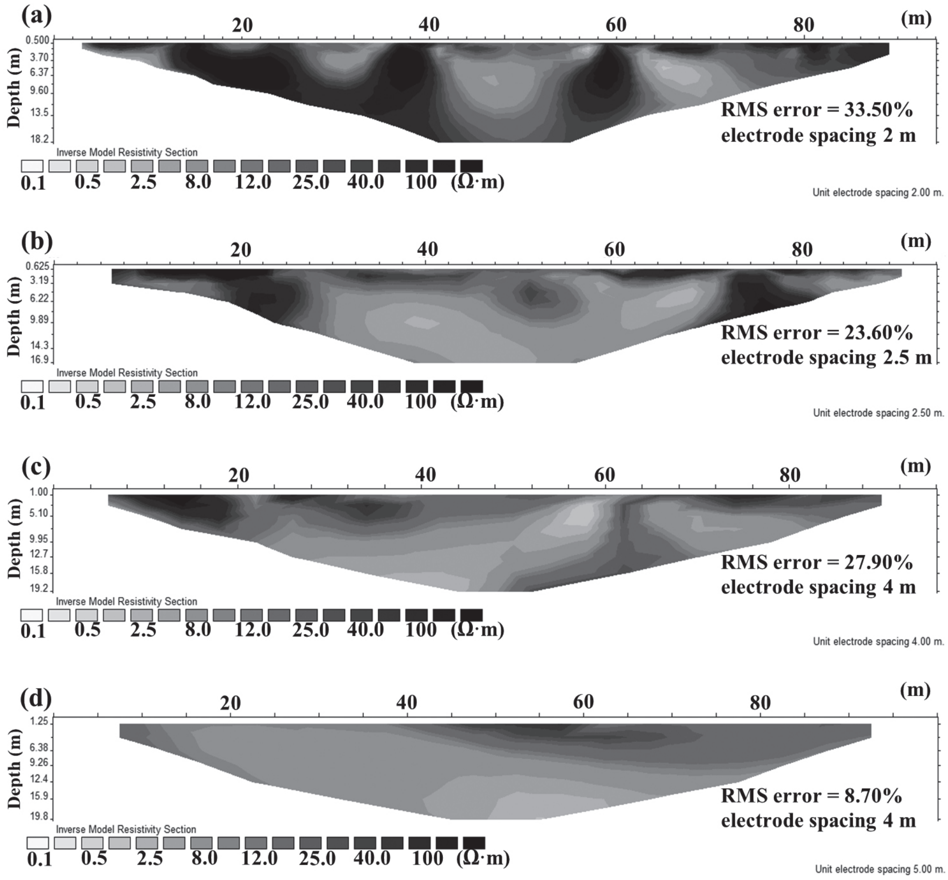

Fig. 8. True resistivity inversion models of the apparent resistivity data from surveying with spacing values of a) 2 m, b) 2.5 m, c) 4 m, and d) 5 m.

et al. [32], who reported that the electrical resistivity of soil in landfills varies from 25 to 30 Ω·m. The last zone type is the low resistivity plume (2.5-8 Ω·m) which can be interpreted as a leachate plume or saturated waste zone. Previous studies have reported that materials saturated by leachate or water have electrical resistivity values of less than 2.5 to 10 Ω·m [2, 32-35]. Leachate usually shows low resistivity due to intense ion dissolution, which can maintain electrical conductivity within the plume [36, 37]. From this study's results, a high resistivity zone is located on both left and right sides of the models. This high resistivity zone was largest in the model using a 2-meter electrode spacing (Fig. 8a). The model using an electrode spacing of 2.5 m is the most similar to the 2-meter electrode spacing model. At all electrode spacing values, a low resistivity zone was recorded in the center of the model, which tends to be in the lower part of the model. As discussed above, low resistivity features typically correlate to high moisture levels. Moisture tends to sink to the bottom of the dumpsite due to gravity [38] and thus appears as a conductive area in the ERI model.

A low resistivity plume was recorded in the model using an electrode spacing of 2 m (at approximately x = 62-70 m); however, the resistive zone in the model using a 2.5-meter electrode spacing value was smaller than that recorded in the 2-meter spacing model. In contrast, in the 2.5-meter spacing model, the conductive zone (at approximately x = 30-70 m) was wider than in the model measured using a 2-meter electrode spacing (Fig. 8b). The inversion model using a 4-meter electrode spacing shows similar features to the 2.5-meter model, however, the size of the resistive zone was smaller in the 2.5-meter model (Fig. 8c). Using an electrode spacing of 5 m, the model shows only the resistive zone in the upper right and a conductive zone throughout the rest of the model area (Fig. 8d). The resistivity models from surveying with spacings of 2 m, 2.5 m, and 4 m provide greater detail than the 5 m spacing model. This shows that ERI surveys with a spacing of 5 m may be unsuitable for open dumpsites with complex internal structures. Variability in the identified subsurface features in the disposal site, as reconstructed with different electrode spacing values, may originate from the effect of varying electrode locations, consistent with the study by Udosen and Potthast [39]. The RMS error values of the resistivity models derived from the real-world survey were found to be 33.5%, 23.6%, 27.9%, and 8.7% for electrode spacing values of 2 m, 2.5 m, 4 m, and 5 m, respectively. Accordingly, measurement outliers may cause higher RMS error values. Zhou and Dahlin [40] reported that outliers usually occur due to the high resistance of some electrodes used in the measurement. In this study, the surface of the measured area consisted of plastic and resistive material, leading to high electrode resistivity. Thus, using electrode spacings of 2, 2.5, and 4 m generates a larger RMS error than measurement using an electrode spacing of 5 m due to the greater number of electrodes required. The resistivity model from surveying with a spacing of 5 m achieved the best RMS error, however, as identified by Abdul-Nafiu et al. [24], models with a low RMS error are not necessarily the most accurate representation of an area's subsurface structure.

Model Accuracy and Comparison

The RMS error, average electrical resistivity value, average sensitivity, and NSE coefficient of each model are shown in Table 1.

The RMS error values of the real-world survey models were high due to the loose surface of the dumpsite. This loose surface leads to imperfect contact between the electrodes and the ground, and poor contact quality results in greater RMS error [41]. However, the low RMS error values of the inversion models for the synthetic case (1.34–3.00%) illustrate the difference between calculated and raw data. The RMS error of the synthetic model increases with increasing electrode spacing, in contrast to the real-world data where the RMS value decreases as the electrode spacing increases. The average sensitivity of the real-world survey models was similar in each case. The lowest average model sensitivity was recorded when using an electrode spacing of 5 m. Similarly, for the synthetic model, the lowest average sensitivity in the inversion model was recorded for an electrode spacing value of 5 m. Overall, the average sensitivity of inversion models using narrower spacing was greater than for those using wide spacing, however, this high sensitivity leads to increased model accuracy.

From this study's results, the average electrical resistivity of the model was found to be inversely proportional to the electrode spacing-models using

Table 1. Electrical resistivity model information.

Model	Real cases				Synthetic model			
Spacing (m)	2	2.5	4	5	2	2.5	4	5
RMS error (%)	33.50	23.60	27.90	8.70	1.24	1.32	2.40	3.00
Avg resistivity (Ω·m)	14.33	15.54	10.33	8.77	86.48	33.60	29.27	27.37
Avg sensitivity	4.61	4.06	2.99	2.53	4.46	4.71	4.54	3.26
NSE	0.85	0.75	0.61	0.96	0.998	0.999	0.996	0.994

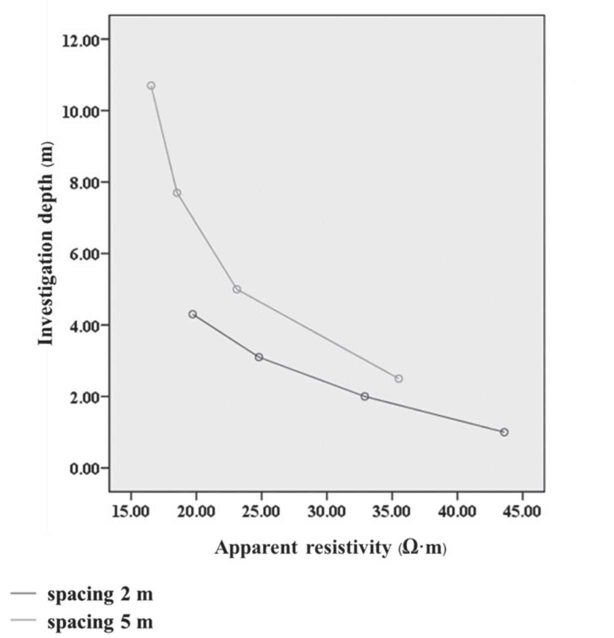

Fig. 9. Apparent resistivity values with depth for electrode spacings of 2 m and 5 m.

a wide electrode spacing yielded lower average electrical resistivity values than those with narrow spacing. This result can be explained based on the study of Gourdol et al. [26]. The first layer of data measured in the model using wide electrode spacing was deeper than that measured using narrow electrode spacing, i.e., wider electrode spacing values measure less of the uppermost part of the subsurface. However, the most resistive zone of the waste pile is usually located close to the surface due to high evaporation or low compaction in the shallowest material. Thus, the average electrical resistivity of the model using wide electrode spacing was low due to a lack of resistive data close to the upper model surface. Fig. 9 shows the measured electrical resistivity data using electrode spacings of 2 and 5 m. The investigation depth of the first measured data point using an electrode spacing of 5 m was deeper than that recorded when using an electrode spacing of 2 m, thus the upper resistive zone was entirely omitted when using an electrode spacing of 5 m.

The NSE coefficient values of the real-world survey models using electrode spacing values of 2, 2.5, 4, and 5 m were 0.85, 0.75, 0.61, and 0.96, respectively. The models using electrode spacings of 2, 2.5, and 5 m showed good prediction accuracy based on the NSE coefficient parameter; however, the model accuracy using an electrode spacing of 4 m (0.61) indicated only a satisfactory prediction model. The NSE coefficient of all inversion models from synthetic data was close to 1 (approximately 0.99). This result indicates that the inversion models from synthetic data are highly accurate, thus, inversion of synthetic data produces excellent predictive models [42]. Overall, our results show that model accuracy using narrower electrode spacing values tends to be higher than when using wide electrode spacing; this trend is broadly consistent with the synthetic cases, although a minor discrepancy was observed in terms of the NSE values. These trends are related to the amount of observed data, where shorter electrode spacing values provide more observed data, thus yielding higher quality inversion results.

Conclusions

This is the first study to use the forward modeling technique to determine proper electrode spacing values for ERI surveys in open dumpsites. The simulation results and actual measurements illustrated that 2- and 2.5-meter electrode spacings were appropriate for ERI surveying of open dumpsites. These spacing values allow the electrical resistivity model to reflect waste characteristics very close to the true subsurface conditions. Electrical models collected using this electrode spacing can effectively be used for open dump mining planning, which can enhance RDF productivity and support the circular economy. This study's results also illustrate that using an electrode spacing greater than 2.5 m results in low-resolution profiles due to fewer resistivity blocks and data points.

At present, no studies have investigated the use of forward modeling for planning mining waste in sanitary landfills. Therefore, a similar approach could be applied to identify the appropriate electrode spacing for ERI surveys in sanitary landfills; this technique can be used to optimize the model parameters and obtain resistivity models with an appropriate resolution to characterize subsurface waste as realistically as possible. In addition, the forward modeling approach should be implemented before field surveying in other geophysical methods, such as induced polarization and electromagnetic methods, to create accurate models that can be used in landfill applications.

Acknowledgments

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Conflict of Interest

The authors declare no conflict of interest.

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