

## Geophysical methods for the investigation of a closed dumping ground

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**Abstract.** Reclamation of closed dumping grounds is a potential solution to solve land scarce problems. Traditional geotechnical investigations of closed dumping grounds face some problems, such as the emission of hazardous liquids and gases, and the lack of ground information due to the discontinuity between two boreholes. Thus, noninvasive and continuous investigation methods are needed to supplement traditional geotechnical investigations. In this paper, two types of geophysical investigation methods, Seismic Analysis of Surface Waves (SASW) and 2D Resistivity, were carried out to study noninvasive and continuous site investigations for dumping grounds. The two geophysical methods are able to profile the distribution of physical properties of the fill and original materials, by which the extent of the dumping ground can be found and some anomalies in the subsurface can be located. Boreholes were used to assist in locating the dumping material-ground interfaces. The results show that dumping material-ground interfaces obtained from the two geophysical methods are roughly consistent. Moreover, attempt is made in the paper to use the geophysical methods to classify the types of dumping materials. The results show that the classification of dumping materials using the geophysical methods follows the results of the manual sorting of the dumping materials from a borehole.

**Keywords:** dumping ground; geophysical investigation; SASW survey, 2D resistivity survey

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## 1. Introduction

Fast expansion of many cities all around the world leads to the demand for more land resources. Reclamation of closed urban dumping grounds is a potential solution for land recycling. It has been gaining increasingly interests in the research area in recent years (Xia and Miller 2007, Balia and Littarru 2010, De Carlo *et al.* 2013). A comprehensive investigation on the geotechnical and environmental conditions of dumping grounds is a necessary step. Traditional geotechnical investigation methods in dumping grounds face two problems. First, the subsurfaces of dumping grounds are very heterogeneous, compared to common stratified subsoils. Thus, conventional borehole data can hardly represent true subsurface situations because of the lack of information between two boreholes. Second, borehole drilling needs to pierce the impervious stratum of the landfill, causing potentially the emission of hazardous gases and liquids. Geophysical methods are the alternative options which can avoid or minimize the abovementioned problems. There are many available geophysical methods that can be used for the delineation of landfills. These methods can basically be categorized into several types according to the parameters measured, including electrical, electromagnetic, seismic, and magnetic methods (Soupios *et al.* 2008). Applications of these methods in landfills include: (1) finding the geometrical extent of landfills and locating the boundaries of different strata; (2) classifying buried materials; (3) detecting leachate plumes; (4) detecting possible damages in the liners and locating leakages; (5) locating gas migration pathways; (6) determining dynamic characteristics of landfills for engineering analysis, etc. (Soupios *et al.* 2008, De Carlo *et al.* 2013). Due to the complexity of the problems facing in the investigation of landfills, it is suggested that a combination of different geophysical methods that are sensitive to different physical properties should be used together to provide a more meaningful delineation of waste bodies (Boudreault *et al.* 2010). In this study, two investigation methods, Seismic Analysis of Surface Waves (SASW) Survey and 2D Resistivity Survey, were tested at a closed dumping ground.

In SASW Survey, excitation at ground surface generates surface waves at various frequencies. The surface wave velocity can be obtained at discrete frequencies by analysing the ground surface response at two points with known distance apart. The plot of surface wave velocity versus frequency is known as dispersion curve. Shear wave (S-wave) velocity profile can be modelled from the dispersion curve (Kavazanjian *et al.* 1996, Anderson *et al.* 2008). S-wave velocity is a function of the elastic properties (shear modulus), and thus is directly related to the hardness and the stiffness of the materials (Fujiwara 1972, Santamarina *et al.* 2001, Jafari *et al.* 2002, Hasancebi and Ulusay 2007). Common applications of SASW Survey in the investigation of landfills include profiling the waste mass, evaluating the cover thickness, searching the waste/original soil interface, and identifying underground obstructions (Kavazanjian *et al.* 1994). A disadvantage of SASW Survey is that the maximum depth is limited to about 25 m (Soupios *et al.* 2008).

In two-dimensional (2D) Resistivity Survey, the electric resistivity profile of the ground can be obtained by measuring the electric resistivity using an array of electrodes stuck into the ground (Soupios *et al.* 2008). Common applications of 2D Resistivity Survey for environmental geology investigation include locating contaminants, identifying the quality of contaminant immobilisation, determining faults and fractures, and searching interfaces between waste and original soil (Greenhouse and Harris 1983, Abu-Zeid *et al.* 2004, Meju 2000, Frid *et al.* 2008, Soupios *et al.* 2008, Sankaran *et al.* 2010).

This research was carried out in Phase III of Lorong Halus Dumping Ground (LHDG). LHDG was a large used dumping ground that was operated from early 1970s till late 1990s. It has been

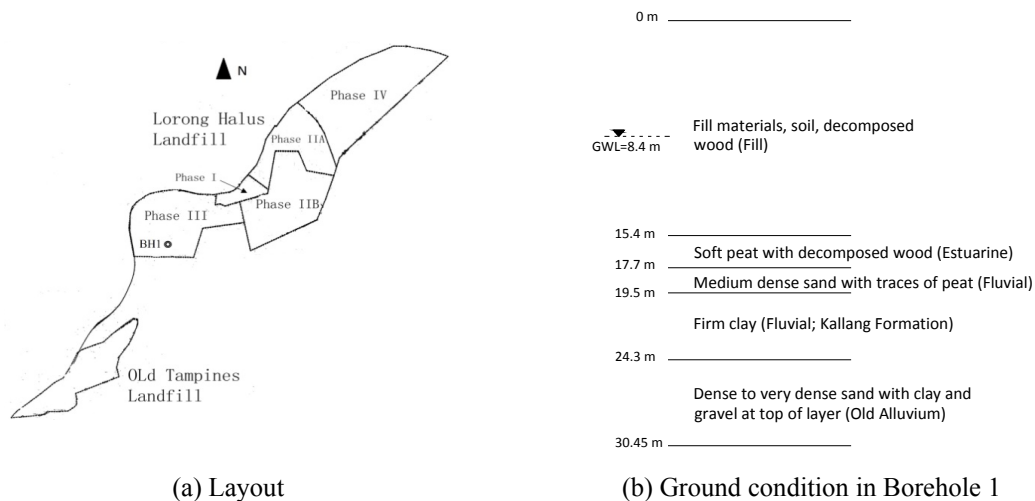


Fig. 1 Lorong halus dumping ground

closed for about 15 years till now. It is located in the north of Singapore with its western and northern perimeter bordering on Sungei Serangoon River. Across the river in its northern orientation lie the newer residential developments of Sengkang and Punggol. The dumping ground was divided into several segments by operational periods as can be seen in Fig. 1(a). The dumping ground was formerly mangrove swamps. Dumping materials basically consist of municipal wastes, and construction and demolition (C&D) wastes. Phase III covers an area of 44 hectares. Its operational period was from 1983 to 1989. Primary dumping materials in Phase III were C&D wastes rather than municipal wastes. It was an uncontrolled dump site with little engineering consideration, i.e. there was no liner material or leachate collection system in place. The terrain in Phase III is slightly sloped and mounded towards its center. So the surface runoff is generally away from its center. As there are no treatment facilities on-site for leachate or surface-runoff, rainwater is simply diverted by perimeter drains around Phase III. The original grounds of Phase III were found to be a mangrove swamp underlain by marine clays, organic and fluvial Kallang Formation deposits as well as dense sand and gravel of the Old Alluvium. The thickness and depths of these strata are rather variable. The ground condition from a borehole (BH1) is given in Fig. 1(b).

In this paper, the feasibility of two geophysical methods, SASW and 2D Resistivity, were examined for the ground investigation of a used landfill. The search of the dumping material-soil interfaces was done using geophysical data with the assistance of borehole drilling. Manual sorting of filling materials from one borehole was also carried out to validate the classification of the types of filling materials from the geophysical surveys.

## 2. Methods and test plan

Two types of geophysical investigation methods, SASW and 2D Resistivity, borehole drilling, and manual sorting of filling materials were carried out in this study. All field tests were carried out in two test plots. The location of the test plots are at LHDG Phase III as shown in Fig. 2. Fig. 3



Fig. 2 Location of the test plots for geophysical investigation

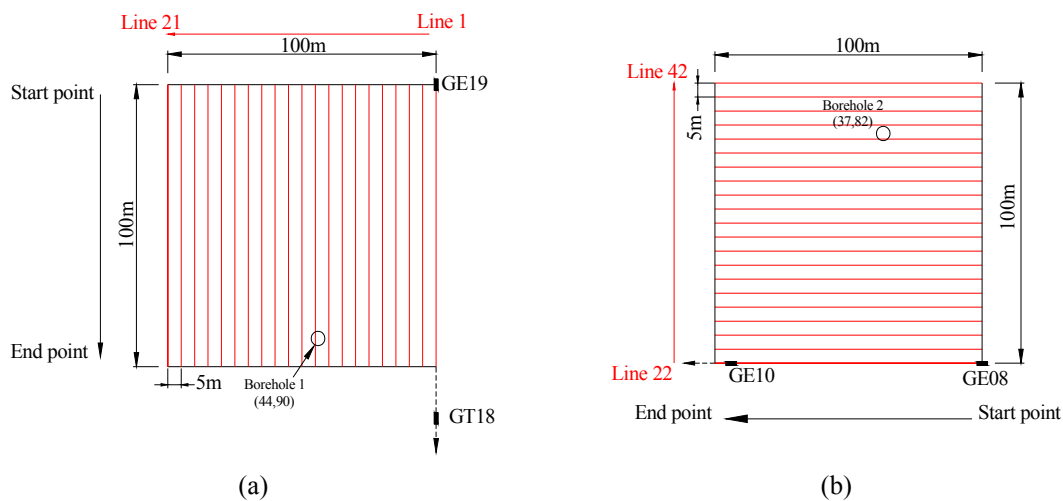


Fig. 3 Survey line orientations of test plots: (a) Test Plot 1; (b) Test Plot 2

shows the layout of geophysical survey lines. Both geophysical methods were conducted at 21 survey lines of each test plot. In Test Plot 1, Line 1 is located on the connection line of GE19 and GT18. The other lines were parallel to Line 1 with 5 m spacing. In test plot 2, Line 22 was the first survey line. Line 22 was on the connection line of GE08 and GE10. The other lines were parallel to Line 22 with 5 m spacing. GE08, GE10, GE19 and GT18 were existing gas extraction wells which were used as landmarks for locating the test plots. The SASW equipment used in this study was a 24-Channel seismograph. The model was McSeis SX-XP. It is manufactured by Oyo Corporation, Japan. The model of 2D Resistivity equipment was McOHM Profiler 4. It was a fully automatic multi-electrode resistivity meter.

Geophysical investigations cannot completely replace borehole investigations. The information obtained by intrusive methods is required to constrain and verify geophysical interpretations. But the latter can significantly reduce the number of required boreholes. In this study, one borehole was drilled in each test plot. The locations of the boreholes are marked in Fig. 3. The purposes of the boreholes were: (1) to find the real dumping materials-soil interface to assist in locating the continuous interfaces obtained from the geophysical surveys; and (2) to find the types of materials through manual sorting in order to verify the dumping material classification through the geophysical methods. The manual sorting of dumping materials was done for the samples collected from Borehole 1 in Test Plot 1. Seven samples are collected at 1 m interval from 8m to 15 m.

### 3. Results and discussion

#### 3.1 Ground profiling using geophysical data

Fig. 4(a) is the SASW profile of Line 11 in Test Plot 1. In Fig. 4(a), the subsurface zone can be divided into several different types of regions according to the colour contours which denote different values of S-wave velocities. According to the colour scale, the red colour represents low S-wave velocity ranging from about 0.02-0.16 km/m, and the blue colour represents high S-wave velocity ranging from about 0.34-0.44 km/m. In general, S-wave velocity reflects the hardness of the media (Xia *et al.* 1999, Xia *et al.* 2002, Moss 2008). Thus, the red regions are soft materials, and the blue regions are hard materials. The other regions are in-between. Based on the pattern of the colour contour, we can see that the distribution of material hardness in the upper part of the profile is different from that in the lower part. In the upper layer, regions of various colours are mixed together randomly. This phenomenon implies that different materials with varying hardness are mixed together heterogeneously. The lower part of the profile gradually changes from green colour to blue in the vertical direction, and there is only very gentle colour variation in the horizontal direction. This observation indicates that, in the vertical direction, the hardness of subsurface materials in the lower layer increases with depth. In general, the lower layer is harder than the upper layer.

Fig. 4(b) is the SASW profile of Line 22 in Test Plot 2. Although there is almost no blue area in the upper part of the picture, it shows the same features as that in profile of Line 11. Depending on the colour contour, the subsurface can be divided into two parts. The upper one is heterogeneous. It is an irregular mixture of different colours. In this layer, materials with different hardness are mixed together. In the lower layer, the colour contours change from green to blue as the location goes deeper, indicating the increase in the material hardness.

Another example is Line 32 in Test Plot 2 which is shown in Fig. 4(c). Compared to Lines 11 and 22, there are less red colour contour and blue colour contour. But the pattern of subsurface is still similar to those in Lines 11 and 22. That is, the upper part is heterogeneous and the lower part shows a gradual increase in the S-wave velocity. The lack of red colour contour in the upper layer indicates that subsurface materials are relatively hard. The lack of blue colour contour in the lower layer may be caused by the limitation of the investigation depth.

Based on the analysis of the three SASW profiles given above, we can see that there are some similarities in these profiles. Thus, it is a reasonable prediction that the upper part consists of dumping materials and the lower part is natural soil ground. In the upper part of the subsurface, the

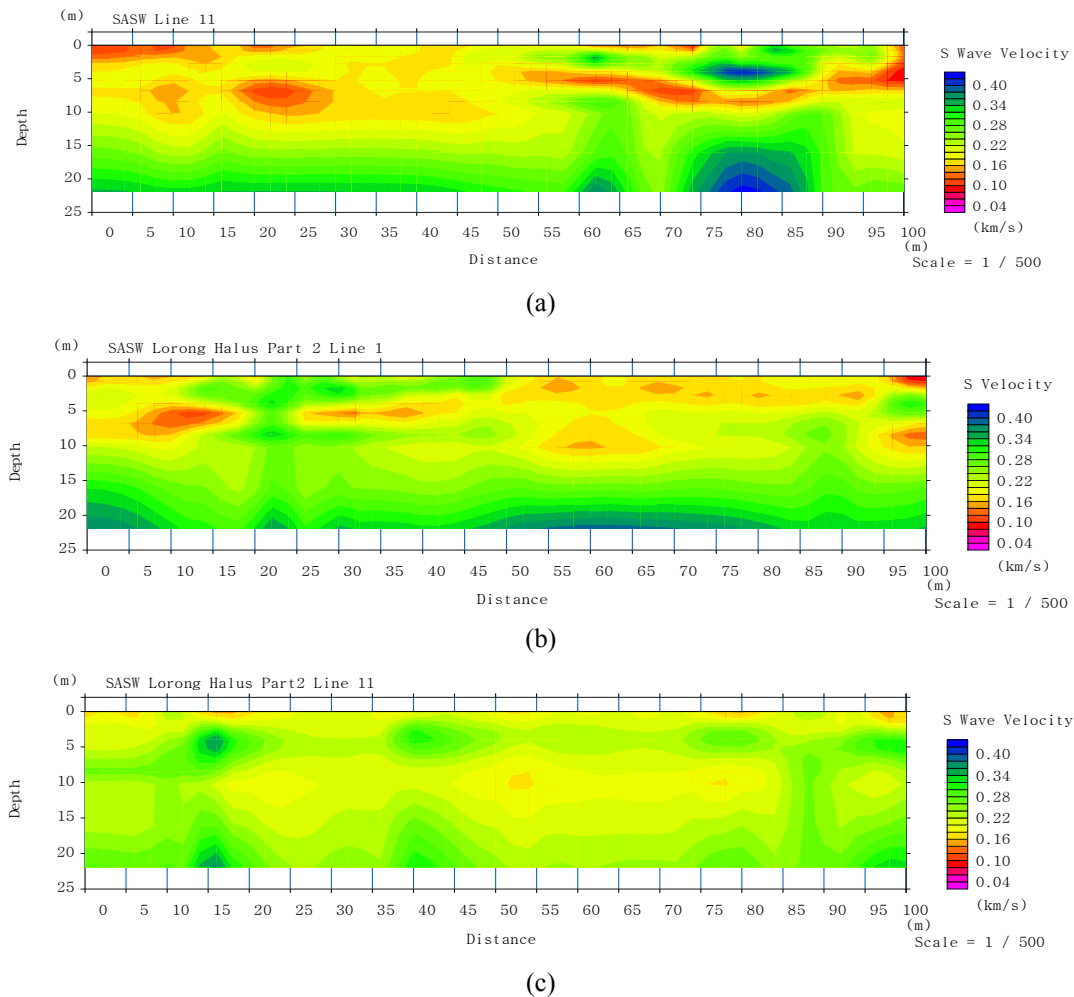


Fig. 4 SASW profiles: (a) Line 11; (b) Line 22; (c) Line 32

red colour regions could be soft materials or even voids, and blue colour regions could be hard materials. The lower part, which seems to be natural soil ground, shows a regular pattern of variations in the hardness. However, there is only gradual transition in S-wave velocity between upper and lower parts. As a result, the determination of the boundary between natural soil and fill needs the aid of other investigation methods.

Figs. 5(a) and (b) are the profiles of 2D Resistivity Survey of Line 6 in Test Plot 1 and Line 23 in Test Plot 2, respectively. According to the colour contour, the profile can be divided into different areas. Red areas represents high values of resistivity ranging from about 250-340 ohm-m, and blue region represents low values of resistivity ranging from about 5-45 ohm-m. The resistivities of yellow and green areas are in-between. From colour contour in Figs. 5(a) and (b), it can be seen that the pattern of electric resistivity variation within about 15m depth is different from that beyond 15 m depth. The upper part within around 15 m depth contains red and yellow zones surrounded by green zones. The distribution of red and yellow zones is irregular. The

distribution of resistivity in this layer is rather random and radical. These phenomena indicate that this layer could be a mixture of different dumping materials. Compared to the upper layer, the lower layer beyond 15 m depth shows a gradual decrease in resistivity with depth, with the exception at some bottom locations where irregularly low resistivity (blue colour) is seen. These observations suggest that the lower part of the ground could be natural soils. The irregularly low resistivity zone, which can be easily seen in Fig. 5(a), may be caused by the intrusion of seawater, as resistivity is sensitive to water content and ionic concentration. Most of the other 2D Resistivity profiles show similar patterns to Lines 6 and 23.

The results presented above show that both SASW and 2D Resistivity methods are able to provide continuous profiles of some material properties in the subsurface of the dumping ground. These profiles of material properties can be used to find the extent of the dumping ground and locate some anomalies in the dumping material bodies and in the original ground, such as voids, soft pockets, hard debris, and seawater intrusion. However, due to the limitation in the profile resolution and other uncertainties in the ground, determination of the dumping material-original ground interface requires the aid of other tools such as borehole drilling, which will be introduced in the following section.

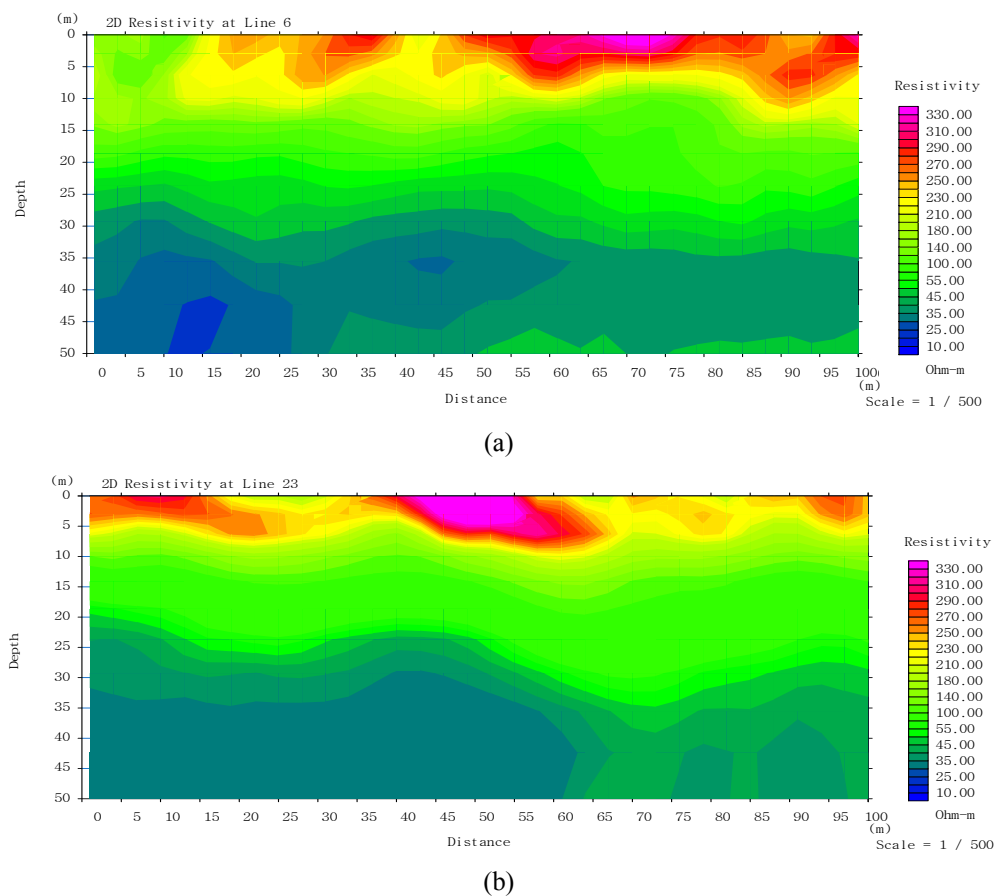


Fig. 5 2D Resistivity profiles: (a) Line 6; (b) Line 23

### 3.2 Searching the dumping material-ground interfaces

The subsurface ground is composed of filling materials and original materials. Two boreholes were drilled to assist in finding the dumping material-ground interfaces. Borehole 1 is close to Line 10 and Borehole 2 is close to Line 38, as shown in Fig. 3. In Figs. 6 and 7, the locations of boreholes are marked on the geophysical profiles.

Fig. 6(a) shows Borehole 1 in the SASW profile of Line 10. The data of Borehole 1 indicate that the interface between dumping materials and original soils is at 15.4 m. Colour contour shows that S-wave velocity here is between 0.28 km/s and 0.30 km/s. In Fig. 6(a), the interface of the profile is drawn according to the colour contour as indicated by the dotted line. On the interface, the S-wave velocity is the same. When the interface is out of the investigation limitation, the dotted line is drawn by the extrapolation from the colour contours nearby. Fig. 6(b) shows Borehole 2 in the SASW profile of Line 38. The depth of the interface in the borehole location is 19.0 m. S-wave velocity here is between 0.26 km/s and 0.28 km/s according to the colour contour. The interface (the dotted line) is also drawn on Fig. 6(b).

Fig. 7(a) shows Borehole 1 in the 2D Resistivity profile of Line 10. The dumping material-ground interface is at a location where the resistivity value ranges from 55~77.5 ohm-m. Based on the colour contour, the interface is drawn as shown by the dotted line. The dumping material-soil interface is also drawn in the profile of Line 38 according to the borehole data, as shown in Fig. 7(b). The resistivity at the interface is also in the range of 55 to 77.5 ohm-m.

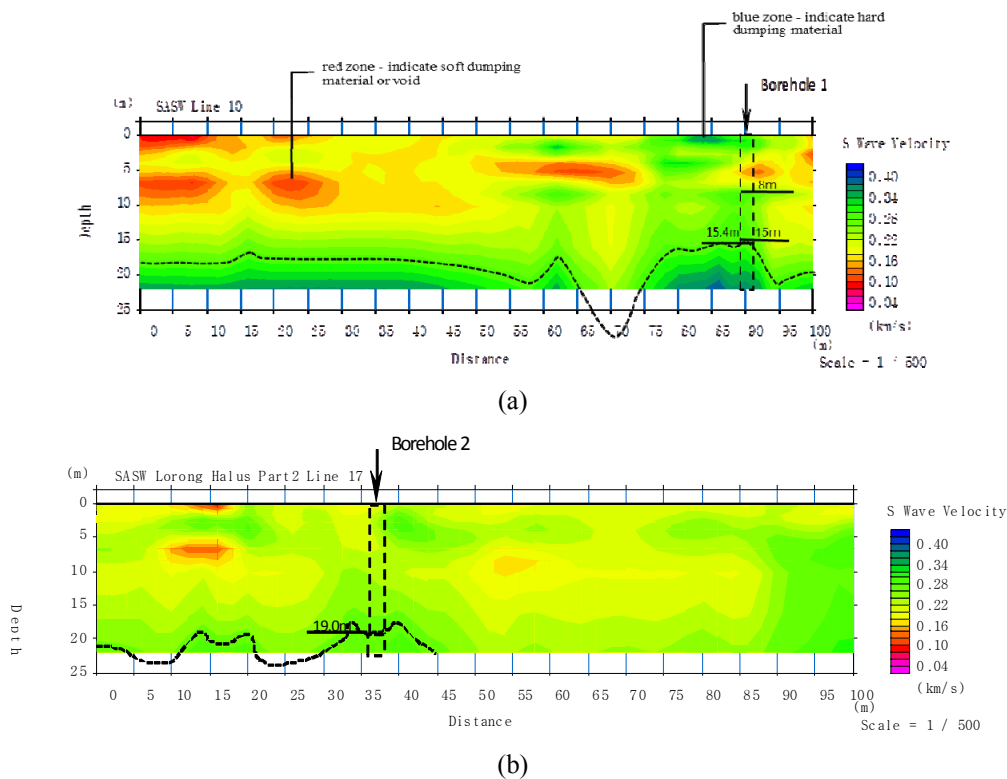
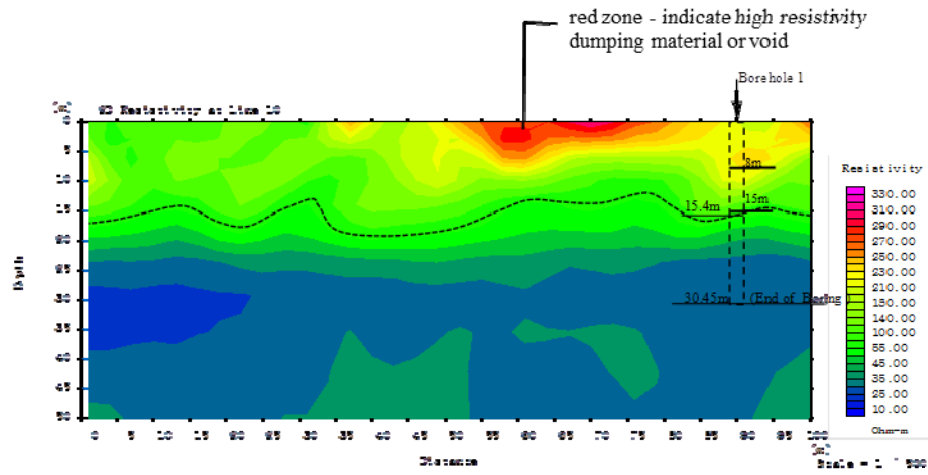
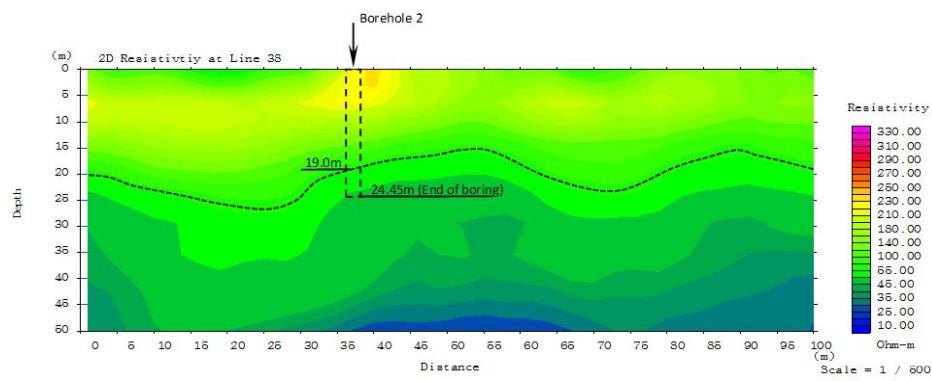


Fig. 6 Dumping material-soil interfaces obtained from SASW: (a) Line 10; (b) Line 38





(a)



(b)

Fig. 7 Dumping material-soil interface obtained from 2D Resistivity: (a) Line 10; (b) Line 38

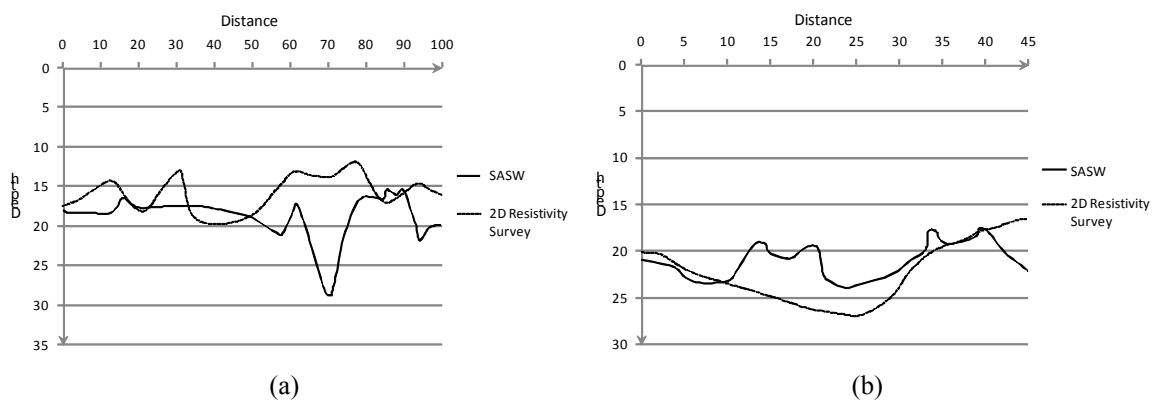


Fig. 8 Comparison of the dumping material-soil interfaces: (a) Line 10; (b) Line 38

Comparison is made here on of the dumping material-soil interfaces obtained from the two different geophysical methods as shown in Fig. 8. Figs. 8(a) and (b) are the dumping material-ground interfaces in Lines 10 and 38, respectively. The solid line is from SASW Survey and the dotted line is from 2D Resistivity Survey. By and large, two boundaries are roughly consistent, except at a distance of around 70 m in Line 10. Fig. 6(a) shows that, the SASW boundary at around 70 m distance in Line 10 is from extrapolated data instead of true investigation results, as the boundary here is beyond the survey depth of SASW. Thus the 2D Resistivity Survey here may provide more accurate results. However, within other ranges of measurements, the difference in the two detected boundaries is sometimes as high as around 5 meters, which is not too small to be ignored. The reason could be that the material properties at the boundary may be variable. This intrinsic limitation can affect the accuracy of boundary determination. Nevertheless, geophysical methods, especially when two or more methods are used together, can still be a convenient and cost-effective way to roughly profile the geometric boundaries of dumping grounds. Detected boundaries, such as the case shown in Fig. 8, are still usable for some purposes, such as the evaluation of the volume of dumping materials.

### 3.3 Classification of filling materials

Manual sorting of filling materials was carried out in Borehole 1 from a depth of 8 ~15 m. The results are used here to examine whether geophysical results are able to classify the types of filling materials. The results of manual sorting are given in Table 1.

Based on the hardness and the resistivity, filling materials can be divided into several categories as can be seen in Table 2. It should be noted that, in Table 2, glass is marked as soft materials. Because they are loose aggregates, although a single glass particle is very hard.

SASW detects the velocity of S-wave propagating in subsurface materials. S-wave velocity is related to the hardness of the materials. 2D Resistivity Survey detects the electric resistivity of subsurface materials. As shown in Fig. 6(a), within the depth of 8~15 m in Borehole 1, the green colour in the SASW profile indicates that the materials here are moderately soft, as compared with some abnormally hard and soft zones as marked in the figure. This prediction basically agrees with

Table 1 Manual sorting of filling materials in Borehole 1 (Percentage by mass)

Components	Depth (m)							overall
	8-9	9-10	10-11	11-12	12-13	13-14	14-15	
Wood	45.3%	14.1%	54.7%	31.7%	32.3%	94.8%	35.1%	39.1%
Plastics	9.1%	2.6%	2.1%	12.3%	1.8%	0.0%	2.7%	3.7%
Textiles	4.3%	5.1%	0.0%	0.2%	0.7%	0.0%	0.0%	1.8%
Rubber	11.0%	0.0%	0.0%	0.2%	0.0%	5.2%	0.0%	1.6%
Paper	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
Cement	0.0%	0.0%	0.0%	18.3%	0.0%	0.0%	0.0%	1.9%
Metal	0.2%	0.6%	0.0%	0.3%	1.2%	0.0%	0.2%	0.4%
Rock/Gravel	5.7%	0.4%	1.9%	2.2%	1.7%	0.0%	0.0%	1.4%
Glass	0.0%	0.1%	0.0%	0.0%	0.3%	0.0%	0.4%	0.1%
Soil fraction	24.4%	76.7%	41.4%	34.9%	62.0%	0.0%	61.6%	49.8%

Table 2 Classification of filling materials

		SASW results	
		Soft materials (low S-wave velocity)	Hard materials (high S-wave velocity)
2D resistivity results	High resistivity materials	Plastic, rubber, glass	
	Medium resistivity materials	Wood, textile, paper, soil	rock, gravel, cement
	Low resistivity materials		metal pieces

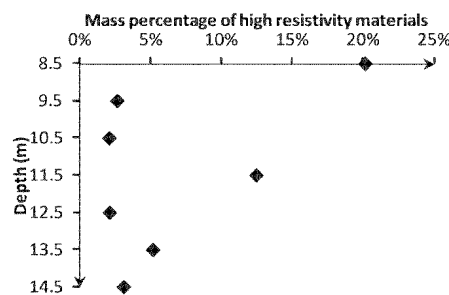


Fig. 9 Percentage of high resistivity materials along depth

the manual sorting results, which shows that most of the materials here consist of woods and soils. On the 2D Resistivity profile as shown in Fig. 7(a), there is green colour (relatively low resistivity) within this range. However, at the location of around 8.5 m depth, the resistivity is irregularly high compared with the filling materials underneath, implying that this location could exist some high resistivity materials. The evidence of high resistivity materials at 8.5 m depth can be seen from the manual sorting results in Fig. 9, which shows the percentage of high resistivity portion (plastic, rubber and glass) along depth. Fig. 9 shows that materials at 8.5 m depth contain more high-resistivity portion than materials at other depths.

The comparative analysis given here proves that the physical properties of dumping materials provided by these two geophysical methods can be used to classify the types of dumping materials. However, since the compositions and distribution of dumping materials are rather random, the determination of specific materials using geophysical methods is difficult without the aid of core sampling.

#### 4. Conclusions

The feasibility of two geophysical investigation methods, SASW and 2D Resistivity, for the investigation of a used dumping ground are evaluated in this paper. The following conclusions can be made:

- (1) The two geophysical investigation methods can provide a rough distribution of material properties (hardness and electric resistivity) in the subsurface. These properties can be used to find the geometric extent of the dumping ground and locate some anomalies such

as soft pockets, hard materials and seawater intrusion in the fill and original ground.

- (2) The search of dumping material-ground interface is done using the geophysical data with the aid of borehole drilling. The results show that the dumping material-ground interfaces detected by the two geophysical methods are roughly consistent, although in some ranges the discrepancies in depths of the two detected boundaries are up to around 5 meters, which is not too small to be ignored.
- (3) Dumping materials can be classified according to their hardness and resistivity, which can be obtained from SASW and 2D Resistivity, respectively. Manual sorting of dumping materials in a borehole was carried out. The comparative analysis shows that the results of manual sorting agree with the predicted types of dumping materials from the geophysical methods. Hence geophysical methods can be used to classify the types of dumping materials.

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