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Mapping Refuse Profile in Singapore Old Dumping Ground through Electrical Resistivity, S-wave Velocity and Geotechnical Monitoring

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Abstract

The purpose of this study was to track the refuse profile in Lorong Halus Dumping Ground, the largest landfill in Singapore, by electrical resistivity and surface wave velocity after 25 years of closure. Data were analyzed using an orthogonal set of plots by spreading 24 lines in two perpendicular geophone-orientation directions. Both geophysical techniques determined that refuse boundary depth was 13 ± 2 m. The refuse boundary revealed a certain degree of variance, mainly ascribed to the different principle of measurements, as well as the high heterogeneity of the subsurface. Discrepancy was higher in spots with greater heterogeneity. 3D analysis was further conducted detecting refuse pockets, leachate mounding and gas channels. Geotechnical monitoring (borehole) confirmed geophysical outcomes tracing different layers such as soil capping, decomposed refuse materials and inorganic wastes. Combining the geophysical methods with borehole monitoring, a comprehensive layout of the dumping site was presented showing the hot spots of interests.

Keywords: Landfill, geophysical methods, 2D resistivity, surface wave, borehole

Introduction

The monitoring of closed or abandoned dumping grounds is of great interest because of the expansion of communities toward these site that were originally sited some distance away from the nucleus of the community. The reclamation of closed dumping grounds requires more comprehensive investigations to determine the existing dumpsite conditions and ensure cost-effective remediation. As recommended by the US Environmental Protection Agency's brownfield initiatives, the redevelopment involves site investigation to identify the type, quantity, and extent of contamination prescribing drilling techniques, groundwater and gas sampling (EPA 2002). Such traditional field investigation methods inevitably involve surface penetration by drillings to obtain accurate ground-truth information from a specific location with respect to subsurface material, groundwater and leachate, and gas constituents. Given the size of the dumping grounds, a large number of drillings is required to ensure optimum coverage.

Geophysical techniques are non-invasive investigative methods that do not require significant penetration past the surface. They are alternatively labeled as indirect methods or methods of remote sensing that function on the principle of measuring certain geophysical properties of media (Dahlin et al. 2002). Unlike traditional

invasive methods that make direct measurements on physical samples obtained from the subsurface, geophysics measures the properties of the media and deduces the parameters of interest. For instance, by measuring the arrival time of a reflected seismic wave, the hardness of a soil stratum or its distance to underlying bedrock can be determined (Hebeler and Rix 2001).

Geophysical techniques have been used for site investigations of landfills and abandoned dumping grounds worldwide (Lopes et al. 2012). Electrical resistivity is a popular geophysical exploration technique which is carried out on earth surfaces in order to obtain apparent-resistivity profiling data, which qualitatively reflect the vertical or horizontal variations in subsurface resistivity. Electrical resistivity tomography was applied to track groundwater and leachate plume movements based on their conductive properties (Dahlin et al. 2002; Yoon et al. 2003; Abu-Zeid et al. 2004; Al-Tarazi et al. 2006; Martinho and Almeida 2006). To improve the confidence level, a geophysical technique is rarely used alone. Seismology is often used in conjunction to detect physical boundaries and delineate features within the site (Watson et al. 2005; Balia and Littarru 2010; Djadia et al. 2010). However, there have been cases where seismic refraction provided unclear findings due to distortion of energy wave penetrations through unconsolidated upper soil material (e.g. disturbed fill-layers) (Abdullah et al. 2011).

Recently, Lorong Halus Dumping Ground (LHDG) has been included in the urban planning for future redevelopment in Singapore. Therefore, there is an urgent need for detailed characterization of the subsurface. The aim of this study was to map the refuse profile of LHDG utilized more than twenty five years ago for municipal waste disposal. Geophysical techniques provided 3D analysis of the refuse materials, while its validation was conducted by geotechnical field work.

Material and Methods

The LHDG Phase III was an uncontrolled dumping ground operated from 1983 to 1989. Situated on the north-eastern part of Singapore and landmarked by the Serangoon River on its north-western fringes, it was originally a mangrove swamp covering about 44 hectares (Fig. 1). The predominant geology was dense sand and gravels of the quaternary period termed Old Alluvium, and recently deposited marine clays, organics and fluvial deposits termed Kallang Formation. The area climate is classified as tropical rainforest climate, with no true distinct seasons. Owing to its geographical location and maritime exposure, its climate is characterized by uniform temperature, high humidity and abundant rainfall throughout the year. Since closure till present, no significant reclamation activities have been conducted except 2-4 m soil cover. In 2002, a flaring system was installed to combust the landfill gas. According to records, half of the buried material was municipal solid wastes, with the other half was comprised of construction and demolition (C&D) wastes, stabilized industrial wastes and incineration ashes (Meinhardt 2004; CPG consultants 2005). During the operation period, the old dumping ground rarely employed engineering works or hygienic measures.

Site characterization was conducted by geophysical surveys and geotechnical field works. Two geophysical methods were used, including two-dimensional electrical resistivity (2D resistivity) and spectral analysis of surface waves (SASW). The

former used electrical current for measuring potential difference (PD) in order to obtain the soil/refuse material resistivity distribution. The surface wave or S-wave velocity distribution was selected, given its established relationship with geotechnical parameters like standard penetration tests (SPT). SASW may provide accurate assessment for intermediate soft layers on site, but up to 20 m depth. By using these two non-invasive methods, the geological structure of the site could be depicted in 3D. Test plots of 100 × 100 m dimensions were demarcated on LHDG for geophysical surveys. On the other hand, the geotechnical works involved borehole drilling, providing physical samples from soil for verification of results obtained by the two geophysical surveys.

The 2D resistivity survey entailed the laying of stainless steel electrodes every 5 m in a straight line on the ground connected by cable, and then to a multi-electrode resistivity meter connected to a power booster (McOhm Profiler 4, OYO Corporation, Japan). In total, 32 electrodes were distributed in each survey line by use of an internal scanner. A two dimensional earth model was applied using the finite-element method (FEM) inversion to process raw data for generation of tomography (Holcombe and Jiracek 1984; Loke and Barker 1996). 2D resistivity tomography was obtained by staking 2 lines (155 m × 2) data together to get the 100 m data by cutting both ends. Roll-along measurements using 5 m spacing were carried out until a grid of 21 × 21 electrodes was covered.

Fig. 1 The Lorong Halus dumping ground in Singapore with the position of the pilot plot

For SASW, the following details were set: sampling rate - 500 microseconds; data length - 1024 samples; pre-trigger - 256 samples; low cut filter - 5Hz; high cut filter - 1000Hz. The type of geophone used was HS-J type with a natural frequency at 28 Hz (OYO Corporation, Chiyoda-Ku, Tokyo, Japan), which is suitable for measurement of soil profiles carrying high plasticity. A total of twenty-four geophones (spacing at 3 m) were fixed on the ground surface with the spike poked into the ground. 12-geophones overlap condition was set up for continuous adjacent spreads on the line. The SASW survey was measured with a McSeis SX-XP 24 channel seismograph with the wave source generated by hammering on a percussion plate.

2D resistivity and SASW surveys were performed on the orthogonal test plot (Fig. 1). The plot was orientated with existing gas extraction wells for spatial control. The field test consisted of 24 survey lines (indicated by red lines), each line comprising 2D resistivity and SASW survey readings. The finite-element method was performed to calculate the model values in order to invert the measuring data for building apparent resistivity and surface wave velocity tomography at the cross section under each distribution line 1-21. A 3D analysis was then employed in the matrix at specific planar depths of 0, 2.5, 5, 7.5, 10, 12.5, 15, 17.5 and 20 m via a kriging algorithm (software Surfer 9, Scientific Software Group, Provo, UT, USA) (Bentley and Gharibi 2004).

Geotechnical work in the field was conducted by a local company (SETSCO Services, Singapore). Figure 1 presents the location of Borehole-1 drilling between line 9 and 10 (44 m from line 1), and 10 m away from the line C. A hand auger or trial pit was initially used to drill the top 1 m to ensure the site was clear of any underground services. The soil boring was continued using a machine driven solid stem 150 mm diameter spiral auger to advance the boring between sampling intervals. Borehole-1 was drilled to 30 m termination depth. Drilling, soil sampling and loggings were done in accordance with BS5930 (Code of Practice for Site Investigations 1981). Soil samples were collected using 75 mm unit dose (UD) sampler or standard penetration test (SPT) sampler. The soil samples were then kept in a laboratory supplied glass jar, covered with aluminum foil and stored in a cooler box while on site. The UD and SPT samples collected were used for filling material sorting and testing.

Results and Discussion

The refuse profiles of 2D resistivity and SASW (lines 9 and 10) in LHDG are presented in Fig. 2. The refuse boundaries and original layers estimated via plotting the corresponding value of resistivity/surface wave distinguishing the refuse from original ground. The cross section of the subsurface could be distinguished into two layers: the upper layer contained large areas of warm color (red and yellow) in a random and irregular way, in contrast to the more homogeneous lower layer having cold color (green). The upper layer exhibited abrupt vertical changes throughout the plotting area indicating refuse distribution. The high heterogeneity was mainly ascribed to the great variation in the corresponding material properties, like moisture content, structure, compression, consolidation, degradation, biogas existence, burial methods etc. (Grellier et al. 2007; Reddy et al. 2009). In addition, the original surface of the dumping site (prior waste disposal) was soft and water rich, which may have further facilitated the formation of irregularities over years of biotransformation. On the contrary, the lower layer, Kallang Formation, could be easily identified by the sustainable value strip of the resistivity/shear wave, together with a gentle rolling tomography (Lee and Zhou 2009). Some irregular blue zones of low resistivity (down to 50 m) were observed in the lower layer. These low resistivity zones were probably caused by the intrusion of salt water, which most likely came from the original mangrove swamp in connection to the open sea. Historical site investigations across the old dumping ground e.g. the Meinhart report (2004) and MW report (2005) have given extra useful information on the depth of the buried waste and soil. It is assumed that the properties of original ground surface (before

landfilling) have not been significantly transformed by the overlaid refuse over time.

Fig. 2 Integration of bore log (Borehole-1) with geophysical profile of 2D resistivity and SASW, at lines 9 and 10, respectively (Note: dashed line represents the boundary layers best estimated by two geophysical methods; bore log was demarkated with blue lines from surface down to the underlying old alluvium) (Geotechnical profile - 1: stiff sandy silt with coarse gravel (0-2.3 m); 2: loose fine to medium sand with clay at bottom layer (2.3-5.5 m); 3: soft to firm clay with silt and some organic matter (5.5-7.2 m); 4: composed wood with peat and fill materials (plastic) (fill end) (7.2-15.4 m); 5: peat with decomposed wood (estuarine) (15.4-17.7 m); 6: medium dense fine to medium sand with traces of peat at top layer (fluvial) (17.7-19.5 m); 7: firm clay (fluvial; Kallang Formation) (19.5-24.3 m); 8: dense fine to coarse sand with clay and gravel (old alluvium) (24.3-30.45 m))

The depth of the refuse layer was estimated at 13.04 ± 2.05 m with 2D resistivity and 12.92 ± 1.64 m with SASW, respectively. The standard deviation of 2D resistivity ($\pm 15.7\%$) was slightly higher than that of SASW ($\pm 12.7\%$), probably attributed to the wider spacing of electrodes in 2D resistivity survey (5 m vs. 3 m in SASW). Historical site investigations across the old dumping ground have demonstrated similar findings on the refuse depth and distribution (Meinhardt 2004; CPG consultants 2005).

Geotechnical investigation involved Borehole-1 drilling between lines 9 and 10. Figure 2 shows the geotechnical profile of refuse material integrated with geophysical surveys. The bore log demonstrated that the boundary of refuse layer was at 15.4 m, while the geophysical survey at two adjacent lines (2D resistivity and SASW) indicated their boundaries in the range of 14-18 m. Despite the great heterogeneity in subsurface, the estimation by geophysical methods was of high consistency with the bore log, exhibiting a considerable reliability of the geophysical methods.

218 The bore log provided more information than just the refuse boundary, including
 219 refuse composition. The results showed eight different sub-layers in the refuse
 220 with distinguished characteristics (Fig. 2). The top two layers were comprised
 221 mainly of silt and sand (0-5.5 m), believed to be the soil cap layer. Starting from
 222 third layer, some organic matter was detected. Refuse materials (e.g. plastics)
 223 continued to be present until the end of the fourth layer at 15.4 m. The boundary
 224 between Kallang formation and old alluvium was identified at 24 m below the
 225 surface. Controversial findings were observed with electrical resistivity
 226 tomography, possibly due to the shielding effect caused by high moisture content.
 227 Nevertheless, the integration of bore log with geophysical methods may help to
 228 establish a more comprehensive interpretation of the refuse material.

230 Figure 3 validates the two geophysical methods by tracking the refuse boundary
 231 data of three perpendicular lines A, B, and C, at 0, 50 and 100 m in the test plot,
 232 respectively (as shown in Fig. 1). Data were collected at intersections between
 233 lines 1-21 and the perpendicular lines A, B, and C. Data plots of electrical
 234 resistivity values showed a more notable scattered relationship compared to
 235 surface wave values. This higher discrepancy was due to wider spacing of
 236 electrodes and/or heterogeneity of subsurface. Aside from that, it is well known
 237 that refuse material moisture could substantially affect the measurements of the
 238 2D resistivity. Since the geophysical survey was conducted in a typical tropical
 239 landfill, the subsurface moisture level was much higher due to percolation of rain
 240 water leading to increased uncertainty with the 2D resistivity method (Samouëlian
 241 et al. 2004; Brunet et al. 2010). Variances were also found in SASW results
 242 suggesting that disturbances might have derived from other factors apart from
 243 moisture, especially in a complex environment such as landfill site.

244

245

246 **Fig. 3** Validation of geophysical methods on the three perpendicular lines (line A,
 247 B and C shown in Fig. 1) (Note: LA, LB, and LC represent line A, B, and C,
 248 respectively; 2DR and SASW represents the 21 refuse depths spreading by lines
 249 1-21 in the respective points 0, 50 and 100 m, respectively)

250

251 The 3D boundary profile between refuse and Kallang Formation in LHDG is
 252 illustrated in Fig. 4. The 3D color contour presents the refuse depth distribution
 253 with the respective geophysical methods (Fig. 4a). It clearly revealed a tendency
 254 of random change of the boundary due to the heterogeneity of the subsurface
 255 environment. The majority of the boundary (>70%) had a depth of 10-15 m. The
 256 deeper areas (more than 15 m) mostly appeared at the bottom of the plot, in
 257 agreement with the geophysical methods. Within a specific depth interval
 258 (represented by the same color), it was interestingly found that a relatively small
 259 area being examined, the less matchup of the data between the two geophysical

methods. For example, the red color represents depth range from -16 to -18 m with a relative small area in the contour map, the overlap here between the two methods was significantly lower than that of yellow color (-14 to -16 m), which occupied a much larger area in the plot. Furthermore, regional peak points (less than 10 m deep) rarely concurred at the same spots, perhaps attributed to the joint effects from the local site situation as well, as the different mechanisms behind the methods.

Fig. 4 a 3D color contour, b 3D map; between refuse and original Kallang Formation constructed by 21 geophysical profiles of 2D resistivity (left) and SASW (right) using kriging interpolation

It is noteworthy that spacing of geophones affected the boundary detection as well (Fig. 4b). The estimated refuse boundary depth by 2D resistivity ranged wider than that by SASW, probably attributed to the wider spacing of electrodes in the 2D resistivity survey (5 m in comparison to 3 m for SASW). The high water level in the tropical landfill could also contribute to the higher magnitude of extremes detected by 2D resistivity, because this method is more sensitivity to the moisture content (Samouëlian et al. 2004; Brunet et al. 2010). However, there is no clear evidence that SASW provided better results, particularly in the deep landfill beyond its maximum penetration depth.

Figure 5 presents pseudodepth slices of 2D resistivity and SASW in vertical as well as in lateral plane. The background electrical resistivity was 160-180 ohm·m indicating that waste materials spread all over the site, mixing together with silt/clay/sand. High electrical resistivity was depicted in some spots (warm color) especially close to surface (0-5 m), in contrast to cool color frequently presented in deep layers (15-20 m). Meinhardt (2004) reported that the high resistivity was due to the characteristics of capping soil/sand. Some blue spots in the capping soil were due to moisture content (clay with high water-holding capacity). At the deeper layer of 10-15 m, the occurrence of abnormally lower resistivity readings at certain spots indicated the potential presence of leachate mounding. It would be interesting to trace the distribution of contaminants at leachate moulding sites in order to recommend further remediation technologies. Pseudodepth slices of

SASW exhibited more complexity in terms of stiffness of the buried materials. Enormous soft materials were interestingly found at depths 10-15 m (low wave velocity, blue color) mainly consisted of decomposed wood, peat and plastic. These findings were consistent with borelog data presented previously. In the same layer, relatively hard materials (high wave velocity, red color) appeared, possibly attributable to construction and demolition (C&D) wastes. In contrast, the pseudodepth slice at 12.5 m showed a minor change of SASW distinguished from its nearby strata, suggesting an artificial constructed layer for hygienic purposes, such as middle cover.

Fig. 5 Pseudodepth slices showing data taken with the 2D resistivity and SASW

In the capping layer (0-5 m), the low surface wave and high electrical resistivity suggested large amounts of soft sandy materials. At 12.5 m, both tomographies showed a layered stratum with great uniformity demonstrating a formatted area. The circled soft-rich zones at 10 and 15 m (lower surface wave velocity) most likely contained higher amounts of refuse, but considering the low moisture level (reflected by resistivity) the materials presented hydrophobic characteristics, possibly from plastics.

The geophysical methods provided certain types of information on the subsurface strata, both vertically and laterally, with minor discrepancy. The correlation of waste types and geophysical properties may serve as a reference for interpretation in other tropical landfills. Combination of the two geophysical methods to locate hotspots will be useful in determining the environmental properties of the landfill. In particular, the 2D resistivity was able to detect the pollution plume and leachate mounding in the landfill, while SASW indicated pockets with large volume of wastes by the hardness of the subsurface materials. Together with other investigative methods, e.g., borehole drilling and analysis, it may present further details which would help to identify the types of refuse material at certain landfills. Proper application of these techniques would eventually upgrade the conventional geotechnical methods with cost saving and extra data integrity.

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