Use of geophysical survey and sonic drilling for site characterisation and material property derivation for a municipal waste landfill

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ABSTRACT

Traditional intrusive site investigation techniques are unable to be applied to the abnormal ground conditions associated with municipal waste landfill sites due to the presence of effectively impenetrable materials within the subsurface. Accordingly, alternative investigative techniques, including a Multi-channel Analysis of Surface Waves (MASW) geophysical survey and sonic borehole drilling techniques, were utilised by Aurecon to model the extents of, and characterise the materials within, a closed cell area of a medium sized town's landfill site in South East Queensland. As the landfill site was commissioned approximately 40 years ago and operated continuously for nearly 30 years, the exact depth of, and composition of landfill material within, the site was unknown prior to investigation. The site investigations undertaken and laboratory tests completed on recovered materials were able to estimate the engineering properties of the fill material located within the site. Areas of differing material properties were identified and Finite Element Method (FEM) modelling of the site's potential to settle over time and under additional loading was also completed. The paper presents details of both the field testing and the numerical simulation used to identify the fill boundaries, characterise the fill materials present within the landfill and model the expected deformation of the existing material under additional loading scenarios. The results of these investigations and analyses were then used to assess the suitability of the site to be used as the base for vertical expansion of the site, thereby potentially reducing the urgency for additional greenfield landfill sites to be procured.

Keywords: Landfill expansion, sonic borehole drilling, MASW, Finite Element Method (FEM), differential settlement

1 INTRODUCTION

Ensuring the integrity of both liner and leachate drainage paths are the most important aspects of vertical landfill expansion design, even after the deformation of the lined base due to additional loading. Thus, for any site under consideration for landfill expansion, realistic characterisation of the existing landfill material is required in order to assess the expected magnitude of differential settlement once the site is surcharged with additional waste. As the magnitude of compression and consolidation is a function of the load applied and the properties / thickness of a compressible material, the identification of the extents of the existing landfill also becomes critical to the modelling of differential deformation across the site.

The purpose of this paper is to demonstrate how modelling of the deformation of a landfill in response to additional loading has been achieved for a specific site where, using an approach of compiling and comparing multiple information sources, a model that characterises the landfill cell to an acceptable resolution has been constructed. Such an outcome has been historically difficult to achieve due to the inherent nature of the landfill material which precludes many traditional forms of site investigation.

2 SITE DESCRIPTION

The site under consideration is the primary landfill that services Toowoomba, a large (approx. 165,000 inhabitants), inland regional city in Queensland, located 125km west of Brisbane (refer Figure 1). The Toowoomba Waste Management Centre (Bedford Street landfill), is licensed to accept between

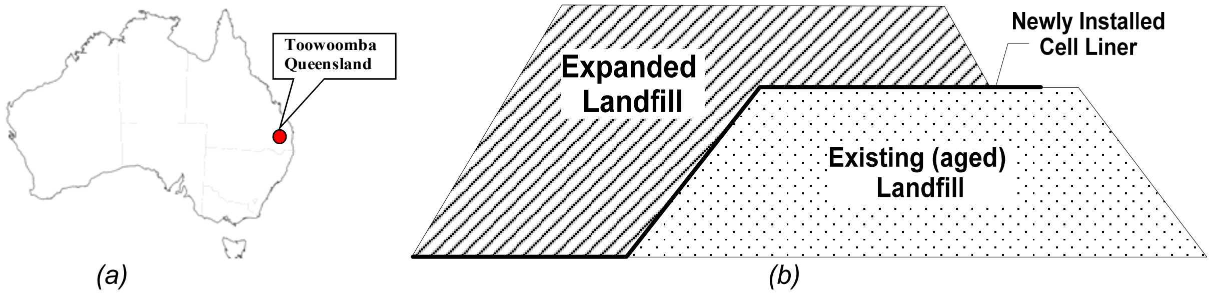


Figure 1: Location map of site and (b) concept of proposed "piggyback" expansion of site, where additional fill is placed both vertically and immediately adjacent to an existing landfill cell.

100,000 and 200,000 tonnes of domestic waste per annum and, after more than 30 years accumulation of uncontrolled fill material – mainly of domestic and industrial waste – the site is now approaching its airspace capacity under existing licences.

In 2011, as part of a suite of considered options, the possibility of expanding a portion of this site via a "piggyback" expansion was investigated by Aurecon. This method of landfill expansion aims to increase the vertical capacity of an existing fill site via the installation of a new liner over the existing landfill cell (refer Figure 1b). The site under investigation was approximately rectangular, with side lengths of 400m. It had been partially capped in 2001, after 29 years of operation (commissioned 1972). The landfill currently sits approximately 15 to 20m above the surrounding natural surface.

3 EXISTING INFORMATION

Due to the lengthy timeframe over which the landfill had operated only limited information regarding the extents and depth of the existing landfill cell were available. Five (5) historical surveys of the site, completed both prior (pre-1972) and subsequent to its commissioning as a landfill (1986-2010), were digitised and compared in order to compile a time sequenced image of the site. However, discrepancies within this data suggested that a consistent ground control may not have been maintained throughout the operation of the landfill, thus resulting in uncertainty regarding the exact depth of the landfill cell in its current state. In addition, anecdotal evidence suggested that a series of excavations had been made at the base of the cell prior to the commencement of filling, further increasing the complexity of modelling the thickness of the existing landfill across the site. Identification of these pits were considered important as sudden landfill thickness changes were expected to produce regions of increased differential settlement under additional loading.

A recent geotechnical study (Golders Associates, 2003) had also installed a settlement pad upon the surface of the capped landfill cell. Settlement data included in this study provided information on the deformation of the site under semi-controlled loading conditions.

4 ADDITIONAL INVESTIGATIONS

Once the deficiencies and ambiguities within existing data were identified, the collection of additional site data via the completion of targeted geotechnical and geophysical surveys was completed. Due to the presence of effectively impenetrable substances abnormal to natural subsurface profiles, traditional intrusive site investigation techniques are unable to be easily applied within landfill sites.

Instead, site investigation techniques included both sonic borehole drilling and a geophysical survey. Two (2) sonic boreholes were completed to investigate the depth of natural materials at targeted locations and, in order to achieve adequate investigation of the entire landfill site, a Multi-channel Analysis of Surface Waves (MASW) geophysical investigation was completed across the site. This geophysical survey was aimed at investigating any material and depth variations within the landfill.

The sonic drilling technique involves sending high frequency resonant vibrations down a drill string to the drill bit, whilst an operator controls the frequencies to best suit the specific conditions of the soil/rock geology. The resonating and rotating drill bit fluidises the soil particles at the bit face, allowing for fast and easy penetration through most geological formations. This type of drilling has advantages in landfill investigation as it is frequently able to penetrate substantial obstructions such as steel and concrete. Due to employment of sonic borehole drilling techniques at this site full recovery of material throughout the landfill profile was achieved at two (2) spatially discrete locations.

Key details of the MASW geophysical survey undertaken include the collection of data from approximately 1200 line metres via use of a 50kg drop hammer (seismic source) and a 24 channel land streamer. The investigation provided coverage over two (2) distinct areas of the site, extending around the locations of the sonic boreholes. Further details of the completed geophysical and geotechnical investigations have been presented previously (Suto and Lacey, 2011).

5 MODELLING OF LANDFILL EXTENTS

The data collected from the MASW geophysical investigation were processed via one-dimensional inversion (completed at 6m intervals) and then subsequently interpolated to produce two-dimensional S-Wave velocity sections for each of the seismic survey lines. The S-wave velocity profiles of each line were then isolated at regular depth intervals, and corresponding depth data was compiled and interpolated to construct a series of plan view maps that showed the S-wave velocity across each investigated area and the variation of S-wave velocities with depth. An example of the 2D contour maps produced for each survey line from this investigation is shown in Figure 2a.

Based on a literature review of similar geophysical investigations completed at landfill sites (eg Kavazanjin et al, 1996 and 1999), a range of expected shear wave velocities (V_s) consistent with landfill materials was defined and adopted for a first pass interpretation. V_s values were anticipated to increase with the depth of the landfill and, based on the expected landfill depth (up to 25m), a shear wave velocity of between 200m/s and 300m/s was considered likely to represent landfill materials.

The results of the geophysical investigation were compared with the available survey data to estimate the shear wave velocities (V_s) associated with both landfill and natural materials. By overlaying the base of the landfill, as interpreted from survey data, it was observed the interpreted landfill base crossed a range of shear wave velocities (V_s = 150 to 300m/s). These values were within the expected shear wave velocity range for landfill materials, but a distinct V_s contrast that could represent the fill / natural interface could not be consistently identified at the depth of the survey derived landfill base.

Sonic borehole drilling indicated that the depth of landfill was, at the points of investigation, between 3.4m and 5.5m deeper than that indicated by the analysis of historical survey information. This further supported the suggestion that discrepancies were present within the survey data. When borehole strings were overlaid upon the geophysical data a distinct interface was observed between the landfill and natural material at a shear wave velocity of V_s = 230m/s at both borehole locations.

This shear wave velocity threshold was adopted and used to filter the geophysical survey coverage of the site. Accordingly, a quantification of the difference in extent / volume of the landfill cell modelled via the historical surveys and onsite investigation data was achieved. As per the sonic boreholes investigations, this comparison of models showed that the onsite investigation data consistently increased the modelled landfill thickness by approximately 5 to 7m. However, the general shape of the landfill base was reflected across both the survey and geophysical datasets, and only at a single isolated location was the landfill base determined from survey data calculated to be at a lower level than that interpreted from analysis of the geophysical data. The “pits” known to be excavated within the base of the landfill cell were also generally reproduced, albeit spatially offset from the locations included in the survey data. Likely locations of additional excavations not shown on historical survey data were also identified by this analysis of the geophysical results.

Following this methodology produced a three dimensional model of the landfill cell with the interpreted existing base of the landfill cell directly comparable to the survey of the existing ground surface (2010). In the areas where no geophysics coverage existed the overall average value of landfill deepening (~5m) across the investigated landfill area was applied to the survey data. Accordingly, at any point within the investigated area, the thickness of the landfill material could be estimated.

6 MATERIAL PROPERTIES

Laboratory classification tests were completed on recovered materials to characterise the landfill profile by density and moisture content. Test results were compared to the isolated shear wave value profiles found at the borehole locations from which the tested material samples were recovered. Thus the variation of moisture content and material density (wet / dry) could be compared with the shear wave velocity and depth. Trends present within the laboratory results of samples recovered from both boreholes allowed the identification of two distinct "layers" of landfill material; a material exhibiting qualities similar to that expected of a soft to firm clay material overlying a layer of stiff to very stiff material. Published equations (Kavazanjin, 1999; Mayne et al, 2010) were used to estimate the engineering properties of each material based on applicable V_s values. These derived material properties included unit weight (ρ) and small strain deformation modulus values (G_{max}, E_{max}) (Table 1).

Table 1: Material properties derived for material classes defined within landfill material

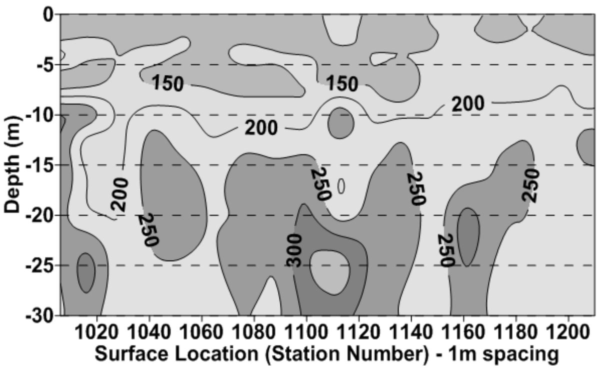
Unit ID	Interpreted Material Consistency	V_s (Average / Threshold) (m/s)	Moisture Content (Average / Range)	ρ (t/m^3)	G_{max} (MPa)	E_{max} (MPa)
1	Soft to Firm	150 / < 200	19% / 8 – 35%	1.5	30	85
2	Stiff to Very Stiff	225 / > 200	33% / 15 – 52%	1.6	80	210

Using the V_s threshold attributed to each defined unit, the geophysical data recognised as landfill material was reanalysed to classify the landfill into either of the identified material units. The average depth to the top of the consolidated (stiff to very stiff) layer was calculated to be approximately 12m from the current ground surface, but varied across the site and was found to be discontinuous at certain locations. In total approximately 70% of the landfill volume was classified as belonging to Unit 1. From this reclassification an additional surface was added to the 3D landfill model that represented the interface of different material units (ie V_s = 200m/s threshold), as shown in Figure 2b.

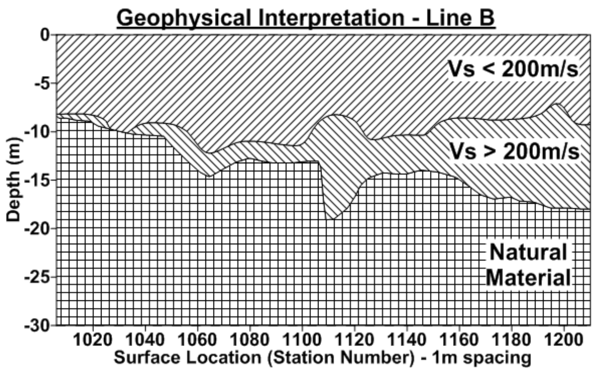
7 FINITE ELEMENT MODELLING OF SETTLEMENT PAD

Using load / deformation analyses, site specific settlement data was subsequently used to check the material properties derived above via a Finite Element Method (FEM) model. Site specific load / deformation settlement curves were available for comparison, as a settlement pad had been installed during recent geotechnical assessments (Golder Associates, 2003). This data included observations of the rate (and duration) of both the mechanical settlements due to: (a) compression of waste by placement of additional overburden (analogous to primary settlement); and (b) continued creep compression and ongoing decomposition (analogous to secondary settlement) after the application of a known surcharge load. A line of geophysical investigation had specifically been completed immediately alongside the longitudinal toe of the settlement pad with the view to compare the interpreted geophysical survey results with the settlement pad data.

Utilising the landfill thickness interpreted from the geophysical investigations and assigning the derived material property values (using total stress and elastic-plastic material models for the landfill materials), a 2D FEM load deformation model was created for the settlement pad site. Deformation magnitudes calculated by this model were extracted and compared back to the on-site observations.



(a)



(b)

Figure 2: (a) Example 2D contour map of shear wave velocities (V_s) produced for each geophysical survey line; and (b) interpretation of same section based on derived material thresholds.

Curve matching between FEM modelled consolidation and onsite deformation observations was completed to validate the FEM input parameters. Initial estimates of the factor applicable for the reduction of G_{max} and E_{max} to account for the relationship between the small-strain levels associated with geophysical investigation and the strains associated with additional loading of the landfill, were obtained from Sabatini et al (2002). Using these revised deformation parameters (E_1 = 3 – 16MPa; E_2 = 18 – 33MPa), the shape and magnitude of the consolidation predicted by the FEM model was found to align very well with the deformations observed onsite. The maximum difference between the predicted and observed consolidation was 11 mm, with an average difference of 8 mm. This equated, on average, to the FEM model estimating the primary compression of the site to within approximately 7% of that observed onsite. Of this 7% variation, the FEM model both over- and under-estimated the observed primary deformation by approximately equal proportions, with the overall total averaged consolidation differing by only 0.5% from that observed onsite. This high level of data matching instilled confidence in both the interpreted thickness of the landfill and derived material properties.

8 DEFORMATION ANALYSIS

Using the calibrated FEM model, iterations of analysis were completed to produce both primary and secondary phase consolidation curves. From the onsite deformation pad data primary compression was interpreted to be complete approximately 34 days after loading. This is consistent with Keene (1977) who found that primary consolidation of landfill material was typically complete approximately one month after the completion of filling. As per Oweis (2006), the age of the fill and duration since landfill capping indicated that approximately 5-10% of the total mechanical and decompositional settlements that would potentially occur at the site remain outstanding.

Due to the difference in modulus values derived for each material unit, and from inspection of the results of the FEM model, deformations due to additional loading were found to be largely contained within Unit 1 of landfill material (V_s < 200 m/s). Thus the magnitude of primary deformation at this site due to additional loading was interpreted to be directly related to the thickness of the Unit 1 landfill material and the magnitude of the surcharge load rather than the overall thickness of the landfill. Primary consolidation due to the load of the settlement pad (55kPa) was calculated to range between 0.6% and 1.2% of the thickness of the Unit 1. For the larger loads associated with the placement of up to 20m of additional landfill (as per the proposed vertical expansion), it was calculated that deformations of up to 6% of the thickness of Unit 1 material may occur.

In addition to primary consolidation, secondary consolidation in the form of creep settlement was also estimated. This long-term mechanical deformation is largely due to the self-weight and slow decomposition of the landfill material. The existing settlement pad data was also used to provide site specific information regarding the rate of creep settlement, with estimations placing the settlement at approximately 0.2% of the total thickness of the landfill, per log cycle of time. This value is lower than published estimations (eg Watts and Charles, 1990), however it is thought that this may be due to the age of the landfill when tested (ie greater than 25 years). From graphs published by Oweis (2006), it was estimated that, due to the age of the existing landfill, approximately 10% of the total secondary consolidation (creep and decomposition) remains to occur, over a period of approximately 40 years.

9 DIFFERENTIAL DEFORMATION DUE TO VERTICAL EXPANSION

Via the use of the calculated load/deformation curves and the proposed expansion plans the estimated magnitude of total deformation experienced by all points of the modelled landfill cell was computed for a number of log cycles of time (30 days, 1 year, 10 years and 100 years). This estimate was based on (a) thickness of the existing landfill, (b) thickness of existing landfill with V_s < 200 m/s (Unit 1 material) and (c) thickness of the vertical expansion surcharge.

As preliminary design only indicated the height of maximum airspace capacity, calculation of the thickness of maximum surcharge material to be placed at each datapoint was also required. This was completed via the construction of an additional model surface representing the final airspace capacity, and the difference between final (expanded) design height and the existing landfill cell surface calculated (up to 20m). Contour plans quantifying the thickness of additional material to be placed, as well as the expected magnitude of total deformation for each modelled timeframe were produced, assuming maximum airspace height was achieved with the additional landfill placement across the entire cell. Expected deformation magnitudes associated with both the rapid (30 day) and ongoing phases of consolidation (30 and 100 years) were calculated. Contour maps showing both the total and differential consolidations across the site were produced for each analysed time step. By combining the most recent existing ground surface survey (2010) with the calculated deformation magnitudes of each survey point, a 3D deformed surface was derived for each modelled time period. This deformed surface was then subjected to slope gradient analysis in order to identify any areas where localised leachate ponding may occur, or where the minimum drainage slope grade (1%) was not achieved.

The zone of highest deformation noted to exist within the differential settlement modelling was associated with the area of maximum Unit 1 material thickness. However, even after the modelled deformation magnitudes were applied to the existing landform no significant ponding effects were produced. It was thus concluded that only minimal remedial earthworks would be required to ensure that the existing drainage paths / overall design slope could be maintained after the vertical expansion.

10 CONCLUSION

The effective characterisation of a landfill – spatially, in terms of engineering properties and prediction of future behaviour – is a challenging exercise. It is considered that this was accomplished at this site through careful planning and implementation of an appropriate investigation and analysis program. The outcomes achieved were due to the use of a multiple component investigation combined with an analysis methodology that included repeated cross-checking and correlation / calibration between information sources. No single investigation method could be relied upon to provide all the data necessary for the subsequent analysis phases to be completed.

A number of components of this investigation were utilised to clarify the previously uncertain extents of a landfill cell, derive characteristic material properties and estimate variation within the landfill materials. The investigation documented in this paper has resulted in the production of a calibrated model that is considered an acceptable characterisation of the landfill and its behaviour under an imposed surcharge loading, calibrated to small-scale onsite deformations.

The benefit of such as approach is an increase in confidence in the reliability of the constructed model of the landfill. This in turn has clear benefits in terms of Regulator involvement, particularly in terms of adoption and acceptance of innovative engineering, such as vertical or “piggyback” landfill expansion.

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