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INSTRUMENTATION AND LONG-TERM MONITORING OF IN-PLANE STRAINS WITHIN GEOMEMBRANES TO LANDFILL STEEPWALL LINING SYSTEMS

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Abstract: Historically, a range of novel lining systems has been developed to provide effective containment to waste depositories in deep quarries with steep side walls (so called "canyon landfills" in the USA). These have often relied upon geomembranes as the primary lining material within a multi-layered sequence of geosynthetics. Various technical challenges must be addressed to create suitable conditions for lining with geomembranes at angles greater than 45 degrees from the horizontal. One of the principal loadings on the steepwall lining system is caused by downdrag of the settling waste body leading to in-plane stresses on the geomembrane liner. Long-term monitoring of strains within the liner is the best method to investigate and quantify the effectiveness of the layered geosynthetics in minimising these downdrag forces.

The authors have undertaken development work over the last decade on a number of steepwall systems. This has included experimental performance testing as a key tool in the design of steepwall lining systems. The next stage is field trials where the steepwall system itself is installed with the means to demonstrate that the key design objective of minimal transfer of strains to the geomembrane has been achieved.

This paper describes the design of an instrumentation unit that measures directly the strains (and temperatures) in a steepwall geomembrane liner. The unit, which is based upon a series of linear variable displacement transducers (LVDTs), each monitoring 2m lengths of geomembrane, was designed to do this without being adversely affected by the lateral and vertical pressures and environmental conditions of a working landfill. Results were collected by automatic datalogger and interrogated remotely by modem link. Data are presented on the first four years of live loading in an operational landfill from construction of the steepwall system.

Keywords: field monitoring, full-scale test, geomembrane, long-term behaviour, landfill liner, strain.

INTRODUCTION

This paper describes research undertaken over a four year period to investigate the effects of downdrag forces from the settlement of non-hazardous (municipal plus other) waste within an operational UK landfill on the geomembrane-based steepwall lining system installed at that site. Some steepwall systems rely on a geomembrane as their principal barrier layer to prevent egress of leachate and gases from the landfill and prevent ingress of atmospheric air and groundwaters to the waste body. It is noted that since the introduction of the European Landfill Directive (Council of European Communities, 1999) into UK legislation (Stationery Office, 2002) with associated regulatory guidance (Environment Agency, 2002), purely geomembrane-based steepwall systems would no longer be considered compliant with regulatory requirements. Notwithstanding these changes, there is still considerable value in understanding the mechanisms at work between steepwalls and a degrading waste body. This research involved investigating the extent to which the integrity of such a geomembrane liner was affected over time by stresses being induced by movements in the adjacent waste body.

The lining system in question comprised multiple layers of geosynthetics overlying a revetment styled rigid steel framework. The evolution of revetment-type steepwall lining systems has been described previously (Gallagher *et al.* 2000, 2002, 2003 & 2004). Typically, these consist of a steel framework arrayed in a 1.5m x 1.5m grid and rigidly dowelled into the quarry wall, the framework being faced with galvanised mesh and backfilled with free draining stone. The lining system build up (starting from the revetment framework and working towards the waste body, see also Figure 1) comprised:

- needle-punched non-woven (NPNW) geotextile as the quarry-side membrane protection layer, underlying
- double textured, flexible polyethylene (FPE) geomembrane as primary barrier layer, underlying
- geocomposite acting as both drainage layer and waste-side membrane protection layer, underlying
- double layer of low-friction, woven geotextiles creating a preferentially low shear interface between the waste body and the underlying geosynthetics.

The quarry-side protection layer and the geomembranes were fixed to the steepwall system at 3m vertical intervals (one ‘lift’ of geomembrane was 3.6m wide, obtained by cutting a standard 7.2m wide roll in half) using angle sections bolted through the two geosynthetics into the revetment system. Angle sections were used as spreader bars to distribute the self-weight load from the geosynthetics and avoid stress concentrations at the bolt locations. Each 3.6m lift of geomembrane was deployed straight onto the framework from a vertically oriented bar and positively fixed at its upper edge to the framework by means of the angle sections. It was also fixed at its lower edge by overlying the lift of geomembrane immediately below by approximately 200mm and being horizontally extrusion welded. The geocomposite and the double layer of woven geotextiles were effectively held in place by lateral pressure from the waste body and thus were installed just before waste body placement. To prevent damage to the geomembrane the initial layer of material to be placed directly adjacent to the steepwall was contained in bulk material sacks prior to placement. These sacks contained predominantly granular quarry run material (see Figure 3a). As an additional precaution, the landfill operator was instructed that compaction plant should not work immediately adjacent to the steepwall to avoid damage to the lining system; hence a narrow zone of uncompacted waste existed immediately adjacent to the steepwall system. Potential implications of this zone on movements recorded at the steepwall are discussed later in this paper.

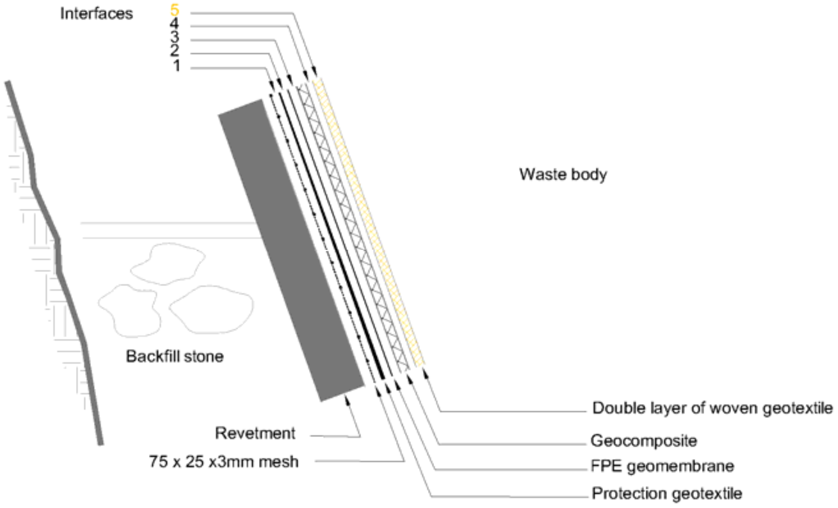

Figure 1: Sequence of geosynthetics and interfaces in steepwall lining system, shown schematically.

The method chosen to monitor the geomembrane was to measure in-plane movements over a representative length within a lift of geomembrane. A robust housing, described in a subsequent section, was designed to protect the instrumentation array within the context of an operational landfill site.

The lining system was designed to avoid excess strains being induced in the geomembrane by incorporation of a sequence of preferentially low shear interfaces between it and the waste body. A range of candidate materials were investigated for each of the layers required. The various geosynthetic materials were selected on the basis of both their specific function (protection, barrier, drainage, etc.) and their interface shear behaviour relative to each other. In the initial stages of assessment index data as supplied by the manufacturers were examined to narrow down the range of materials. The next stage was to undertake 300mm x 300mm constant contact area shear box tests with the test set up in performance mode using the proposed sequence of site-specific materials, to determine peak shear friction and peak apparent adhesion at particular interfaces, and compare their relative values. To simulate field loading conditions normal stresses of 30, 60 and 120 kPa were used. Rate of shearing was 2mm/minute. There is a sequential increase in interface shear resistance in the multi-layer lining system from the waste to the steepwall, as indicated in Figure 1 and Table 1, with significant differences in shear resistance with successive interfaces.

Table 1: 300mm x 300mm shear box test data used for steepwall design.

Interface, as per Figure 1	**Description of materials forming interface**	**Peak shear friction angle (also post peak where measured)**	**Peak apparent adhesion (kPa)**
5	Woven geotextile – woven geotextile	11°	4
4	Woven geotextile – geocomposite*	14°	2
3	Geocomposite* – textured geomembrane	19° (12° post peak)	7
2	Textured membrane – NPNW geotextile	22° (15° post peak)	12
1	NPNW geotextile – steel mesh	34°	9

Note: * geocomposite in this instance is a geonet core with thermally bonded filter geotextiles adhered to each side.

It is generally agreed that the critical strain (i.e. the strain beyond which irreversible changes in the orientation of molecules within the membrane occurs) for polyolefin geomembranes such as HDPE is of the order of 6%, i.e. about 50% of the yield strain. Thus, measuring strains lower than this value would indicate that stresses which could cause long term damage to the geomembrane have successfully been avoided. This approach is probably conservative for FPE noting its higher yield strain and, by inference, higher critical strain.

AIMS AND OBJECTIVES OF THE RESEARCH

The principal aims of this work were: (i) to investigate the potential level of downdrag forces which might be transmitted from the waste body to the geomembrane liner and (ii) to review of the effectiveness of geosynthetic layering incorporating preferential slip surfaces in minimising downdrag transfer.

The objectives of the detailed design of the instrumentation unit included: (i) that it might be constructed remote from the landfill site (in a suitable workshop) and (ii) that it would accurately measure local strain in the geomembrane without the observations being significantly distorted or affected by the environmental conditions of an active landfill sidewall. A further objective was that the instrumentation unit should be robust enough to withstand transportation, handling, installation and long term exposure in a landfill environment.

Long term monitoring was implemented using a series of three vibrating wire displacement transducers linked to a data logger located remotely from the instrumentation unit. This was to provide easy access to the stored and live data with the option of a telephone link-up to allow regular review and downloading of the results.

DESIGN, INSTALLATION AND COMMISSIONING

Instrumentation panel design

The overall principles upon which the design of the instrumentation panel were based were that representative movements in the geomembrane should be measured without affecting the barrier function of the geomembrane and that the process of monitoring should not itself significantly affect any measurements taken. The instruments were conceived as ‘large strain gauges’ to be connected to and supported only by the geomembrane, with the protective housing having the function of preventing damage from the landfill waste and ensuring undisturbed collection of data.

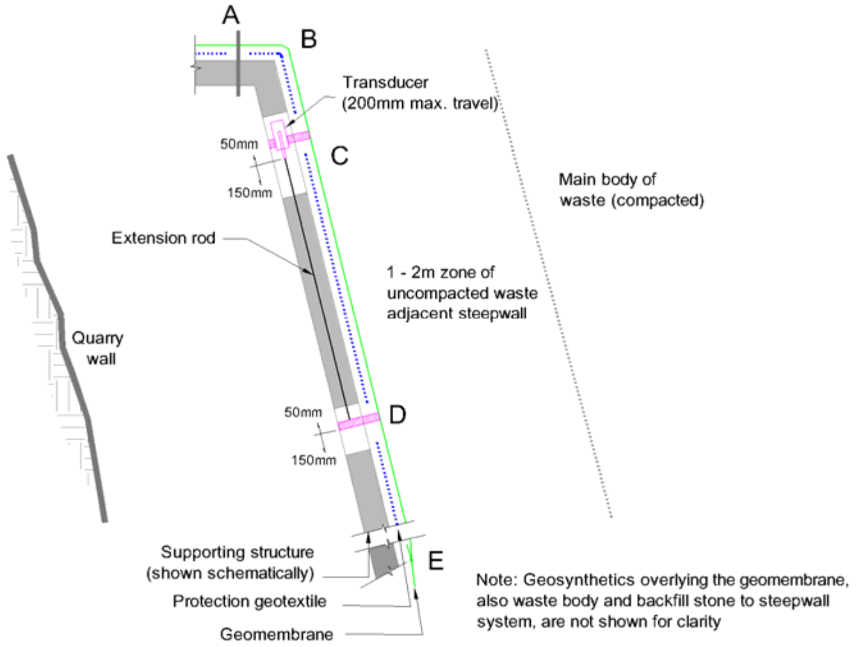

Figure 2 Schematic of instrumentation panel showing position of transducers ‘behind’ the geomembrane and range of relative movement between monitoring points C and D. A and E represent points of fixity of the geomembrane to the revetment framework and lower lift of geomembrane, respectively.

Instrumentation panel – protective steel housing

To allow these objectives to be met, the instrumentation panel was conceived as a replacement to a section of revetment framework. In practice a 3m x 3m section of standard revetment framework was replaced by a specially constructed galvanised steel panel. Each instrument body was 500mm in length and 30mm in diameter. The instruments, including their fibreglass extension rods, were each housed in 80x80x6.3 square hollow section (SHS) members. The three SHSs were welded vertically to the rear of the steel panel separated by 1m horizontally (see Figure 3b). The panel had three sets of two vertically oriented slots of 200mm length and 60mm width cut through both facing panel and SHS (see Figure 4a). The SHS and indeed the steel facing plate added to the strength, and mass, of the 3m x 3m instrumentation panel which was therefore significantly more robust compared to a similar area of standard revetment framework. This increased rigidity was the main difference between the instrumentation panel and surrounding revetment framework. Although in principle this might have made the instrumentation panel less representative, this difference was balanced by the need to ensure the instruments were safely and robustly housed and not influenced by lateral waste body pressure (say) deforming the framework and influencing the readings obtained. The steel facing panel had wire mesh spot welded to its waste-side to simulate the surface texture of the surrounding revetment framework system.

Figure 3: 3a on left is a general view of the revetment system showing bulk sacks and waste in front of steepwall. 3b on right is a rear view of instrumentation panel prior to installation. Three SHS are shown welded to rear face with access slots for installation of the transducers from rear. 'Top' of panel shown in foreground of image.

Instrumentation panel – geosynthetics and instruments

All monitoring equipment was designed to be installed 'behind' the geomembrane (i.e. relative to the waste body). Three vibrating wire displacement transducers, with temperature transducers, were selected to provide a degree of redundancy and allow some cross correlation of results – particularly noting that the instrumentation panel was to be buried beneath about 10m of waste and inaccessible for future maintenance. The maximum travel of the displacement transducers was 200mm. They were set initially to allow 150mm downwards and 50mm upwards travel, thus allowing 150mm of relative tensile movement of the geomembrane between points C and D and 50mm of non-tensile movement (see Figure 2 showing the instruments, fitted with fibreglass extension rods, such that they were positively attached to the geomembrane at two locations C and D). This approach of connecting each instrument to the geomembrane at two locations with 2m vertical separation was designed to allow measurements to be made without local influences on the geomembrane from the process of connecting the instruments to significantly affect results. This approach also avoided rotation at the monitoring points.

To allow HDPE blocks (each 50 x 70 x 50mm) to be fitted to the rear of the 2mm thick geomembrane as anchorage points for the instruments, two strips, each 2500mm long and 10 x 50mm in cross section of HDPE were welded horizontally to the rear of the geomembrane. The anchor blocks were fixed to these. To ensure the two strips did not restrain the movement of the geomembrane, appropriate gaps were left in the wire mesh and quarry-side geomembrane protection layers. See Figure 4a & 4b.

Figure 4: 4a on left shows 3m x 3m instrumentation panel being installed within revetment steepwall. Lower lift of geomembrane visible below. Vertical slots in front face for instrumentation visible. Gap in mesh shown at level of slots. 4b on right shows placement of quarry-side NPNW geotextile protection. Horizontal gaps in NPNW and mesh designed to allow movement in HDPE bars welded to rear face of the geomembrane (see text for further explanation).

Following installation of the geomembrane, it was 'conditioned' for nine days during which time moderate (3kg/m) loads were applied to the lower edge (see Figure 5a) to ensure any inherent curvature was removed. Some distress was observed to the front face of the geomembrane in the locations where HDPE bars had been welded to the rear face. Following discussion with the regulator and noting the instrumentation panel was part of the permanent lining system at an active site it was agreed to overweld patches of membrane at these locations, see Figure 5b.

The precision of the vibrating wire displacement transducers (Geosense model VWS-50006, accuracy <0.5% of full scale output (FSO), resolution 0.025% FSO) and the 150mm downwards plus 50mm upwards range of potential movement were selected in the design of the instrumentation scheme to allow both minor movements (as predicted by the steepwall design objective) and gross movements (exceeding the critical strains of the geomembrane, i.e. >6%) to be measured.

Figure 5: 5a on left shows geomembrane during ‘conditioning’ under moderate (3kg/m) pre-loading before being extrusion welded to underlying lift of geomembrane. 5b on right shows geomembrane prior to placement of overlying layers. Patches shown welded to front face at locations the horizontal strips of HDPE were welded to rear face.

Instrumentation panel installation

The instrumentation panel was pre-fabricated and installed on site between 18 and 27 August 2003 by a specialist revetment contractor. The base of the instrumentation panel was placed at about 5m above the bottom of the steepwall system at the landfill site, and an instrumentation cabinet containing the data logger and accessories was situated about 60m away from the panel. The position of the instrumentation panel, at approximately one third of the height of the steepwall system, was selected to capture movements at a representative buried depth within the waste body and to avoid influences from the base of the waste body which could mask deformations in the geomembrane. At the location selected the steepwall inclination was approximately 70° from the horizontal.

Instrument calibration and recording of data

Three vibrating wire displacement transducers were supplied and calibrated by a specialist instrumentation manufacturer. The movements as recorded by the data logger required translation to displacement readings in millimetres. Based on the calibration factors for each transducer, the raw instrument readings of between 2.0 to 6.6 Hz^2 were later converted to actual displacement values of between 0 to 200mm respectively. The calibration records indicated that the errors were within the range -0.52% and +0.14% FSO.

The temperature readings were recorded in units of degree centigrade ($^{\circ}C$). It should be noted that no further calibration or maintenance was possible after the waste level became higher than the instrumentation panel. The instruments were connected to a Campbell Scientific CR10X data logger housed in a robust, weather-proof steel cabinet located remotely from the instrumentation panel. Its position was selected to allow unimpeded future waste placement. The data logger was powered by a standard 12V car battery.

Ready access to the stored and live data with a mobile/wireless telephone link-up was established to allow regular review and downloading of the results. In addition, there were regular site visits at about 4 month intervals to maintain the system, including battery recharge or replacement.

RESULTS

Recorded data

On day 1 (date of commissioning, 27 August 2003), the data logger was set to take readings at 5 minute intervals for testing purposes. The reading interval was then increased to 1 hour for the first month and 2 hours for the rest of the project life. The reading interval of 2 hours was selected to allow a fully charged battery to last more than 6 months. Given the rate of loading and associated movement, this logging rate was believed to be appropriate. In addition to displacement and temperature readings from the transducers, the data logger also recorded the condition of its battery in terms of output voltage to the data logger. Initially, data were collected on site using a portable computer during regular site visits. Later, data were predominantly downloaded from the data logger remotely using the wireless telecommunication facility.

In total, more than 18,000 sets of readings were recorded during 4 years of monitoring. Data were stored as time based arrays and processed using an Excel spreadsheet. Raw data such as those indicating displacements (between 2.0 and 6.6 Hz^2) were reduced to engineering units for instrument positions between 0 and 200mm. Reduced data against time are presented graphically in Figures 6, 7 and 8.

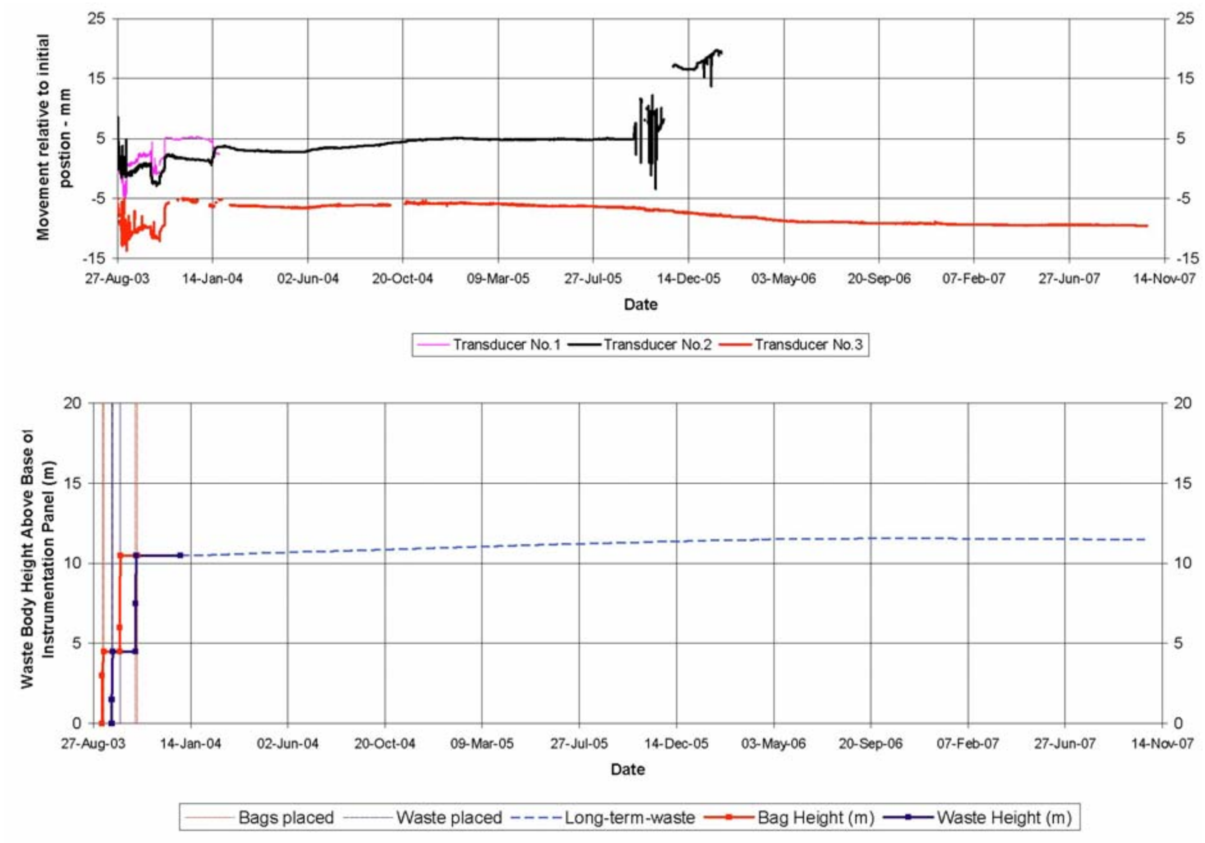

Figure 6: Displacement data and indicative waste body position vs. time

Figure 6 presents the changes in displacement of all three transducers relative to their initial setup positions corroborated with some records of waste filling with time. It should be noted that large displacements clearly beyond those which may reasonably be expected were not included in the derived data set. The purpose of this graph is to demonstrate the continuity in monitoring and indicate the degree of functionality of all three transducers over the project life. Only transducer No. 3 remained functional until the end of the project. Figure 6 also gives an indication of the elevation of the waste body surface with time, particularly during the first half year of monitoring. In the absence of actual survey data, later elevations of the waste body surface were postulated, noting that additional waste placements occurred from time to time, also that settlement of the waste body occurred continually.

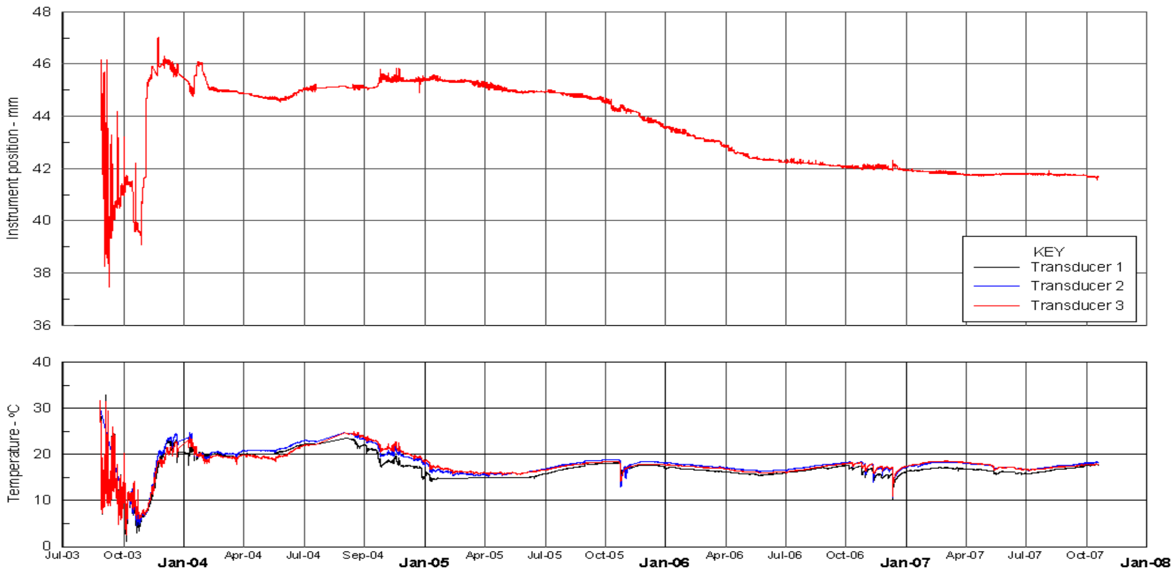

Figure 7: Transducer No. 3 displacement data and all temperature data vs. time

Figure 7 includes the full set of position data as recorded by transducer No. 3 against time. The data were reduced to millimetres to present the actual measured position in relation to the total potential travel distance of 200mm. The temperature data for all three transducers are also presented in this graph showing the relationship between displacement, time and temperature.

Figure 8 shows the data from the three transducers against time on a logarithmic scale. This graph suggests an apparent diurnal relationship between measured displacement and temperature in the early phase of monitoring. The position data for transducer 3 have been extrapolated from about 1,500 to 10,000 days based on the observed trend over the previous half log cycle of time (refer dashed line from years 2007 to 2030) indicating a potential 7mm movement over about 30 years. Implications of the relative movements are discussed later.

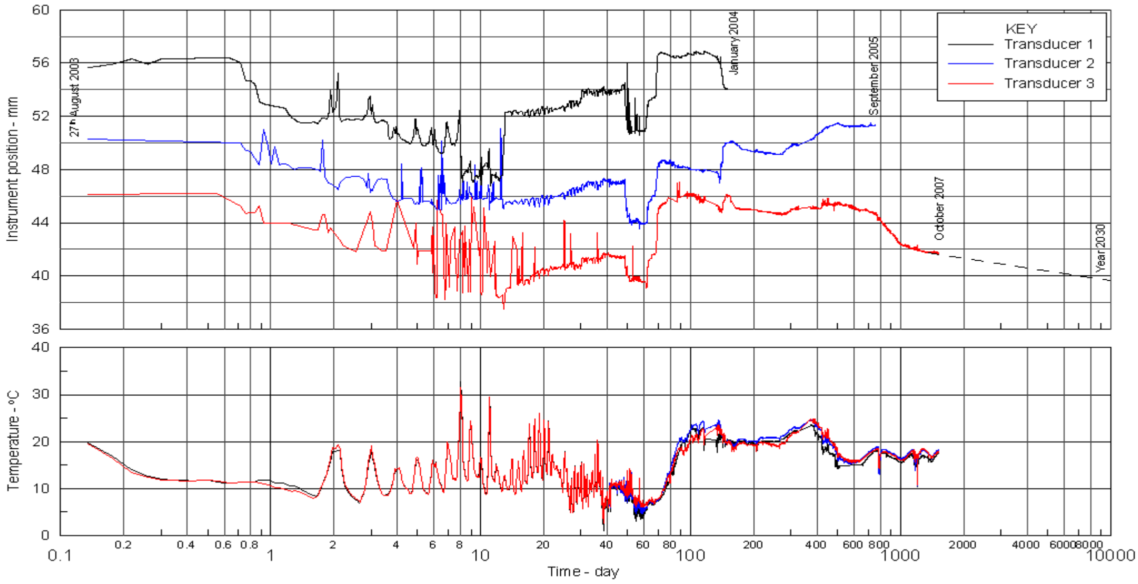

Figure 8: Displacement and temperature data vs. time on logarithmic scale

Instrumentation performance

The performance of all three transducers over the project is summarised below:

Transducer No. 1

- In January 2004, this displacement transducer started to produce a constant out of range reading at the negative limit of the instrument's range, indicating a fault. This was investigated and the instrument was found to be beyond repair.
- In general, the temperature readings were in reasonable agreement with those from transducers No. 2 & 3 during most of the project. Some erratic readings were recorded between January 2005 and June 2005.

Transducer No. 2

- Transducer No. 2 started producing apparently erroneous and inconsistent readings which were well outside the expected range (i.e. 2.0 to 6.6 Hz^2) in September 2005. Between September 2005 and February 2006, the behaviour of this transducer was monitored more frequently than the others in order to determine whether the transducer might have developed a temporary fault or not and that readings might be restored. By the end of February 2006, a constant out of range value at the negative limit of the instrument's range was recorded indicating that this fault was permanent, associated with the transducer and hence beyond repair.
- During the period from day 1 up to October 2003, this transducer registered a constant erroneous temperature reading of -105°C. Thereafter, temperature readings were in reasonable agreement with transducers No. 1 & 3.

Transducer No. 3

- Based on analysis of the data derived and the conclusion that the output was within a region to be expected from previous experience, this transducer appears to have functioned satisfactorily for the whole 4 year project both in terms of displacement and temperature.

DISCUSSION

General

Analysis of the data suggested that the instrumentation went through an initial 'settling-down period' from start of the project on 27 August 2003 until about January 2004 when the waste surface level was well above the instrumentation panel. During this period, there was evidence of many erratic readings, including some electrical 'noise', noting that waste placement was ongoing at the time. In February 2004, the data logger was comprehensively checked, as the transducers were no longer accessible, and was confirmed to be in good working condition.

From February 2004 onward, the readings appeared to stabilise, coincidently as the fill level became much higher than the monitoring panel, although occasional short periods of erratic readings and electrical noise were still recorded. On one occasion in October 2004 when the instruments were being monitored telemetrically, readings appeared to show atypical movements at the monitoring points. The landfill site staff confirmed that for about a three-week period and at about the same time as the atypical monitoring results capping related activities with associated plant movements were taking place in the vicinity of the instrumentation panel. This information also confirmed that capping occurred approximately 15 months after installation of the instrumentation panel.

One displacement transducer (No. 3) was still functional at the end of the 4 year project. The first transducer became non-functional after just 5 months and the second after approximately 2 years. This represents about 60% functionality of all instrumentation over the duration of the project. The instrumentation panel had been designed to provide sufficient physical protection to the transducers, therefore it may be surmised that the failures of transducers No. 1 and 2 may have been more likely to be electronic related than mechanical, noting that the two faulty transducers did still produce temperature readings.

Apart from some erratic readings as mentioned above, the temperature data recorded by the three transducers showed similar patterns of change in temperature but there were differences in magnitude of 3°C to 5°C. Data from transducers No. 1 and 3 appeared comparable from the beginning until the second week in October 2003, see Figure 8. About 95% functionality of the temperature transducers was achieved over the four years of monitoring.

During the settling-down period, the instrumentation panel was partially exposed to the weather and recorded temperature varied between 1°C and 32°C, see Figure 7.

From January 2005, the instrumentation panel was covered by up to 10m depth of waste and the temperature became more steady and varied between 15°C and 18°C, with occasional reduction to 11°C in the winter months. Note that extreme temperature data outside the range which may reasonably be expected were excluded from the data set.

Displacement Measurements

Overall, displacements measured by all three transducers were less than 5mm from the datum points over the four year period of monitoring. These are regarded as minor movements in absolute terms.

Transient spurious data (i.e. outside the transducer measurement range) have not been included in graphs. The discontinuities shown in the graphs of all three transducers in Figure 6 indicate periods of erratic readings.

Noting that the ‘strain gauges’ measure relative movement between points C and D, decreases in displacements relative to their datum points indicate movement of the monitoring point C towards D (refer Figure 2). In practice this implies non-tensile strains in the geomembrane between points C and D, 2.0m apart. Gross strains in the geomembrane can be derived from knowledge of this displacement. (The geomembrane as a thin sheet will not readily suffer true in-plane compression, it being more likely to fold. True compressive strain will only occur if the sheet is completely laterally confined. The convention adopted here is to designate tensile strains as positive and non-tensile strains as negative.) Conversely, an increase in displacement readings relative to the datum indicates movement in the geomembrane of point C away from point D. This implies tensile strains being generated in the geomembrane between point C and D.

During the settling-down period (Aug 2003 – Jan 2004), the data appeared unreliable with significant noise and it was difficult to assess clearly what was happening at the time. It appears that the instruments were generally subject to tensile movements (C away from D) in the first few months. In November 2003, i.e. about the time that the instrumentation panel was being buried by waste placement within the landfill cell, transducer No. 3 showed a tensile displacement of about 8mm, from 39mm to 47mm. However, as discussed below, the effect of temperature may have also contributed to expansion of the geomembrane in this case.

From the end of 2004, displacement readings became more stable; electrical noise/interference was only infrequently recorded. The measurement position of transducer No. 3 returned to its initial datum position at 46mm approximately. The shape of the displacement graph thereafter appears to be analogous to that of a typical consolidation settlement curve (i.e. self-weight settlement), particularly for the period between November 2004 and September 2007 as illustrated in Figure 7.

A total non-tensile displacement (C towards D) of less than 5mm over nearly four years of monitoring has been measured based on the data provided by transducer No. 3 after January 2004, as shown in Figures 6 and 7. The overall strain during this period was less than -0.0025 or -0.25% over a distance of 2.0 metres between point C and D. The displacement data suggesting that non-tensile strains were being developed is therefore counter intuitive if displacements at the monitoring points are predominantly due to waste body self-weight settlement, which can be expected to occur in the first few years after placement. (It is noted that in this instance settlement data of the surface of the waste body from regular surveys were not available to confirm this assumption.) Although counter intuitive, this is considered to be a significant field observation.

Two hypotheses have been suggested to explain these observations. Note that the instrumentation effectively measures relative movements between C and D. The experimental set up is such that absolute movement of the zone between C and D is not known. Accepting that both C and D will move under loading from the waste, the following may well be happening in the case of non-tensile movements between C and D:

(i) both C and D are moving downwards and D is moving downwards to a lesser extent than C, or

(ii) both C and D are moving upwards and D is moving upwards to a greater extent than C.

Hypothesis 1 considers a general downwards movement of the waste body and instrumentation as per case (i) above and is based upon soil mechanics theory of self weight settlement. In brief, where a zone of soil is subject to settlement, including that due to self-weight, and the movement is limited by a rigid horizon at depth, the settlement at a point within the ground is a function of its height above the rigid horizon. In other words, settlement at point D should be less than that observed at point C, 2m above. This assumes that the overall settlement in the waste body is homogenous and acts on the waste-steepwall boundary in a uniform manner.

Hypothesis 2 considers a general upwards movement at the instrumentation as per case (ii) above. As noted previously the landfill operator is required not to use a compactor within about 1m of the steepwall to avoid damage being caused to the lining system. This creates a continuous zone of relatively uncompacted waste (including the bulk sacks containing uncompacted waste) between the steepwall and the compacted waste within the main waste body. It is therefore kinematically feasible that the downwards movement of the main waste body some metres away from the wall may cause a lateral squeezing and some upwards irrecoverable movement within the 1-2m wide zone of uncompacted waste immediately adjacent to the steepwall.

These hypotheses remain to be proven and should be the subject of further research. Conventional wisdom would point towards hypothesis 1. Whilst seemingly feasible in this case, both explanations may not apply across the whole of this particular steepwall system or to other steepwall systems. The observations may be a function of compaction practice, the degree of use of bagged waste and the nature of the waste placed. The displacements measured in October 2004 suggest that capping operations may well initiate transient, but potentially high, levels of liner movement.

Discussion of temperature readings

Temperatures show significant fluctuations in the first 100 days of monitoring, with readings between 1°C and 32°C. There appears to be some correlation between temperature and measured displacement in this early phase of monitoring. One year after the instrument panel was covered with about 10m of waste temperatures appear to have reached a steady value of about 18°C.

During the settling-down period (Aug 2003 – Jan 2004), the pattern of change in displacement appeared to coincide with diurnal changes of temperature as shown in the time-logarithmic plots (see Figure 8). For instance, in November 2003, an increase of 19°C-20°C and a change of 8mm in displacement were recorded by transducer No. 3; this change can be correlated with anticipated strains related to thermal expansivity over this temperature range for comparable polyolefin geomembranes (coefficient of linear thermal expansivity, CTE, in the order of 2×10^{-4} /K for HDPE). This apparent correlation was not observed later in the project; also it may be more influenced by thermal expansion of the steel framework than that of the geomembrane (CTE in the order 12×10^{-6} /K). In December 2006, the temperature decreased from 17°C to 11°C (i.e. 6°C difference) and the displacement reading changed by only 0.3mm, as indicated by transducer No. 3 (refer Figure 7). It is possible that the recorded temperature during the settling-down period may not always reflect the actual temperature at the lining because the transducer measures temperatures in a relatively well protected environment, whereas the geomembrane and the metal frame of the instrumentation panel were more directly exposed to the weather during this period. On this basis and noting the diurnal variations of both sets of data indicated in Figure 8, temperature can be inferred to have some effect on the displacement measurement in the short term but probably not a significant effect in the long-term condition where the whole system is well protected from the weather and large temperature fluctuations. In addition, long term the geomembrane is probably relatively constrained from thermal induced expansion due to the waste body pressure.

Lessons learnt

The instrumentation panel can be considered to serve as a model of how monitoring of in-plane strains within a geomembrane can be undertaken. Additional instruments would have been very desirable. It is accepted that some refinements to the design would be appropriate. For example, one or more of the strain gauges could have been inverted. It would be beneficial to have measured absolute movements as well as relative movements between C and D. Having established the instrumentation it would have been useful to continue monitoring until the instruments were no longer functional. Consideration should be given to installation of monitoring equipment in different locations within a landfill, i.e. at different heights relative to the landfill waste body, also with different waste types. There may be benefit in considering the use of a series of smaller strain gauges direct on the geomembrane to map strains over the geomembrane – assuming that the technical challenges of working in a landfill environment can be overcome. Also, it would be beneficial to explore the use of pressuremeter data from the waste body, particularly in the zone immediately adjacent to the steepwall, to complement the monitoring at the geomembrane. It would certainly be beneficial to track changes in the waste body surface profile and correlate this with movements at the sidewall, potentially by means of geographical positioning systems (GPS) monitored remotely or by traditional survey techniques.

The various challenges encountered with the displacement transducers have been noted including apparent intermittent failure of the electronics, also total loss of function; some of these problems are inevitable when working in the aggressive environment of an operational landfill setting. Minor, transient issues may right themselves, for example where an instrument is affected for a period by water ingress. Some judgement is obviously required in considering data which varied significantly from expected norms, hence the decision to declare some instruments out of commission. These temporary and permanent losses of data are disappointing but not totally unexpected. It would have been very desirable, however, to obtain more data from the second half of the study. The remaining instrument did at least allow continued monitoring for the four years.

CONCLUSIONS

The instrumentation panel was constructed to the design specification and successfully installed in an aggressive environment, above the fill surface and then progressively buried 10m below the surface of an operation landfill. After four years, it has been proven fit for purpose. The panel was able to withstand the pressure of the waste and function as a monitoring point for displacements in the plane of the geomembrane. About 60% functionality of the displacement transducers and about 95% functionality of the temperature transducers were achieved over the course of the project. Over a period of four years these data have provided further understanding the interaction between geomembrane lining and waste settlement. Some erratic data were experienced but are considered to be primarily instrument performance related.

The magnitude of the measured displacements in the liner suggests that the design of the steepwall system has been proven to perform within acceptable limits. Likewise, the design integrity of the steepwall lining system in terms of its multiple layers of geosynthetics has been shown to be robust. The geomembrane lining was seen to be subjected to an average of -0.25% (non-tensile) strain noting that the limiting critical strain (i.e. the point beyond which irreversible changes in the orientation of molecules within the membrane occurs) for polyolefin geomembranes is of the order of +6%. This is considered a comfortable margin. When strains are extrapolated based on a logarithmic expansion of the time domain, anticipated strains over the first 30 years are also within about -0.5% which gives confidence in the long-term performance of the lining system. This may be an overly conservative estimate on the basis that the main (compacted) waste body self-weight settlements can be expected to reduce in the first few years after the placement, hence the driver for further movements is significantly reduced, also that the geomembrane is a flexible polyethylene.

Virtually continuous temperature readings were obtained over a four year period indicating steady state temperatures of the buried steepwall system at about 18°C. These are valuable new data giving an insight into the environment in which the liner is to operate.

Counter intuitively, non-tensile displacements of the geomembrane were recorded at the monitoring points. These are very minor movements in absolute terms and, translated to in-plane strains in the geomembrane, are greater than one order of magnitude lower than the critical strain for such polyolefin geomembranes.

Two hypotheses have been postulated. Hypothesis 1 considers a general downwards movement of the waste body and instrumentation in the case that both C and D are moving downwards (refer Figure 2) and D is moving downwards to a lesser extent than C and is based upon soil mechanics theory of self weight settlement. Hypothesis 2 considers a general upwards movement at the instrumentation in the case that both C and D are moving upwards and D is moving upwards to a greater extent than C and is based upon the idea that the downwards movement of the main waste body some metres away from the wall may cause a lateral squeezing and some upwards irrecoverable movement within the 1-2m wide zone of uncompacted waste immediately adjacent to the steepwall.

These hypotheses remain to be proven and should be the subject of further research. Conventional wisdom would point towards hypothesis 1. Whilst seemingly feasible in this case, both explanations may not apply across the whole of this particular steepwall system or to other steepwall systems. The observations may be a function of compaction practice, the degree of use of bagged waste and the nature of the waste placed.

These are significant field observations made in an aggressive environment and, in the view of the research workers, represent an advance in the understanding of long-term liner behaviour during landfilling.

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