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Investigations of geomembrane integrity within a 25-year old landfill capping

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ABSTRACT

Investigations have been undertaken at a 16 ha landfill capping to assess performance of the geomembrane component some 20–25 years after installation. The site has been the subject of quite extensive monitoring together with hydrological and other studies. Although environmental monitoring has shown no major concerns, there have been discrepancies in calculated water balance, leading to the recent investigations reported here. The capping, which is an interim solution, comprises about 1 m of cover soils over 0.375 mm LDPE geomembrane and surrounded by a perimeter drain. A robust final capping system will be constructed at a later date. Various remedial works were undertaken between 2010 and 2014 at the cap perimeter drains, also at a series of gas vent/probe holes through the geomembrane, to address the discrepancies in water balance, and the opportunity was taken to investigate the condition of the geomembrane which revealed a series of unanticipated gaps in the geomembrane. These investigations were subsequently extended over the whole cap to characterise the nature and extent of those defects and assess likely causes.

The series of investigations reported here represents a significant case history, one of relatively few, and which describes: the approaches adopted to pursue the series of investigations; the findings of that work; options considered to address the issues; lessons learnt and the intervention strategies which are under consideration in response. It also has implications for other landfill caps and highlights the importance of construction processes including construction quality assurance to ensure the integrity of geomembranes following placement is not adversely affected, also the need for good records management to assess system performance in service and plan future interventions.

1. Introduction

Investigations have been undertaken of a 16 ha interim cap at the UK's principal site for disposal of low level radioactive waste, known as Low Level Waste Repository, some 20–25 years after installation. These investigations, some of which were undertaken as precursors to phases of remedial works, were undertaken in stages over a number of years. The site has been the subject of quite extensive monitoring together with hydrological and other studies. Although environmental monitoring has shown no major concerns, there have been discrepancies in the calculated water balance. To better understand these discrepancies the investigation works described here have examined the integrity of the geomembrane of the capping system at particular locations: (i) near the perimeter drains as the adjacent geomembrane was exposed during remedial works to those drains, (ii) at gas vent probes through the capping to examine the gas vent-to-geomembrane connection and (iii) across the interim cap generally, with a focus on welds and tears. [This paper expands upon and updates Gallagher et al. (2015) which primarily reported on work in locations (ii) and (iii).]

1.1. Site setting

The site is situated on the coastal plain in north-west England, around 0.5 km from the Irish Sea coastline. A quite variable waste body was disposed on site from 1959 into a series of seven adjacent trenches (Trenches T1–7; Fig. 1 for cross section). Trenches T1–6 are typically about 5–8 m depth and trapezoidal in cross section; Trench

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7 is similar in depth but of variable width. The waste was tumble tipped into the trenches and covered, prior to installation of an interim cap system. The interim cap was constructed in two phases in 1988/89 (T1–6) and 1995 (T7). The purpose of the interim cap is to:

- minimise the percolation (or infiltration through the cap) of rainwater into the trenches;
- control the release of gases generated by waste decomposition; and
- provide a visually acceptable, protective cover for the trenches.

Design drawings show a multi-layer system, comprising bulk fill to profile, overlain by a low density polyethylene (LDPE) geomembrane, with a soil cover layer typically around 1.0 m over the geomembrane [The term 'LDPE' is used in this paper for the geomembrane, consistent with contemporaneous references (White Young, 1991); see also Section 2.1.1 for further discussion on the geomembrane classification]. The cap was profiled to a 1:25 batter with runoff to stone-filled perimeter drains, continuous around the whole of the trenches. A series of steel probes was driven through the cap into the trenches to provide passive gas venting, discussed further below. A significantly more robust final capping system will be constructed at a later date.

2. Investigation and remedial works

Investigations took place in 2010 to the geomembrane adjacent to the perimeter drain and in 2013–14 to the geomembrane on the remainder of the capping. These two stages of investigations are described below.

2.1. *Investigations in 2010 of geomembrane adjacent to the perimeter drain*

Surface water run-off from the interim trench cap is collected in trench cap perimeter drains and monitored at two gauges for the western and eastern parts, respectively. Detailed inspections associated with the annual monitoring had reported evidence of defects in these drains such that not all run-off was being collected and carried away, hence recharging the perimeter area groundwater. The entire trench cap perimeter drainage system was replaced in summer 2010. The original trapezoidal stone-filled channels were replaced with more efficient semi-circular open channel drains; this refurbishment led to at least a threefold increase in the volumes of waters being recorded during peak rainfall events due to a combination of more effective channelling of large flows and reduction in losses at the perimeter of the trenches.

During these remedial works the opportunity was taken to inspect the areas of the interim trench cap adjacent to the perimeter drains, exposed during the works. Fuller details are given below. In brief, the areas of the interim cap exposed were found to be in quite good condition considering the length of time for which it has been in place. The number of defects was moderate, consistent with a thin geomembrane without particular protection measures. Some more significant defects (tears) encountered were almost certainly the result of activity to expose the liner. The other main defects were a variable number of small holes, some of which may have been caused by exposing the liner, but most of which probably date back to construction. There was no particular evidence of deterioration with time.

Investigatory field work, comprising sampling of the LDPE geomembrane in the 5–10 m wide zone that was exposed during remedial works adjacent to and upslope of the perimeter drains, was conducted from late May to early July 2010, see Fig. 2. Samples of the LDPE geomembrane, typically 1 m × 1 m, were taken from adjacent to the cap perimeter drain at approximately 50 m intervals. The overlying soil material was removed using an excavator to expose the geomembrane as gently as practicable. Each sample was photographed and inspected for defects (holes, tears, dents and ripples) – these were counted and logged; refer Table 1. Geomembrane samples were tested to determine:

- Thickness (ASTM D5199);
- Density (ASTM D1505);
- Carbon black content (ASTM D1603);
- Tensile properties (ASTM D6693); and
- Notched constant tensile load (NCTL, ASTM D5397 – single point)

Three 1 m length samples of geomembrane welds were also obtained during the investigation and these samples were tested for shear and peel strength (5 coupons per sample length) to ASTM D6392.

Particle size distribution (PSD) tests to BS 1377: 1990: Part 2 (Methods 9.2 wet sieve and 9.4 pipette) were carried out on the soil materials directly above and below the liner from seven sample locations to determine the composition of the soil material and allow a comparison between the levels of damage (dents, holes etc.) of each geomembrane sample and the large particle content of the immediately adjacent soil. The PSD testing also allowed an assessment of any damage to the subgrade and overlying soils which may have occurred due to washout or similar.

2.1.1. *Results of 2010 geomembrane testing*

A total of 31 LDPE samples was taken for inspection of which 17 were sent for detailed laboratory testing. Results are summarised in Table 2 and discussed below.

The average thickness measurement (based on 31 field measurements with a micrometer and 17 laboratory tests) was 0.385 mm, with results ranging from 0.309 mm to 0.464 mm. The measured thickness generally exceeds the 0.375 mm thickness indicated in design drawings.

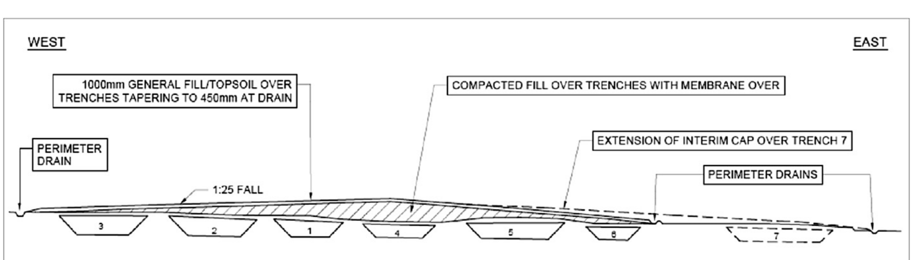

Fig. 1. Schematic cross section through Trenches 1 to 7 and interim capping. Not to scale.

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Fig. 2. Image during 2010 remedial works to perimeter drain. Original 0.375 mm LDPE geomembrane upslope of the drain exposed for examination.

Measured geomembrane density values ranged from 0.927 g/cm^3 to 0.942 g/cm^3 (16 data points), with an average of 0.938 g/cm^3, closely comparable to the typical density of LDPE of 0.939 g/cm^3, as reported in GRI – GM17. It is noted that ASTM D883 (2012) classifies geomembranes with a density between 0.926 g/cm^3 and 0.940 g/cm^3 as medium density (MD) or linear medium density (LMD), depending on manufacturing process. The spread of results showed no significant variation in densities across the samples as would be expected. No data concerning the density of the LDPE at placement are available, although post-construction records describe: "*The membrane used for the cap was low density polyethylene (LDPE), it was produced by film extrusion and was 0.375 mm thick.*" (White Young, 1991).

Table 1
Summary of geomembrane defects from near perimeter drain.

Sample ref.	No. holes	No. tears	No. dents	No. ripples
S101	1	0	15	0
S102	0	0	2	0
S103	0	0	4	0
S104	0	0	1	0
S105	6	1	3	0
S106	0	0	6	7
S107	2	0	1	6
S100/200	0	0	2	0
S202	0	0	2	0
S203	5	0	6	0
S204	Sample contains too many defects to accurately assess			
S205	>75	Sample contains many defects		
S206	1	0	3	0
S207	1	0	3	0
S208	0	0	1	0
S209	0	0	7	0
S210	0	0	9	0
S211	3	0	8	0
S212	0	0	3	1
S213	1	0	3	0
S215	0	1	2	0
S216	1	1	2	1
S217	0	0	1	0
S218	3	1	5	0
S220	0	1	1	1
S221	1	0	1	1
S222	0	2	1	1
S223	2	4	1	2
S224	0	0	2	0
S225	0	2	2	0
S226	0	0	3	1
Total	**>102***	**13**	**100**	**21**

Notes: * Without including defects from S205 there were 27 holes for all other areas. Defects identified within the geomembrane sample were qualitatively defined as follows:

Hole: Small, approximately circular defect though which light from a light box can pass.

Tear: Larger, irregularly shaped defect through which light from a light box can pass.

Dent: Small, noticeable deformation of the geomembrane through which light from a light box cannot pass (i.e. the liner has not been pierced).

Ripple: Larger, usually long, deformations (i.e. folds) through which light from a light box cannot pass.

The average carbon black content of 16 samples was 3.25% (range: 2.55%–3.77%, a relatively wide variation). The minimum recommended carbon black content to provide adequate UV protection is 2–3% (GRI – GM17). All results from the recent tests are within or exceed the recommended range. No data concerning the carbon black of the LDPE at placement are available.

Four samples were tested for single point NCTL, with results of >304 h (twice), >310 h and >311 h. It is appreciated that stress crack resistance as measured using ASTM D5397 (single point) is generally only undertaken for the more crystalline HDPE geomembranes rather than LDPE or linear low density polyethylene (LLDPE). For comparison the latest version of GRI – GM13 (2015) specifies a value of 500 h for HDPE, previously 300 h. Further, GRI – GM10 (2015) indicates that thicknesses for NCTL samples are typically in the range 0.75 mm–3.0 mm; the average thickness of samples tested was half this lower limit.

The stress at break of the geomembrane was tested both in the machine (L-way) and transverse directions (X-way) – where this could be determined, otherwise assumed. The measured break stress ranged from 4.22 kN/m to 7.83 kN/m, with an average of 6.05 kN/m. From correlation of measured break stress with elongation at break and extrapolating these limited test results (14 data points) to the 800% elongation typically specified for LLDPE (GRI – GM17), a material of this type and age might be expected to have had a break stress of around 7 kN/m on installation. By comparison, modern materials might be expected according to GRI – GM17 to have a break stress of about 10 kN/m. The lower measured values of break stress may indicate some degradation of the liner over time, but noting that no original test data are known. Comparing break stress results with the reported thicknesses it can be seen that the thinner samples generally correspond to the lower break stresses. The results are generally encouraging and suggest quite limited changes with time.

The corresponding elongations at break of the geomembrane ranged from 266% to 589%, with an average of 416%. It would be anticipated that the elongation at break of an LDPE geomembrane on installation would be around 800% (GRI – GM17). Again this suggests some limited embrittlement and loss of performance, which in turn can be considered evidence of relatively satisfactory performance over some 20+ years.

Weld tests were carried out on 15 coupons from three samples and showed that the shear strength of the welds ranged from 3.52 kN/m to 4.68 kN/m, with an average of 4.19 kN/m. The weld shear strength is generally lower than the strength at break of the parent material. Very limited details of welding are reported in White Young (1991): "*The sheets were joined by heat fusion which is a manual operation carried out by bringing two clean edges of sheeting together and holding them in contact while heat in excess of 110 °C is applied. The membrane and seams were visually inspected prior to backfilling*". Site examination and contemporaneous photographs (Figs. 3 and 4) appear to show single track welding techniques were used. The results are probably indicative of the welding methods used at the time. It is encouraging to note that the welds still possess significant strength after this length of time. Indeed no defects associated with welds were found in this phase of investigations.

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Table 2
Summary of 2010 geomembrane testing data.

Test	Number of samples	Average result	Maximum result	Minimum result
Thickness (Lab) ASTM D5199 (mm)	17	0.383	0.450	0.340
Thickness (Site, micrometer) (mm)	31	0.385	0.464	0.309
Density ASTM D1505 (g/cm^3)	16	0.938	0.942	0.927
Carbon black content ASTM D1603 (%)	16	3.25	3.77	2.55
NCTL ASTM D5397 (single point, hours)	4	N/A	>311	>304
Tensile properties ASTM D6693				
L-way break stress (kN/m)	16	6.16	7.77	4.83
X-way break stress (kN/m)	15	5.94	7.83	4.22
L-way elongation at break (%)	16	421	589	290
X-way elongation at break (%)	16	411	583	266
Weld tests ASTM D6392				
Shear strength (N/mm)	15[a]	4.19	4.68	3.52
Shear elongation (%)	15[a]	>100	>100	>100
Peel strength (N/mm)	15[a]	2.29	3.80	0.71
Peel separation (%)	15[a]	N/A	N/A	N/A

[a] 5 coupons were tested per 1 m length weld sample; three weld samples in total.

Fig. 3. Contemporaneous image of original work of fusion welding of the cap geomembrane to the perimeter drain liner. Of note: single track welding machine being used; also behind the welding team the geomembrane shortly after its installation is in a significantly wrinkled/folded condition.

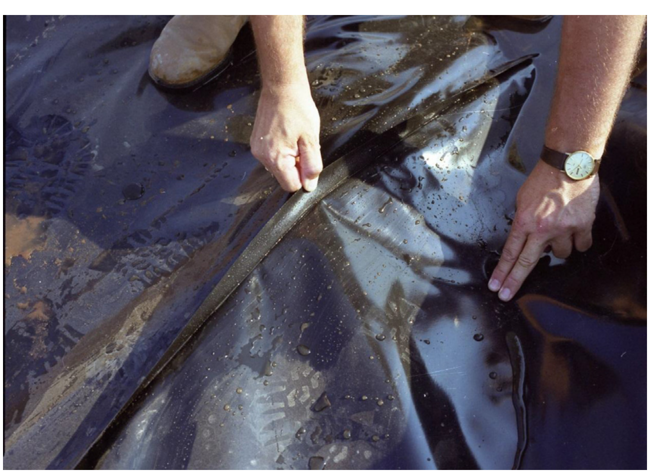

Fig. 4. Contemporaneous image/close up of single track weld.

Peel strength ranged from 0.71 kN/m to 3.80 kN/m, with an average of 2.29 Nk/m. Testing shows the peel strength to be significantly lower than both the geomembrane break stress and weld shear strength, particularly at one sample location. The peel strength would nowadays be specified to exceed the break stress of the geomembrane. However, this was probably not the case previously and the results again probably reflect the contemporary construction procedures.

2.1.2. Results of 2010 soil testing

PSD tests to BS 1377: 1990: Part 2 carried out on the seven soil samples *above* the liner show that the material is predominantly sand (0.06–2 mm – average 79%, range 63–94%), with a variable amount of silt (0.002–0.06 mm – average 18%, range 0–29%) and clay (<0.002 mm – average 3%, range 0–6%). The fraction of material classifying as gravel (2–60 mm) was low: average 1%, range 0–6%.

PSD tests carried out on samples from *below* the liner taken at the same seven locations show the soil predominantly to classify as sand (average 63%, range 30–95%), but that a significant proportion of the material is made up of gravel sized particles (average 23%, range 0–60%). The rest of the material classifies as silts and clays (<0.06 mm – combined average 11%, range 0–18%). Fig. 5 shows the two sets of PSD curves. Below the geomembrane the seven soil samples classify as well graded gravelly sands (3 samples), well graded sandy gravel (1) or sands (3); above the geomembrane all 7 soil samples classify as sands.

PSD results from two locations above the liner showed a relatively much higher proportion of gravel than in other areas (40% and 60%). One geomembrane sample of about 1 m^2 area from one of these locations is reported to have had "too many defects to accurately assess" – see Table 1. It is probable that these defects are a result of the liner moulding to the shape of the gravelly material below. It is likely that some limited tears within the liner at this location were also caused during excavation.

2.1.3. Discussion on 2010 investigations

It was found that weld strengths were poorer and weaker than the parent geomembrane material, whereas the opposite is typically the case with modern seaming. This is thought to relate to the welding methods then used, rather than showing degradation. The adjacent fill materials were generally soft and without hard or sharp objects which might cause damage. However, the most defects were found in a few areas of comparatively hard, abrasive underlying materials (gravels). Protector geotextile was not used, as would be required by modern design procedures, although protector geotextile was used in the reinstatement works (Fig. 6).

Performance of the liner may be compromised when the liner is perforated; dents and ripples are indicative of points of weakness which may become perforations with time. It is considered likely

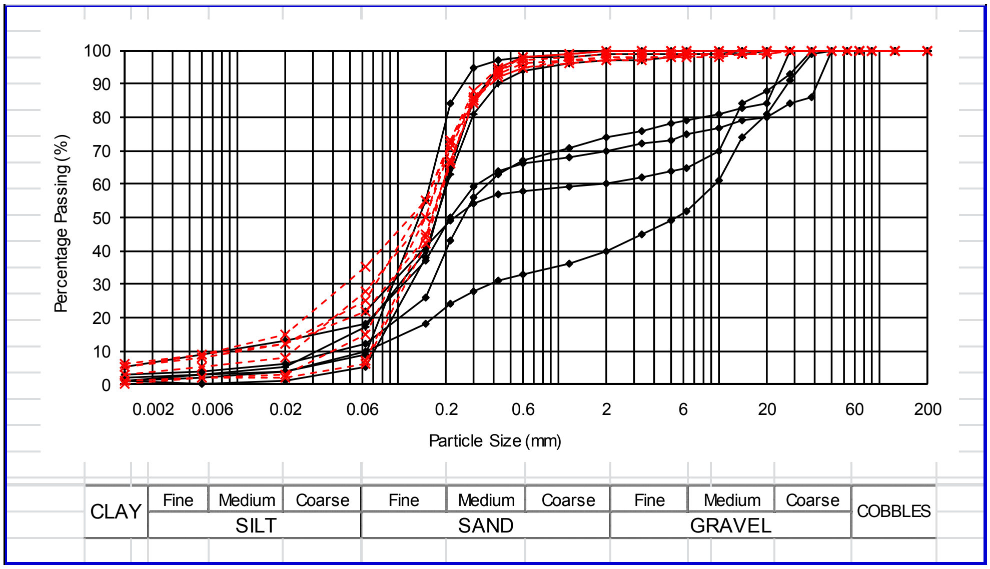

Fig. 5. PSD curves soil samples taken from seven locations near the perimeter drain in 2010. Soils from below the geomembrane indicated with black solid line + diamonds; immediately adjacent soil samples from above the geomembrane indicated with red dashed line + crosses. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

that a significant proportion of the tears within the geomembrane samples may have been caused by plant during excavation and may not be a result of in-situ liner damage or degradation. This damage during excavation was observed in some locations.

It is noted that samples from two locations were extremely dented and rippled with many small holes. It is likely that these holes were a result of the liner being punctured by gravelly material below the liner (see Section 2.1.2). In general these holes were small and appeared in clusters. The rest of the liner contained a large number of dents where the geomembrane had deformed and moulded around the gravel without being perforated.

No significant differences were found between the 1989 geomembrane lining works to Trenches 1 to 6 and the 1995 work to Trench 7. The perimeter locations inspected were thought likely to be, if anything, more vulnerable to damage than the general cap – later to be disproved; see below. These findings from 2010 gave some confidence in the ongoing suitability of the interim cap at that time.

Fig. 6. Geomembrane reinstatement works including use of geotextile protector following 2010 installation of replacement perimeter drain.

2.2. Investigations and remedial works in 2013–14 adjacent to trench cap probes and across the main cap

A total of 96 steel probes had been driven through the cap into the trenches to provide passive gas venting – reportedly installed using a tracked excavator equipped with a hydraulic hammer. These are labelled GV X.y (X to match trench numbers, y sequentially along each trench). The probes have also subsequently been used for monitoring of leachate and gas within the trenches.

The probes comprised a perforated length of steel pipe from the base of the trench to the underside of the cap profiling fill (approx. 7.5 m); each probe was fitted with a driving shoe. A solid section of pipe continues from the underside of the profiling fill up through the cap, with an upstand section above ground level. A cowl was fitted to the upstand to prevent ingress of water and protect the installation from debris. Monitoring has been carried out in the trenches since October 1989.

Although the 2010 investigations had not indicated significant damage to the geomembrane where it had been exposed it was subsequently thought that the remaining discrepancies in water balance may be due to the 96 probe holes/gas vents (GV) which had been installed through the geomembrane. The initial scope therefore was to investigate and remediate seals around the probe holes and included a number of trial pits to confirm depth of geomembrane. As defects in the geomembrane were discovered trial pits were extended into exploratory strip trenches (ST). Preliminary findings revealed different and more extensive damage to the interim cap geomembrane than previously anticipated or indicated from examination of geomembrane adjacent to the perimeter drains. Further investigations were subsequently implemented in the light of these findings and ultimately the additional work was extended to include representative exploratory ST across the whole cap.

In summary, remedial and investigation works in 2013–14 comprised the following sequence:

A1. Investigation works to 96 trench cap probes (of which 86 required remediation)
A2. Trial pits (60) across whole of the trench cap to investigate geomembrane depth and condition
A3. Trial trenches to investigate the Trench 6-to-7 seam followed by additional investigations:
B1. Phase 1: strip trenches ST1 – ST9
B2. Phase 2: strip trenches ST10 – ST12
B3. Phase 3: strip trenches ST13 – ST23

A1–A3 were planned to address what were considered the most likely defects. It had been postulated that potential preferential pathways existed at the monitoring probe-to-geomembrane interfaces caused by down-drag of materials caused by the gas vent pipes and possible associated damage of the geomembrane during probe installation, hence allowing infiltration around the annulus surrounding each monitoring probe. The initial interventions comprised repairs to the geomembrane in the immediate vicinity of these gas vents.

During these initial repairs and investigations, significant unexpected damage was identified to the geomembrane in places, essentially at seams, including gaps/areas of missing geomembrane. Additional investigations were undertaken to identify the nature, location and extent of that damage. The scope of these additional investigations was amended and extended as greater knowledge was obtained, ultimately comprising three further phases of investigations, B1, B2 and B3, described below and indicated in Fig. 7.

2.2.1. Geophysical approaches

The investigations ultimately undertaken were essentially intrusive: extensive trial trenches and other excavations to expose the geomembrane. Consideration was given to using geophysical approaches – electrical leak location (ELL) by electrical resistivity techniques, also ground penetrating radar (GPR). GPR was considered potentially of use in determining the depth to the geomembrane subject to sufficient contrast in soil properties above and below the liner. However, although soils above and below the geomembrane varied in some places in many locations effectively they were the same. GPR was not considered an appropriate technique for geomembrane hole and defect location. GPR was therefore discounted because it would not address the primary requirement (identifying defects), and its ability to determine geomembrane depth was both questionable here and of only secondary interest.

An ELL would have been feasible if the cap geomembrane was able to be isolated electrically from the soil material below the geomembrane and the surrounding ground. If not a full circumference trench would have been necessary. On review, the perimeter drain trench was assessed as not being sufficient to isolate the soils above the cap geomembrane. Additionally, it was considered very possible that signals from the high spatial density of steel vent pipes across the cap, acting as current flow routes, could swamp signals from any tears or defects in the geomembrane. On this basis the likelihood of ELL being able to achieve the survey objectives to a sufficient degree of certainty was assessed as low and geophysical approaches were not employed.

2.2.2. Remedial and investigation works A1, A2 and A3

A 'boot' repair was used to provide a seal between the geomembrane and the gas vent pipe. The boot comprised a polyethylene 250 mm diameter pipe with a skirt of 1 mm thick low density polyethylene (LDPE). All 96 probes were investigated and at 86 of these over T1–6 were found to be as per available information; these were without seals to the geomembrane and all were remediated with boots. All these showed some damage/lack of seals. The other 10 probe locations, all in T7 were found to have been originally fitted with boots (not previously known or expected) and already satisfactory.

More significant damage to the geomembrane was found at 12 locations. Of these, eight were considered to be minor damage and were either covered by the boot skirt or a small patch was installed. The damage at the remaining four locations was more significant and in two cases extended beyond the initial excavation. All were rectified. Four GV locations showed nearby damage to seams, all of which were remediated locally. – refer to Fig. 8 for damage at GV 4.13. The discovery of this damage led to further investigation works to establish the extent and representativeness of data obtained up to that stage, and these investigations are discussed below. Six locations had significant depressions local to the probe-geomembrane interface, in the order of 50–100 mm maximum depth, generally less. They were all remediated by being infilled with bentonite powder before backfilling.

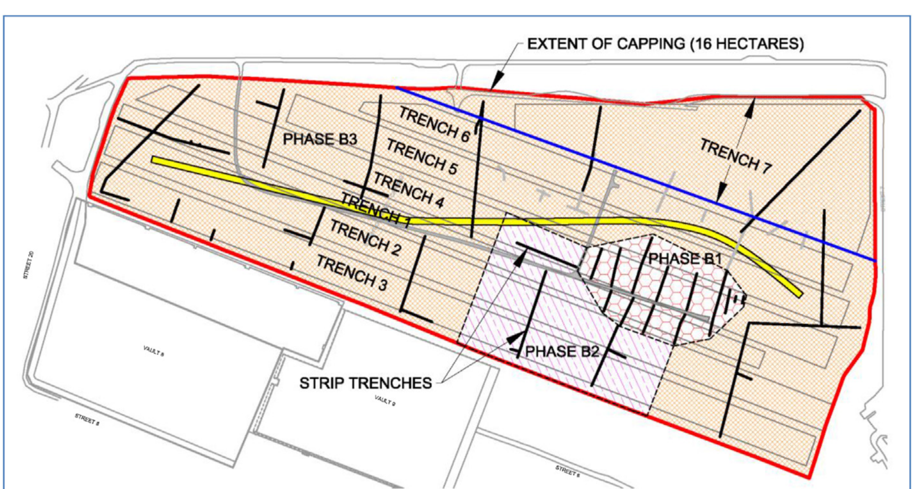

Fig. 7. Site plan: positions of 2013 strip trenches (black) and inferred position of original construction-phase haul road (yellow) at crest of cap. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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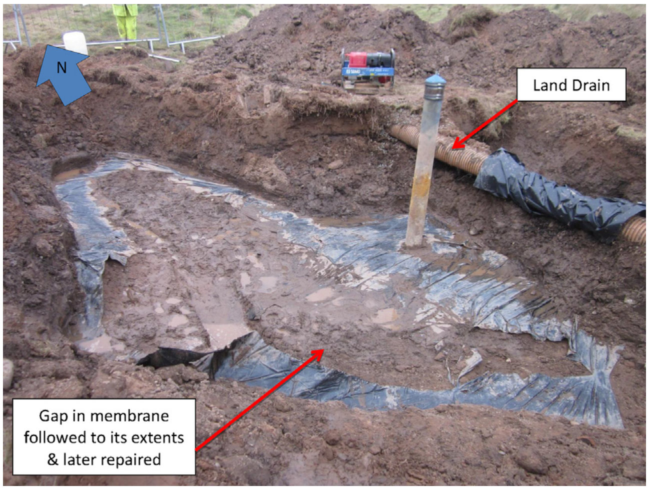

Fig. 8. Damage to liner near gas Vent GV 4.13 – 2013 investigations. Note the observed damage here is not at a seam.

A series of 60 small trial holes was excavated during phase A2 down to geomembrane level, with the objectives of determining the geomembrane depth below ground level and assessing its condition.

A number of narrow linear trench excavations were undertaken during phase A3 to locate and investigate the joint between the T7 and T1–6 capping some 18 years after its installation in 1995. The position of the joint was established and its condition was found to be intact (4 locations), which indicated that the weld between T7 and T1-6 is not a significant cause of infiltration.

2.2.3. Additional investigations B1, B2 and B3

Ultimately three phases of additional investigations were implemented, with the areal extents of investigations increasing each time until the full extent of the trench cap had been investigated to some degree (Fig. 7). It was initially thought that the main damage might be in a limited area around the southern crest and associated with a construction haul road (Fig. 9). As the investigations proceeded it become clear that this was not the case. Strip trenches of about 1 m width were located throughout the cap area, essentially random, but extended to follow seams, particularly where gaps were found (Fig. 10).

In all 23 strip trenches were excavated, of total length 1942 m, i.e. approximately 1.2% of the cap geomembrane and adjacent soils was viewed. Significant previously unknown damage was found, notably major gaps between geomembrane panels at seam locations, up to 2.5 m wide over T1–6. Approximately 7% by length was missing. T7 had missing geomembrane at four locations and the T7 subgrade was observed to be affected by numerous hummocks, discussed below. Limited other damage/defects to the geomembrane was found (approximately 3% by length), apparently almost entirely at or adjacent to seams – see Fig. 11 for an example of a tear in the geomembrane near an intact seam at ST 4B.

Design drawings refer to 'Polyethylene membrane Ref No. V804A Black 995'. Unfortunately contemporaneous material data sheets, manufacturer's quality control (MQC) or construction quality assurance (CQA) data have not been traced to allow baseline comparisons to be made. At three locations (e.g. ST 4) the following marking was observed sprayed in blue onto the geomembrane: "VISQUEEN POLYTARP 8YD32". This was investigated but no further information was available from manufacturer British Polythene Ltd, no longer trading.

Variable depths of cover soils were found, about 19% by area being equal to or less than the specified 1 m. Limited areas (3%) were less than 0.75 m, with 0.45 m the minimum cover. About 24% was greater than 1.25 m and in places over 2 m thick, up to 2.36 m maximum. Variable thicknesses and distributions of cover soils were observed: mostly sandy clays but with substantial amounts (around 20%) of clayey sands, hence providing a moderately low permeability cap but unlikely to have permeabilities $<10^{-9}$ m/s. The distributions are mixed and include random areas and depths of mainly clayey sands.

Corresponding variable levels and profiles of geomembrane and surface were noted. Surface deformations are attributed to settlements of the underlying wastes since capping. Inconsistencies in thickness and geomembrane level indicate some significant construction departures from design profiles, possibly related to construction damage discussed below.

Subgrade soils were only exposed in places, where there were gaps in the geomembrane. They were generally mixed sandy clay and clayey sand fills, similar to the cover soils. No distinct differences were identified. Save the presence of occasional concrete blocks (apparently former survey points), which may have caused some localised damage to the geomembrane, no particular unsuitable materials which related to damaged geomembrane were observed.

The geomembrane referred to in design drawings is reported to have been 0.375 mm thickness. The average measured thickness over the whole cap was 0.382 mm (range 0.290 mm–0.464 mm from 51 data points). There were some areas where the geomembrane was significantly folded, and there may be related areas where it has been significantly stretched, but it was not considered practical to identify any particular representative features or testing here. In general and away from the gaps the geomembrane appeared in good condition with few holes and little minor damage.

Panels were 7.5 m wide and typically 40 m long. For T1–6 the panels generally ran parallel to the trenches i.e. largely oriented transverse the slope (not recommended practice, see below). In contrast the T7 panels appear to have been placed transversely to T7, i.e. running downslope.

The seams examined during the additional investigation works generally appeared satisfactory, even some 20–25 years after installation. They appeared consistent with heat welding. Seams generally appear to have been installed satisfactorily and hence the defects to have occurred subsequently, i.e. probably during placement of cover soils, see below.

Apart from the major gaps, there are no substantial signs of degradation of the geomembrane or other obvious material defects. A few minor defects were found, and a few tears apparently caused during the current excavations.

The initial probe hole investigation showed roughly 87% of the 86 probe locations had minimal or no wrinkling (less than 15 mm height); 12% showed some wrinkling, from 15 mm to 30 mm height; and the remaining 1% showed wrinkling, greater than 30 mm height and/or extensive in concentration (various authors used the terms ripples and wrinkles interchangeably). Additional data collected from the strip trenches appear similar. If these data are extrapolated to the whole cap potentially 13% (or 20,800 m^2 of about 160,000 m^2) of capping may be affected by wrinkles greater than 15 mm in height.

Some larger size 'folds' were observed in just a few (eight) places. These appear consistent with the damage mechanism of construction plant 'dragging' some panels. Some related stretching of the geomembrane might therefore also be expected (elsewhere, as well as at the gaps) but it has not been possible to positively identify such, or related damage in the strip trenches.

Fig. 9. Aerial image circa 1989–90: apparent downslope cap soil placement consistent with construction haul road position along crest spine of cap.

Fig. 10. Strip trench showing split near membrane seam – 2013 investigations.

There was no evidence at ground surface of significant post-construction movements, such as scarp features or veneer slope failures. The movements, wrinkles and gaps seen within excavations at the geomembrane level appear consistent with movement in the cover soils during construction, although there was no remaining evidence of soil movements at the ground surface. It is noted that slope inclinations are very modest. It is considered most likely that failures within the geomembrane such as tears and perforations were induced during the construction phase, due to plant movements and practical difficulties such as working with excessively wet soils (discussed below in Section 3.1). These gaps and wrinkles therefore are thought likely to have been present from that period and it is thought most likely that these occurred soon after placement of the initial layers of cover soils over the geomembrane, while plant was emplacing subsequent cover materials.

3. Assessment and implications

The 2013–14 investigations have revealed, previously unexpected, defects in the interim capping system.

3.1. Primary defects

About 7% by length of the investigation trenches (over T1–6, but not T7) show linear gaps, up to 2.5 m wide and 40 m length found (maximums recorded or followed to their limits). The gaps are immediately adjacent to seams, with tears in the geomembrane rather that the seam itself. They appear consistent with downslope panels having been dragged away from the upslope panels by unsatisfactory construction plant operations (these panels are oriented transverse to the slope, rather than downslope, which is better practice).

The geomembrane installation and seams were reportedly inspected during construction, but no records have been traced. It appears the damage was from subsequent operations. No related surface features have been identified. No correlations have been found with historical records or photographs or other features.

The most probable cause is considered to be damage during original placement of the cover soils, associated with locally poor soils, wet weather and/or poor construction practice. Of note:-

- Slope angles are suitably low, at around 1(V):25(H)

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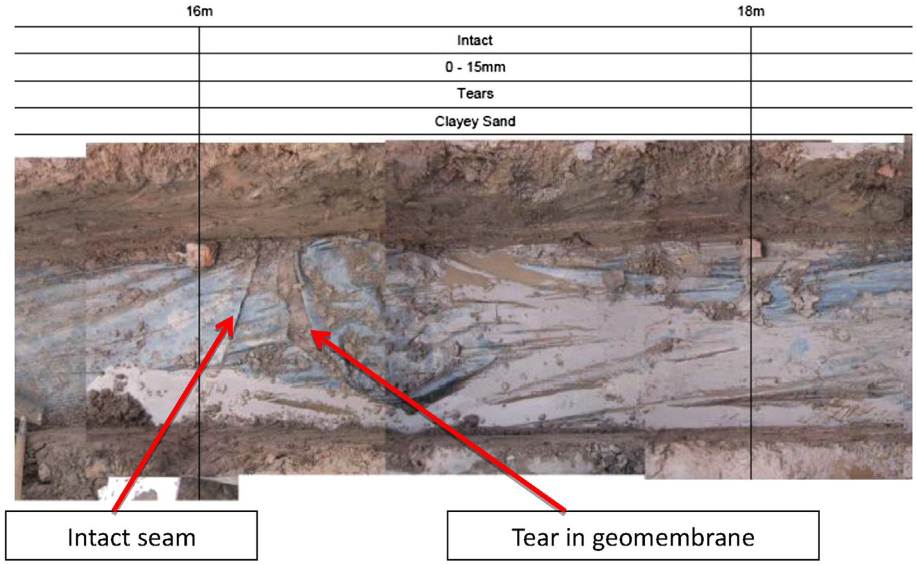

Fig. 11. Strip trench ST 4B showing tear to geomembrane near an intact seam – 2013 investigations.

- Construction photographs clearly show soft ground and plant bogged (Fig. 12), which might be expected to lead to damage in the geomembrane and/or subgrade, consistent with that recently found.
- From review of aerial photographs from around 1989 (Fig. 9) it appears that T1-6 cover soils were generally placed working downslope (not recommended practice; Qian et al., 2001),
- Layer thicknesses and suitability of the fill materials are not known. Problems would arise if too wet (typically >3% wet of optimum, but no earthworks specification are known here).
- Contemporaneous records report the earthworks being problematic over winter and much of the fill reportedly '*unsuitable for earthworks*' (apparently just too wet). There is no indication, however, that the integrity of the cap was compromised by the materials used.

Distribution of the damage appears random and not amenable to prediction of location or extent, relevant data and records not being available or known.

Fig. 12. Contemporaneous image of original cap construction in soft, wet ground conditions showing dump truck bogged to its axles prior to geomembrane placement, indicative of the challenging site and climatic setting.

No damage has been found for the subsequent T7 interim cap seam connection with the previous T1–6 cap. This together with the generally fewer defects in the geomembrane over T7 compared to T1–6 suggests better practice was used, perhaps in the light of learnings from the T1–6 work, possibly assisted by the panels being aligned transverse to the slope (preferable practice, Environment Agency, 2009). No reports, construction records or further details have been traced for this.

Folds were observed in a few (eight) places. These appear consistent with the damage mechanism of construction plant 'dragging' some geomembrane panels. Some related stretching of the geomembrane might therefore also be expected (elsewhere, as well as at the gaps). However, it has not been possible to positively identify such, or related damage in the strip trenches.

3.2. Secondary defects

A further 3% (approximately) of the length investigated (T1–6 and similar for T7) shows limited damage/defects including wrinkles, folds and stretching of the geomembrane, and some limited small holes and tears. This is mainly at the seams and reasonably consistent with the limited general damage and defects commonly associated with geomembranes (albeit these can and should be eliminated by modern good practice and construction quality assurance). Some may be due to poor practice described above, but giving less severe effects.

The impression is of the damage arising at the time of construction, although this cannot be known for certain. There is no particular evidence or reason to suppose any worsening since. There have been limited works and plant movements over the cap since formation. There was no evidence of any operations that appear likely to have caused specific or local damage since.

The geomembrane generally (away from seams) shows no particular damage, notwithstanding being only 0.375 mm thick, far less than the 1 mm normal in more recent practice. Whilst original properties, as installed, cannot be validated, present indications suggest little loss of thickness or key physical properties compared to original specifications. This includes no particular damage from punctures, tears or similar perforations, notwithstanding the fact that the work predates modern understanding and practice to protect geomembranes and prevent such defects.

The defects associated with the 96 probe holes are quite minor by comparison. The 86 probes in T1–6 were installed at or very soon after installation of the capping. There was a general absence of seals (except over T7 where boots had been used), with potential for minor infiltration around each probe, perhaps substantial at 6 locations with significant depressions where groundwater would gather, but still only a very small percentage of the cap area (<0.1%). There were just three associated major defects, again only a very small percentage of the cap area (<0.1%).

3.3. Cap performance implications

The 2013/14 investigations indicate about 10% of the seam lengths could be missing or ineffectual. Taking an average gap of say 1 m and 7.5 m panel width indicates potentially 1–2% by area of missing geomembrane. Since most panels for T1–6 appear to be oriented transverse to the slope, it could be argued that almost all precipitation is likely to encounter a gap, and could therefore infiltrate. The present cover soils provide a moderately clayey capping for much of the area and appear the main reason for such run-off as does occur, i.e. if/where the soils are sandy rainfall might be expected to almost entirely infiltrate past the geomembrane. No evidence was found to suggest the damage was due to excessive total or differential settlements, and environmental monitoring has shown no overall degradation in system performance.

3.4. Implications for remediation options

Although environmental monitoring has shown no indication of large scale failure, the range of defects identified in the existing geomembrane is sufficient to warrant reconsideration of the hydrological management of the trenches to improve confidence in the performance of the interim cap.

In due course a more substantial, final capping will be installed, and optioneering of remedial options for the current (interim) capping includes the range of phasing options, including acceleration of final capping. It appears appropriate to sequentially address selected areas to agreed standards, which should then suffice until final capping.

There do not appear to be specific limited defects that can be easily and locally found and addressed proportionately, in priority order. Rather, the major gaps appear to be randomly located over the T1-6 cap, related to construction issues, covered over, with no known records, and not amenable to prediction.

Any attempt to seam the existing 0.375 mm thick geomembrane to current geomembranes (normally 1 mm minimum thickness) is unlikely to be satisfactory. The irregular existing geomembrane profiles are unsuitable for patching or suchlike. The geomembrane is probably best considered redundant, not key to a future system.

Various options are under consideration including reworking the clay capping without relying on geomembrane. The present cover soils provide a moderately clayey cap for much of the area, but are unlikely to achieve the normally required permeability of $<10^{-9}$ m/s, now or with reworking (Environment Agency, 2010). There are also substantial areas of sands of random distribution. All would need to be reworked and could conceivably achieve a clay cap of 1 m thickness with sandy soils overlying. This would be difficult but appears possible, whether or not a new geomembrane were used beneath.

4. Conclusions

From work in 2010 adjacent to the perimeter drains the geomembrane in the areas of interim cap which were exposed was generally found to be in quite good condition, considering the length of time for which it has been in place. The number of defects was moderate, consistent with a thin geomembrane without particular protection measures. The geomembrane appeared as expected and tests did not suggest substantial changes in properties.

Investigations in 2013 to the gas vent-to-geomembrane interfaces revealed that the majority of these were in good condition, albeit some required localised repairs. What had not been expected were tears and damage to the geomembrane, first identified in the immediate vicinity of the gas vents. Investigations were extended, ultimately to a comprehensive intrusive investigation over the whole 16 ha area of the capping, about 1% of which was exposed. The investigations indicate potentially about 10% of the seam lengths to be missing or ineffectual, which would amount to some 1–2% by area. The panels for T1–6 were found mainly to be oriented transverse to the slope, such that most in-plane flow through the capping soils in that case would be likely to encounter a gap, and could therefore infiltrate, although environmental monitoring has shown no major concerns.

The investigations show the substantial and previously unexpected damage that can result from unsatisfactory construction practice. The original installation work was reportedly under supervision and CQA, although detailed records have not been traced.

The seams appear to have functioned remarkably well, despite the geomembrane itself being only 0.375 mm thick. The effectiveness of the capping as a barrier to infiltration may reflect more the permeability of the cover soils than the integrity of the geomembrane.

It appears most likely that the damage occurred during placement of the cover layers over the geomembrane, possibly related to unsuitable procedures and plant getting bogged on very soft cover soils in wet conditions.

In terms of possible next steps a substantial final capping will be installed at a later date. Hydrological management of the interim capping is under review. Major gaps and defects appear randomly distributed over T1–6; these are difficult to predict in terms of location, hence there is limited possibility of targeted localised repairs. Optioneering of remedial works to the current (interim) cap includes consideration of phasing, also possible acceleration of final capping, also potentially reworking the existing moderately clayey cap without geomembrane. To prevent this in future requires appropriate assessment for veneer stability, suitable specification of cover soils and safe working methods for plant to ensure design objectives are not compromised.

This series of investigations represents a significant case history, one of relatively few. The defects encountered were not reasonably foreseeable. With hindsight the 0.375 mm geomembrane used would have required careful design of installation including orientation of panels (downslope) and potentially crest anchorage. No evidence was found to suggest the damage was due to excessive total or differential settlements. Impacts from plant movement relative to the slope and construction processes have been assessed as the most likely source of damage. The defects point to crucial importance of robust quality assurance during construction to ensure design objectives are met. This case history illustrates the importance of good records management following construction to allow future users access to these data when assessing system performance in service and planning possible interventions.

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[1] ASTM and other standards cited are those applicable at time of testing (2010) unless noted otherwise in the paper.

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