FIELD-SCALE MONITORING AND LABORATORY SIMULATION OF GEOSYNTHETIC LINERS DURING CONSTRUCTION AND AFTER PLACEMENT OF WASTE

by

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Dedication

This Thesis is dedicated to my uncle, Dr. Frank Barone, who is the reason I chose this profession and whose footsteps I humbly follow.
Abstract

Two physical issues of geomembrane wrinkle deformations and downslope shear deformations – that need to be considered to obtain good long-term geomembrane liner performance – are examined.

First, field-scale monitoring of geomembrane wrinkles in a 1.5-mm-thick, black high-density polyethylene geomembrane during placement of cover soil is reported from three field investigations with an emphasis on the effects of cover soil placement techniques, construction equipment and geomembrane temperature on the fate of geomembrane wrinkles. In many cases, wrinkles were found to exist after placement of cover soil and were smaller in size than previously reported dimensions for uncovered geomembrane wrinkles. Post-backfill wrinkle heights between 10 to 50 mm and widths between 70 to 120 mm were measured for wrinkles that did not experience construction equipment loading, while post-backfill wrinkle heights between 10 to 60 mm and widths between 50 to 80 mm were measured for wrinkles that experienced equipment loading.

Second, post-backfill wrinkle geometries attained from field measurements were used in short-term physical experiments to examine the fate of geomembrane wrinkles when subjected to additional overburden pressures. The influence of the field cover soil placement technique, applied pressure, and subgrade material on wrinkle deformations and the fate of the gap beneath the wrinkle were examined. Increasing the applied vertical pressure produced relatively small wrinkle deformations, even at pressures of 3000 kPa due to the high degree of stiffness sustained in the small and narrow wrinkles tested. The gap beneath a 10-mm-high and 55-mm-wide wrinkle was eliminated from downward wrinkle deflection and upward foundation displacement for a hydrated geosynthetic clay liner beneath the wrinkle.
Displacements along a 66-m-long, 3H:1V geosynthetic lined landfill side slope are reported during installation of a gravel drainage layer and subsequent waste placement. During construction of the gravel drainage layer, large downslope displacements were detected in the gravel, geogrid, and geotextile (up to 420 mm), with only minor movements in the geomembrane (less than 35 mm). Placement of waste (to-date 2/3rd up slope) has generated only small (1-2 mm) relative displacements between the gravel and geomembrane and the maximum geomembrane tensile strain was measured to be under 0.2% after 1.6 years of monitoring.
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Chapter 1
Introduction

1.1 Description of problem

Geomembranes are relatively thin (normally less than 2.5 mm thick) polymeric materials that are commonly used in composite with a compacted clay liner (CCL) or a geosynthetic clay liner (GCL) to act as an effective hydraulic and diffusive barrier to contaminant migration (e.g., Rowe et al. 2004). For a composite liner to function optimally, the geomembrane must fully reside on the underlying foundation (CCL or GCL) to achieve intimate contact between the two materials.

During construction, wrinkles can form in the geomembrane from material expansion by solar heating and by placement of overlying materials (Giroud and Morel 1992; Giroud 2005). The primary implication arising from the presence of wrinkles in the geomembrane is that if a gap exists between the geomembrane and underlying foundation after placement of overlying materials like a protective soil cover, and after subsequent additional overburden stress from burial beneath waste in a landfill application, there is an increased potential for leakage if a hole were to develop at or near the wrinkle due to essentially unimpeded lateral flow along the length and width beneath the wrinkle (Rowe et al. 2004). Secondly, the application of overburden pressure can lead to increased tensile stress concentrations from changes in curvatures in the geomembrane wrinkle which could potentially impact the service life of the geomembrane (Gudina and Brachman 2011; Soong and Koerner 1998). Therefore, a need exists to reduce wrinkles in the geomembrane during construction, and if wrinkles persist after being covered by overlying materials, a need to understand the fate of a wrinkle (i.e., the extent to which it may
flatten out onto the subgrade) under simulated landfill pressures becomes critical in understanding the ultimate potential for leakage and possible strains sustained in the geomembrane.

Another topic of interest is the physical performance and interaction of geosynthetic lining elements along a landfill side slope during placement of a gravel drainage layer and subsequent waste placement. Geosynthetic lined slopes require stability assessment where the selection of site specific material interface shear strengths (e.g., peak, residual or a factored strength) are important parameters for the use in stability analysis (Jones and Dixon 2004). Many interfaces involving geosynthetics are strain softening, i.e. the shear strength reduces with displacements beyond peak, whereby relative displacements between geosynthetic layers can be induced during construction and waste settlements. Since mobilised shear strength at these interfaces is dependent upon relative displacements, a need to quantify displacements along the slope exists. In terms of the long-term integrity of the lining system, the extent to which gravel particles in the leachate collection system may translate downslope above the geomembrane and the corresponding overburden pressures are of particular interest as the gravel would then impose both normal and shear loading which can impact local indentation strains in the geomembrane and geosynthetic clay liner protection.

1.2 Current state of practice

In Germany, great effort is made to achieve a wrinkle free installation using the fixed-berm method (Averesch and Schicketanz 1998) whereby a portion of a wrinkled geomembrane is restrained during the warm part of the day, allowing the geomembrane to contract as it cools and placing backfill while the geomembrane is under tension (i.e., in the absence of wrinkles). In North America, it is common to have geosynthetic installation proceed on a large scale with
placement of the overlying protection layer commencing after completion of geomembrane installation. In this case, one approach to minimize wrinkles is to place cover soil only during cool parts of the day (e.g., early in the morning or late afternoon) when minimal wrinkles are present in the liner. However, the preference of earthwork contractors to extend daylight working hours raises questions on the fate of wrinkles when buried, and if wrinkles persist after backfilling, what will their final size and shape be.

Extensive field research has been conducted to quantify the size (height, width, and length) and frequency of exposed high-density polyethylene (HDPE) geomembrane wrinkles in the field prior to placement of any overlying material (e.g., Pelte et al. 1994; Touze-Foltz et al. 2001; Chappel et al. 2011; Rowe et al. 2012). Based on these field observations, many have conducted physical experiments on the sizes of wrinkles observed uncovered in the field (e.g., Soong and Koerner 1998; Gudina and Brachman 2006; Brachman and Gudina 2008) and suggest that wrinkles may exist under high overburden pressures.

However, a paucity of field data exists to assess the extent to which a geomembrane wrinkle can persist when backfilled with cover soil, and if they do exist, what geometry do they acquire in the field prior to additional loading. Some insight was provided in a laboratory experiment conducted by Take et al. (2012) where they found that placement of cool cover soil above a thermally grown HDPE geomembrane wrinkle can reduce the size, but not completely eliminate a buried wrinkle. However, these experiments did not simulate the construction equipment that most likely will be used to place the cover soil. Post-backfill wrinkle geometry is required to assess the extent of leakage and possible strains induced in the geomembrane and can be used as guidance for laboratory studies on the implications of wrinkles. Therefore, a need exists to observe on a realistic scale the behaviour and response of wrinkles during the backfill
process, and the change in geometry they undergo once buried. Furthermore, the physical response of these wrinkles found to exist post-backfill under simulated landfill conditions is of particular concern as the ultimate fate of the wrinkle and fate of the gap beneath wrinkle will govern long-term leakage.

For the case of geosynthetic liners deployed on side slopes, limited information exists on in-situ landfill liner behaviour throughout construction, waste placement and after closure. Zamara et al. (2012) monitored the behaviour of a geomembrane and geotextile lined slope during staged placement of a sand drainage layer however only reported results from a short period during construction. There is a paucity of data for a side slope lining system consisting of a geosynthetic clay liner, geomembrane, geotextile and geogrid configuration in response to placement of a poorly graded gravel with a mean particle size of 50 mm for the leachate drainage layer. For example, such coarse gravel meets the requirements of municipal solid waste landfill regulations in the province of Ontario (Ont. MOE 1998). Analyses of downslope deformations within and between each lining element is required to assess the stability and integrity of the lining system. Quantifying the magnitude of downslope relative displacements between the gravel and geomembrane is of particular importance to understand the loading conditions imposed on the liner as both normal and downslope (i.e. shear) loading conditions have not yet been considered in geomembrane and geosynthetic clay liner protection which may be important for coarse gravels used in Ontario.

1.3 Research objectives

The principal objectives of this research are to:

- Report results from three field investigations on the fate of wrinkles in black, 1.5-mm-thick, HDPE geomembranes after placement of cover soil. Specifically, the effects of
thermal cooling, overburden pressures, construction equipment, and placement
techniques on the fate of geomembrane wrinkles are investigated.

- Present results from short-term physical experiments to examine the fate of
gemembrane wrinkles found to exist in the field after construction of a soil protection
layer when subject to overburden pressure. The influence of field cover soil placement
technique, applied pressure, and subgrade material on wrinkle deformations and the fate
of the gap beneath the wrinkle are examined.

- Report on instrumentation installed on a geosynthetic lined municipal solid waste
landfill side slope to measure temperature, strains and displacements of the
geomembrane, geotextile, geogrid, and gravel during construction of the gravel drainage
layer and 1.6 years after partial waste placement on the slope.

1.4 Scope of thesis

The original contributions described in this thesis are summarized in the following sections

1.4.1 Chapter 2 – Field observations in smooth, black, 1.5 mm thick HDPE geomembranes after
cover soil placement

Three field investigations at two different sites were conducted to observe the fate of
wrinkles in smooth, black, 1.5 mm thick high-density polyethylene geomembranes after
placement of a 0.3-m-thick layer of cover soil. The effects of thermal cooling, overburden
pressure, construction equipment, and placement techniques were examined, and post-backfill
wrinkle geometries were quantified.
1.4.2 Chapter 3 – Physical response of small HDPE geomembrane wrinkles present after cover soil placement

Short-term physical experiments involving a 1.5-mm-thick high-density polyethylene geomembrane were conducted on initial size wrinkles similar to those observed after field placement with sand cover. The influence of field soil cover placement technique, applied pressure, and subgrade material on the fate of the gap beneath the wrinkle and wrinkle deformations was examined.

1.4.3 Chapter 4 – Field monitoring of downslope displacements of a geosynthetic lined landfill side slope

A landfill side slope was successfully instrumented to monitor the in-service physical performance and interaction of geosynthetic lining elements during construction and waste placement. Displacements and strains along gravel / geogrid / geotextile / geomembrane interfaces were measured to evaluate local down-slope shear induced indentations in the geomembrane.

1.5 Format of thesis

This thesis is in accordance with the regulations for a Manuscript Format as set forth by the School of Graduate Studies at Queen’s University in Kingston, Ontario. Chapters 2-4 are original manuscripts incorporated as chapters. Each manuscript is presented with a literature review, method, results and conclusions pertinent to each contribution but without an abstract. References, tables and figures are presented at the end of each chapter. Chapters 2-4 will be revised and submitted for publication. Units of measurement corresponding to the S.I. system (Le Système International d’Unites) are used consistently throughout the thesis.
1.6 References


Chapter 2

Field observations in smooth, black, 1.5 mm thick HDPE geomembranes after cover soil placement

2.1 Introduction

A composite geosynthetic liner consisting of a geomembrane over a low permeable layer – like a geosynthetic clay liner (GCL) – can be very effective at reducing leakage (i.e. fluid flow through holes in the geomembrane under a hydraulic gradient) in many water and waste containment applications (e.g., Bonaparte et al. 2002; Rowe et al. 2004; Koerner 2012; Rowe 2012). In such cases, leakage can be minimized by reducing the potential for holes to develop in the geomembrane and by limiting wrinkles that develop in the geomembrane during installation. Wrinkles are out-of-plane buckles that form in the geomembrane from thermal expansion caused by solar exposure (e.g., Giroud and Morel 1992; Pelte et al. 1994; Koerner 1999; Giroud 2005) that can lead to increased leakage if a hole occurs at a wrinkle because the geomembrane is no longer in contact with the underlying liner over the width and length of the wrinkle (Rowe 1998).

Soong and Koerner (1998) and Gudina and Brachman (2006) have shown that if a wrinkle is buried, it will not “go-away” with application of vertical pressure; so there is a need to minimize wrinkles during installation. A wrinkle free installation can be achieved using the fixed-berm method (e.g., Averesch and Schicketanz 1998) by restraining a portion of a wrinkled geomembrane during the warm part of the day, allowing the geomembrane to contract as it cools overnight, and then placing the cover soil early the next morning while there still are no wrinkles. However, in North America it is common to have geosynthetics installation as a subcontract to a general earthworks contractor. This means that geomembrane installation
proceeds on a large scale (rather than the much smaller portions required for the fixed-berm method) with placement of the overlying protection layer commencing only after completion of geosynthetic installation or after significant amounts have been installed. One approach then to minimize wrinkles is to place cover soil only early in the morning prior to development of significant wrinkling, where what is deemed to be significant may be specific to the application, site, regulatory jurisdiction and engineering judgement. Given the logical desire for earthwork contractors to extend daylight working hours, questions arise on the fate of wrinkles (i.e. will they "go away" and if not, what will their final size be) when buried.

Exposed geomembrane wrinkle size (height, width, and length) and frequency have been quantified prior to placement of any overlying material (Pelte et al. 1994; Touze-Foltz et al. 2001; Chappel et al. 2011; Rowe et al. 2012) for black, high-density polyethylene (HDPE) geomembranes, however the extent to how wrinkles will be different after placement of and burial beneath cover soil has not yet been quantified. There is some laboratory data to suggest sand placement itself can reduce but not eliminate a buried wrinkle (Take et al. 2012). There is a paucity of data to assess the extent to which geomembrane wrinkles may persist after placement of cover soil or whether the geomembrane reverts to a flat, unwrinkled state, and if it does remain, what final geometry will the wrinkle acquire in the field. Final wrinkle geometry is needed as input into design calculations to assess an allowable level of leakage or as guidance for laboratory studies on the fate and implications of wrinkles. There is a need to observe on a realistic scale the effect of soil cover placement techniques (employed by contractors in the field) on wrinkle formation, translation and possible decrease in size throughout construction of a soil protection layer.
The objective of this chapter is to report results from three field investigations conducted at two different sites on the fate of wrinkles in black, 1.5-mm-thick, HDPE geomembranes after placement of cover soil. Specifically at the first site, a technique to quantify wrinkle height and width post-backfill was developed, the size and location of geomembrane wrinkles before and after placement of an overlying sand protection layer was monitored, and the effects of different construction equipment and placement techniques on geomembrane wrinkles during placement of a sand protection layer was investigated. At the second site, the fate of wrinkles that were intentionally buried with cover soil at two different geomembrane surface temperatures was examined.

2.2 Site 1

2.2.1 Description

Wrinkles were monitored before and after construction of a sand protection layer on top of the geomembrane at the base of a municipal solid waste landfill located at a latitude of 44°23′N and longitude of 79°43′W for two separate trials. An initial investigation was conducted June 3 – June 6, 2013 during the construction of the sand protection layer on a 80 m by 35 m base area, referred to herein as Trial A. Trial B involved a more thorough investigation that was conducted April 28 – May 3, 2014 during the construction of the sand protection layer on a 80 m by 125 m base area. The grain size distribution of the sand protection layer consists of: D_{100} = 25 mm, D_{85} = 0.59 mm, D_{60} = 0.35 mm, D_{50} = 0.29 mm, D_{30} = 0.21 mm, D_{10} = 0.15 mm, and 4% passing the #200 sieve. The composite geosynthetic liner for both trials consisted of a smooth, black, 1.5-mm-thick, high-density polyethylene geomembrane overlying a GCL (with a nonwoven, needle-punched cover geotextile in contact with the geomembrane) on top of a native sand foundation
layer. To construct the sand protection layer above the geomembrane, a low ground pressure (LGP) dozer (CAT D6R, track pressure = 34 kPa) fitted with GPS on a standard spreading blade was primarily used. An excavator (CAT 324dl, track pressure = 40 kPa) was also used to place sand on the liner. Rubber tire dump trucks (Komatsu HM300) were used to haul onsite sand onto the liner. The LGP dozer was the only machine permitted to travel on a minimum cover soil thickness of 0.3 m. Equipment exceeding 35 kPa ground pressure was to travel on a minimum of 0.9 m cover soil thickness as per site specifications. At this particular site, the earthworks contractor was responsible for selecting the general approach and specific modes of soil cover placement; hence the observations reported here were not made under controlled experimental design conditions and are impacted by the specific choices made by the contractor.

2.2.2 Method

Visual observations were gathered throughout the construction process of the sand protection layer on the influence and effectiveness of using a dozer to spread sand versus an excavator to place sand on an exposed geomembrane liner. Geomembrane wrinkles were monitored by taking manual measurements of height, width, length, location and orientation prior to backfill. Measurements of air temperature, geomembrane surface temperature, and sand backfill temperature were recorded during backfill of each monitored wrinkle. After the wrinkles were backfilled and graded to a final sand thickness of 0.3 m, observation trenches were manually excavated where the initial wrinkles were located to find if any remaining wrinkles existed beneath the backfill.

In Trial B, a series of four regions where wrinkles were believed to have remained post backfill were noted as well as the observed orientation of the wrinkles upon backfill. Linear
investigation trenches (0.3-m-wide) were excavated perpendicular to the direction of wrinkle orientation in order to intersect all, if not most, of the wrinkles in the observed regions.

2.2.3 Results and discussion

2.2.3.1 Construction methods

The use of a dozer to spread and grade sand across the base liner was found to be problematic when there was slack present in the liner as the pushing of sand across the liner resulted in plowing and amalgamation of wrinkles. From the onset of sand placement during Trial A, noticeable displacement of geomembrane slack caused by a plowing effect of the dozer resulted in geomembrane wrinkles refracting at outward angles to the direction of the sand road shown in Fig. 2.1. As plowing of sand proceeded, wrinkles propagated ahead of the sand pile, amalgamating with oncoming geomembrane slack and wrinkles in the uncovered liner. This accumulation of slack resulted in the formation of large wrinkle features (Fig. 2.2) which could eventually get entombed by the backfill.

Since large wrinkles were not permitted to be buried, the contractor made an effort to bury wrinkles when they were smaller in size to avoid the formation of large wrinkles, with the presumption that smaller wrinkles may "go away" once buried. One method employed by the contractor was to have personnel provide resistance with their feet as sand was advanced by the dozer. In this approach, two to three installation personnel stood ahead of the dozer and sand pile on the opposite side of a wrinkle to provide interface shear resistance between the geomembrane and underlying GCL. This technique was intended to help prevent shifting of the buried slack from out underneath the backfill when the sand was advanced forward by the dozer. It is worth mentioning the obvious safety issues assumed by the contractor with laborers directly in front of
the dozer as it advances forward. The contractor would commonly place small quantities of soil by hand shoveling onto the side of the wrinkle opposite to the dozer and advancing sand pile, in addition to their own self-weight, to increase the likelihood of trapping a small wrinkle beneath the backfill. Although this may seem like an easy and effective method, observations made by carefully spotting shifting in the geomembrane during this process with time-lapse photography showed that the weight of the advancing sand pile and dozer pressure acting above the buried wrinkle was usually sufficient enough to overcome the frictional resistance provided by the personnel and small amounts of soil on the opposing side of the wrinkle. Thus, wrinkles were often translated out from beneath the backfill to form another wrinkle in the uncovered liner. Two consecutive photographs, shown in Fig. 2.3, were taken during sand placement with a dozer during Trial B to demonstrate the effects of sand spreading on wrinkle burial. As the sand cover advanced forward, the wrinkle in between the sand pile and laborer (Fig. 2.3a) continued to shift forward as opposed to getting buried as the dozer advances the sand pile (Fig. 2.3b). Clear evidence of this plowing phenomenon are the wrinkle features that form at an inclination to the advancing sand pile.

A second, and at times, a more effective method to reduce wrinkle plowing involved placement of piles of sand on both sides of a wrinkle using an excavator. The ability to pick up and place sand on both side of a wrinkle before advancing the sand pile above was done to prevent lateral shifting of the wrinkle into the uncovered portion of the liner. An illustration of this technique is shown in Fig. 2.4 where the installer chose to execute this technique as too much slack was accumulated due to plowing with the dozer. Fig. 2.5 illustrates another example of the contractor using an excavator in Trial B to limit the amount of plowed geomembrane slack
by burying wrinkles in place on a heavily wrinkled liner. Despite many visible wrinkles in the uncovered liner, no obvious plowed wrinkle features were noticed adjacent to the sand backfill.

This excavator placement technique was observed to be an effective method of burying small wrinkles individually without amalgamation in some instances. However the technique was ineffective when not enough sand was placed on either side of the wrinkle, causing the buried wrinkle to translate out from underneath the sand cover into the uncovered liner due to the weight of the advancing sand cover and/or equipment loading.

2.2.3.2 Investigation trenches

Four closely monitored areas in the base liner where wrinkles were believed to have remained once sand placement was complete were chosen to excavate a series of 0.3-m-wide trenches to search for possible remaining wrinkles. The trenching details are given in Table 2.1. For Trenches 1 and 2 where an excavator was used to place sand, no remaining wrinkles were found in the observation trenches whereas, for the other two sections where a dozer was used to spread sand, one wrinkle was found to remain in Trench 3, while 5 wrinkles remained in Trench 4.

2.2.3.2.1 Trench 1

Of interest in Trench 1 were the fates of a roll direction and cross-roll direction wrinkle backfilled by an excavator. These wrinkles were solely thermally grown as they were flat in the 10°C geomembrane early in the morning. Their initial locations prior to backfill are shown in Fig. 2.6a, denoted as Wrinkles W1A and W1B. These wrinkles were backfilled on April 28th between 11:00 – 14:00 when the geomembrane surface temperature was 52°C and quickly cooled to 10°C upon covering with sand. Two 12-m-long perpendicular trenches (collectively referred to
as Trench 1A) were hand excavated in the roll and cross roll directions and Trench 1B having lengths of 1.4 m in the roll direction and 0.7 m in the cross-roll direction was excavated on May 3rd at 12:30 to intersect any wrinkles that may have been buried in either orientation. The construction sequence of sand placement in the region where Trenches 1A and 1B were excavated is shown in Fig 2.6. Wrinkles 1A and 1B were two monitored wrinkles (Table 2.2) that were effectively trapped by buckets of sand placed by an excavator before advancing the sand cover on top of them, also done with an excavator. Soil cover Zones 4 and 5 in Fig. 2.6b, used to trap Wrinkles 1A and 1B, each had dimensions of about 2-m-wide by 6-m-long by 0.3-m-deep. Zone 6 was placed in between Zones 3 and 5, 2 and 5, and 4 and 5 as illustrated in Fig. 2.6b. The buried locations of Wrinkles 1A and 1B were marked and recorded such that the investigation trenches would intersect them. There was no evidence of wrinkles translating out from beneath the backfill during and after soil placement (i.e. Zone 7 in Fig. 2.6c). No remaining wrinkles were observed in Trench 1A. To verify that no wrinkles remained in the observation trenches, contact between the geomembrane and subgrade was confirmed by hand pressing on the top surface of the geomembrane and immediately feeling resistance from the underlying GCL. Fig. 2.7a is a photograph looking along the cross-roll direction trench showing no evidence of a remaining wrinkle at the initial burial location of Wrinkle 1B or 6 m on either side. Trench 1B was excavated directly above the burial location of Wrinkle 1A as the 12-m-long roll direction trench likely bypassed Wrinkle 1A (Fig. 2.6b). No remaining evidence of Wrinkle 1A was found in Trench 1B (Fig. 2.7b).

The primary mechanism responsible for the flattening of thermally grown Wrinkles 1A and 1B in this particular case is attributed to thermal cooling of the geomembrane from 52 to 10°C upon placement of the cool cover soil. Slack within the buried liner can be reduced through
thermal contraction developed upon cooling if the material is allowed to compress on cooling. One might hypothesize that the material making up the wrinkle might be more likely to contract than the flat portion when buried beneath cover soil, as there may be less restraint to recovery of thermal strains within the cord length making up the wrinkle feature because of the gap beneath the wrinkle. Whereas the flat portion of the geomembrane adjacent to a buried wrinkle will only be able to recover thermal strains if the thermal contractive stresses in the geomembrane are larger than the frictional forces developed at the geomembranes interfaces. A mechanism that could have contributed to the fate of Wrinkles 1A and 1B in addition to thermal cooling from 52 to 10°C (Table 2.1) was the equipment loading on the sand cover, directly above the wrinkles, possibly inducing compressive forces in the wrinkles to help the geomembrane overcome the frictional forces at its interfaces, and recover more thermal strains.

2.2.3.2.2 Trench 2

Trench 2 consisted of a group of cold (10°C) wrinkles inclined to the roll direction, formed by accumulation of slack through wrinkle plowing with a dozer, then backfilled by an excavator, followed by final grading with a dozer within 20 minutes after sand placement. A construction sequence of sand placement in the region where Trench 2 was excavated is illustrated in Fig. 2.8. As shown in Fig. 2.8a, the west boundary of the base liner consisted of a “tie-in” geomembrane seam to the adjacent cell to the west (constructed the previous year). To allow room for the connection, about 1.5 m of liner from the adjacent cell was left exposed and had accumulated a thin layer (less than 25 mm) of soil from landfill operations to the west.

The wrinkle buried by the excavator in Zone 4 was trapped by 2-m-wide and 0.3-m-thick of cover soil in Zone 3 (e.g., see Figs. 2.8a and 2.8b), and the wrinkle buried in Zone 7 had about
2.5-m-wide and 0.3-m-thick of cover soil to the north in Zone 8 and 3-m-wide and 0.3-m-thick of soil to the west in Zones 5 and 6 prior to loading by the dozer (e.g., see Figs. 2.8b and 2.8c). Close observations made during placement of sand with the excavator suggest that the wrinkles were covered without lateral shifting during burial in the Trench 2 region. However, on subsequent thinning of the sand layer with a dozer, a major quantity of slack appeared outside the backfilled zone in the uncovered liner to the north, and a small amount of slack to the south (Fig. 2.8c) which was not present following sand placement by the excavator. Two 7-m-long cross-roll direction trenches were dug at a 2.5 m spacing to intersect the roll direction wrinkles that were buried. A 4-m-long roll direction trench crossing the other two trenches at the centre was excavated to intersect any wrinkle that might have changed orientation unexpectedly post-backfill. No remaining wrinkles were found to exist in the trenches dug.

The dominant mechanism resulting in flattening of the buried wrinkles in this region is believed to be from lateral translation (i.e., slipping out) of wrinkles into the uncovered liner under mechanical loading of the dozer, despite cover soil already placed across the Trench 2 region. The dynamic, non-uniform loading of the dozer caused by vibrations during movement and spinning of the dozer tracks when turning (i.e., from cross-roll direction heading west to the roll direction facing north) may have had a substantial influence on wrinkle translation once backfilled. It is possible that in addition to the excessive slack appearing outside of the backfill to the north, some of the slack from the buried wrinkles in the Trench 2 region may have shifted further west then where Trench 2 started, into the adjacent geomembrane zone lightly covered with soil and waste. In either case, the amount of cover soil placed on either side of a buried wrinkle appears to have a major influence on whether a wrinkle will get shifted out from under the backfill once equipment loading is introduced. This occurrence may be beneficial at
eliminating wrinkles at the observed location, however causes an issue elsewhere in the liner as the wrinkle slack is simply redistributed into the uncovered region once again.

2.2.3.2.3 Trench 3

Trench 3 involved a warm (28°C), roll direction wrinkle, formed mainly by accumulation of pushed slack and some thermal growth that was backfilled by a dozer. An 11-m-long cross-roll direction trench was excavated to intersect the buried roll direction wrinkle and a perpendicular 12-m-long trench was excavated to search for any cross-roll wrinkles that were possibly buried and remained post-backfill (both collectively referred to as Trench 3). A construction sequence of sand placement in the region where Trench 3 was excavated is shown in Fig. 2.9. Although a small amount of sand was manually hand placed around Wrinkle 8 to help prevent it from translating during backfill, Wrinkle 8 was expected to have remained post-backfill based on the inferred placement pattern of the sand spread by the dozer. In Fig. 2.9c, the placement of sand in Zone 1 (approx. 8-m-wide in the cross-roll direction and 0.3-m-thick) and in Zone 6 (approx. 6-m-wide in the cross-roll direction and 0.3-m-thick) caused the enclosure of Wrinkle 8 in Zone 7 which could not be translated out due to the stresses of sand on the geomembrane acting on both sides of the wrinkle. As anticipated, with only a small degree of thermal cooling and the small likelihood of wrinkle shifting out into the uncovered liner, Wrinkle 8 was found to remain in the cross-roll direction trench, as shown in Fig. 2.10, at a reduced height and width of 12 mm and 50 mm, respectively. The initial size and temperature of Wrinkle 8 is shown in Table 2.2. Wrinkle 8, having an initial length of 2.5 m, connected with other roll direction wrinkles during sand placement in Zone 7 which resulted in a final interconnected wrinkle length of 7 m. No wrinkles were found to remain in the roll direction trench as all of the
wrinkles oriented in the cross-roll direction were plowed in front of the sand pile as the spreading of sand was advanced.

2.2.3.2.4 Trench 4

Trench 4 consisted of numerous cold (10°C), cross-roll direction wrinkles formed by the plowed accumulation of geomembrane slack because of backfilling with a dozer. A single 13 m linear trench was dug in the roll direction to intersect these wrinkles. Fig. 2.11 shows the construction sequence in this region. The peculiar sand placement sequence adopted by the contractor is shown in Fig. 2.11 and first involved placing two long parallel sand piles (Zones 3 and 4) with a gap in between resulted in a buttressing effect, preventing wrinkles from translating to the north or south, and the restraint on the liner by the sand piles prevented the wrinkles from physically shifting out to the east. Cover soil spread in Zone 4 was about 0.3-m thick and 4-m-wide (approx. one dozer blade width) in the roll direction. This technique was used with the contractor’s intent to bury some slack in the form of small sized wrinkles as sand placement progressed, instead of gathering a lot of slack at the boundaries of the base liner and creating a large wrinkle. Since there was no thermal cooling, wrinkles were found to remain in Trench 4 where anticipated as shown in Fig. 2.11c. A summary of the wrinkles found in Trench 4 are detailed in Table 2.1. A wrinkle of particular interest was Wrinkle C found in Trench 4 having a 60 mm height, 50 mm width and 9 m length. Wrinkle C, shown in Fig. 2.12, had formed a “prayer wave” with steep side walls under the sand cover with a sharp curvature at the apex of the wrinkle. The wrinkle was deemed unacceptable by the onsite quality control inspector resulting in removal of this particular wrinkle.
Of the 4 closely monitored regions in the liner where wrinkles were observed to have been entombed by the soil cover, some of the entombed wrinkles remained post backfill while others were forced out from underneath the cover soil. The amount of soil required to prevent post-backfill shifting of wrinkles will depend primarily on factors such as geomembrane stiffness, type of backfill, frictional resistance at the geomembrane interfaces, and the magnitude and orientation of loading. From observations made in the investigation trenches, it was found that wrinkles that were trapped with a minimum 4-m-wide section of 0.3-m-thick soil was consistently able to provide enough normal stress to mobilize sufficient interface friction to prevent the geomembrane from slipping at its interfaces. Inconsistencies arose in the fate of post-backfilled wrinkles when smaller quantities of soil were used to trap wrinkles as some of the entombed wrinkles remained while others were flattened, both of which could be governed by the extent, nature (i.e. vertical, torsional) and spatial variation of equipment loading. The amount of slack within a wrinkle caused by thermal heating and the extent of thermal cooling upon backfill was also found to have an impact on the fate of wrinkles when covered.

2.2.3.3 Wrinkle monitoring

A technique was developed in Trial A to quantify the height and width of a wrinkle after cover soil placement. At first, large observation pits were excavated to expose each wrinkle (initially deemed necessary to locate the wrinkle), causing the wrinkles to rebound off the subgrade, resulting in an increase in wrinkle height and width. This rebound response of the geomembrane was due to stress relief of the 0.3-m-thick overburden sand and, in many cases, rapid thermal heating once exposed. However, minimal effects were noticed to the final geomembrane shape at the end of the observation pits along the trench walls. Therefore, small
narrow trenches (approx. 0.3-m-wide and 0.3-m-long) were subsequently excavated to minimize rebound and thermal changes to the geomembrane during wrinkle inspections in Trial B.

In total, nine wrinkles were monitored during construction of the sand protection layer. Initial and post-backfill measurements of wrinkle size, temperature and orientation are reported in Table 2.2. There was no evidence of a wrinkle remaining for six of the monitored wrinkles and three wrinkles remained under the backfill at a reduced height and width.

For all wrinkles remaining post-backfill (monitored wrinkles and wrinkles found in Trenches 3 and 4 collectively), final wrinkle heights ranged between 11-60 mm and final wrinkle widths ranged between 50-80 mm. These wrinkle dimensions observed after cover soil placement are much smaller than previously reported values of wrinkle height and width made prior to soil placement by Pelte et al. (1994) and Rowe et al. (2012). Consequently previously reported values based on uncovered wrinkles overestimate the wrinkle size when buried even under 0.3 m of soil, which could impact values selected by some for theoretical leakage calculations or physical modelling of the fate of wrinkles.

Of the possible mechanisms contributing to the fate of a wrinkle, the primary mechanisms that govern wrinkle slack elimination are thermal cooling, construction equipment loading, and horizontal translation during cover soil placement. The scatter observed in the wrinkle data, shown in Table 2.2, resembles no direct relationship between initial to final wrinkle heights. This can be attributed to each wrinkle experiencing different degrees of thermal changes as well as unique backfill and loading conditions throughout the construction process. Therefore, any guidance or specifications on burial conditions for “allowable” wrinkling will be sensitive to how the contractor executes the placement of cover soil.
Wrinkles 1 to 5 in Table 2.2 were backfilled by an excavator using large portions of soil to trap the wrinkles in place to prevent shifting. They also experienced a thermal cooling gradient of 42°C from being buried at 52°C and cooling to 10°C by the cover soil. It is quite possible that the contractive stresses developed in the buried geomembrane were enough to recover thermal strains in Wrinkles 1A, 1B, 2, 4 and 5, but not in 3. Wrinkle 3 had a small tributary area (approximately 1 m on either side of the wrinkle) of buried geomembrane undergoing thermal changes and developing contractive stresses to contribute to slack reduction in Wrinkle 3. Therefore, the fate of Wrinkles 1A, 1B, 2, 4 and 5 are principally attributed to thermal cooling while Wrinkle 3 remained at a reduced size due to its very large initial size and the small tributary area contributing to thermal contraction of the buried slack. As previously mentioned in regards to Wrinkles 1A and 1B, equipment loading above the buried wrinkles may have assisted in the recovery of thermal strains by inducing compressive stresses in the wrinkle which would help overcome frictional forces generated at the geomembrane interfaces.

Wrinkles 6 and 7 were similar in that they were first trapped with sand manually with a hand shovel, followed by sand cover with an excavator and grading with a dozer, and experienced no thermal changes post-backfill. There was no clear justification as to why Wrinkle 7 remained and Wrinkle 6 was eliminated, however since thermal cooling was not a contributing factor, translation of the wrinkle from underneath the backfill is believed to be the primary mechanism responsible for wrinkle slack elimination. Therefore, it is believed that based on the specifics of how the sand was placed and spread, and how the dynamic, non-uniform pressures of the construction equipment loaded each wrinkle, Wrinkle 7 was trapped well enough as to resist horizontal translation; while the forces imposed on Wrinkle 6 were enough to cause wrinkle translation and eliminate the slack at the observed location.
As previously detailed on the backfilling conditions, Wrinkle 8 buried in the Trench 3 region was sufficiently trapped by large sand piles placed with a dozer (e.g., see Figs. 2.9b and 2.9c) which eliminated the possibility of wrinkle shifting out from underneath the cover soil. Since backfilled while cold, slack reduction by thermal contraction was neither possible. Therefore, Wrinkle 8 was found to remain post backfill as was expected.

2.3 Site 2

2.3.1 Description

A field experiment was conducted at a second site to quantify the effects of thermal cooling of wrinkles that were intentionally buried after being heated to two different surface temperatures. This experiment was conducted at the Queen’s University Environmental Liner Test Site, which is located 40 km north-northwest of Kingston, Ontario, at a latitude of 44°34’14”N and longitude 76°39’44”W (Brachman et al. 2007). The relevant portion of the test site involved a composite geosynthetic base liner consisting of a smooth, black, 1.5-mm-thick HDPE geomembrane, overlying a multicomponent GCL with a polymer coating applied to the upper geotextile in contact with the geomembrane, on top of a native silty sand foundation layer. Perimeter berms measuring 0.45-m-high and 1.3-m-wide were constructed to create two isolated control sections measuring 6.8 m in the roll direction and 4.4 m in the cross-roll direction as shown in Fig. 2.13. The purpose of the perimeter berms was not to simulate the fixed-berm method of Averesch and Schicketanz (1998), but rather to prevent translation of wrinkles out of the sections and to have a controlled area for geomembrane thermal expansion for wrinkle growth. The location of the sections were selected such that no geomembrane seams, one roll direction wrinkle and 2-3 cross-roll direction wrinkles were present per section. A plan view of
initial geomembrane wrinkles in Sections A and B after berm construction is presented in Fig. 2.13.

2.3.2 Method

Both sections were exposed to solar heating, allowing the wrinkles initially present in the geomembrane to increase in size. A 0.3-m-thick silty sand protection layer was then placed with an excavator bucket on Section A in the morning, and in the afternoon on Section B. Both sections were backfilled using a careful and controlled procedure to minimize wrinkle translation during soil placement. The excavator’s bucket reach was long enough to cover both sections without travelling on the liner. Geomembrane wrinkles were monitored in each section for size, location, orientation and temperature after berm construction, immediately before backfill, and post-backfill the following morning – recorded in Tables 2.3 and 2.4 for sections A and B, respectively. The geomembrane surface temperature for each section was recorded using a thermocouple placed on the top surface of a geomembrane wrinkle. Fig. 2.14 shows the exposure conditions throughout the course of the experiment on September 26, 2014. An onsite weather station recorded air temperature at 10 minute intervals and solar radiation at 30 minute intervals. Air temperature started at 10°C and reached a maximum of 25°C late mid-afternoon, Fig. 2.4b. Geomembrane surface temperature, recorded at an uncovered reference section, followed the trend of solar radiation, reaching a maximum of 54°C just before noon, Fig. 2.14c. The rapid decrease in uncovered geomembrane temperature midday corresponds to a short duration of a partly-cloudy period as indicated by the rapid decrease in solar radiation plotted in Fig. 2.14a.
2.3.3 Results and discussion

Section A was covered when the geomembrane reached a surface temperature of 30-34°C between 9:22 and 9:56 (Fig. 2.14c). All wrinkles that were present immediately before backfill (Fig. 2.15a) were also present in the geomembrane after construction of the perimeter berm at 7:55 (Fig. 2.13). After berm construction the wrinkles ranged between 13-50 mm high and 240-370 mm wide at 13°C. Prior to cover soil placement, the wrinkles experienced an increase in size to 28-58 mm high and 250-410 mm wide (Table 2.3) as a result of thermal heating to 30-34°C. The roll direction feature at the remnant crease from the blown-film manufacturing process (e.g., see Koerner 2012; Chappel et al. 2011) was not a wrinkle feature at this geomembrane surface temperature. The surface temperature of Wrinkle 3 in Section A was recorded to observe the extent of thermal cooling upon backfilling with cool 15°C soil (Fig. 2.14c). Wrinkle 3 was covered at 34°C and experienced a rapid decrease in temperature to 19°C after one minute, before stabilizing at 17°C after ten minutes. The initial soil temperature, measured 0.1 m below the surface of the cover layer, was 15°C which slowly increased throughout the day. This increase in cover soil temperature caused a gradual increase in geomembrane temperature beneath the backfill of 3°C over the course of the day to a final temperature of around 20°C.

Fig. 2.15b illustrates the extent and location of remaining wrinkles in Section A post-backfill. All monitored wrinkles remained after placement of the soil at a reduced height and width. Two additional wrinkles were found to exist post backfill in the north-east corner and one wrinkle in the south-west corner of Section A and were spray painted white. Each of these wrinkles measured approximately 15-mm-high and 90-mm-wide, and remained as a result of geomembrane slack backfilled at the corners of the section but were not well defined wrinkle shapes (see Fig. 2.15a) making them difficult to measure and thus were not monitored.
Comparing the photographs in Figs. 2.15a and 2.15b, it can be seen that the initial location and orientation of each monitored wrinkle remained essentially unchanged with no significant change in length or new connections formed between wrinkles following placement of the soil cover. Following cover soil placement, wrinkles reduced to 10-35 mm high and 75-110 mm wide (Table 2.3). Overall, Section A wrinkles, which experienced an average 12°C drop in temperature (30-34 to 20°C) post-backfill, experienced an average reduction in wrinkle height and width of 45 and 70% respectively.

The initial wrinkles just after berm construction at Section B (Fig. 2.13) ranged between 16-60 mm high and 210-390 mm wide (Table 2.4). These wrinkles then increased to 38-90 mm high and 290-460 mm wide just prior to being covered when the geomembrane surface temperature reached 50-53°C between 13:30 and 14:15 (Fig. 2.14c). Fig. 2.16a shows that the wrinkles present in the geomembrane just before cover soil placement were also present in the geomembrane after construction of the perimeter berm (Fig. 2.13). The surface temperature of Wrinkle 1 in Section B was recorded to observe the magnitude of thermal cooling upon covering with cool 17°C soil (Fig. 2.14c). Wrinkle 1 was covered at a 50°C and experienced a rapid decrease in temperature to 29°C after one minute, before stabilizing at 20°C, 30 minutes later. The cover soil temperature measured at a depth of 0.1 m below the surface of the cover layer increased to 24°C an hour after placement, however, caused no change in geomembrane temperature as the cover soil at the geomembrane interface was not affected by the declining solar radiation as the sun lowered in the sky.

All monitored wrinkles remained after placement of soil at a reduced height and width and were spray painted orange (Fig. 2.16b). Similar to Section A, the initial and final location and orientation of each wrinkle monitored at Section B remained similar. No significant change in
length and no new connections between wrinkles were observed post-backfill. At both sections, careful and strategic sand placement technique with an excavator was found to greatly reduce wrinkle plowing and shifting during construction of the soil cover layer. After cover soil placement, all but one of the wrinkles at Section B decreased in size to about 10-35 mm high and 70-120 mm wide. The exception was Wrinkle 1 which had the largest wrinkle size after perimeter berm construction, and only reduced in height to 52 mm. Overall, wrinkles in Section B which experienced a decrease in temperature of about 32°C (50-53 to 20°C) post-backfill, experienced an average reduction in wrinkle height and width of 62 and 75% respectively.

The response of wrinkle height to the effects of cover soil placement in Sections A and B is plotted in Fig. 2.17 as a graph of initial versus final wrinkle height. A linear trend can be fit through both Sections A and B data sets, and the higher the initial wrinkle height, the higher the final wrinkle height post-backfill. While wrinkles in Sections A and B were intentionally buried at two different geomembrane surface temperatures, they were cooled to nearly the same temperature of 20°C (see Fig. 2.14c) with a 0.3-m-thick layer of soil; installed using the same placement method without additional loading from construction equipment. Consequently, despite Section B wrinkles having larger initial heights before backfill, both sections reached essentially the same final wrinkle heights between 10-35 mm, with the exception of Wrinkle 1 in Section B having a final height of 52 mm. The change in wrinkle width in response to cover soil placement in Sections A and B is plotted in Fig. 2.18. Although the initial wrinkle widths before backfill varied greatly between 250-400 mm for Section A and 300-450 mm for Section B, the final wrinkle widths ranged only between 70-120 mm for both sections following cover soil placement. A discernable but insignificant difference was realized between the post-backfill wrinkle widths in Sections A and B. The change in wrinkle shape on burial is expressed in terms
of the height-to-width ratio before and after backfill in Fig. 2.19. Wrinkles in Section B exposed to a higher intensity of solar radiation resulted in exposed wrinkles with a slightly higher height-to-width aspect ratio, meaning wrinkle height increased more relative to the corresponding increase in width during thermal heating. As one would expect, with the similar range of final wrinkle heights and widths acquired by Sections A and B wrinkles, the final wrinkle aspect ratio also falls within the same range between 0.13-0.32, with the exception of Wrinkle 1 having a final aspect ratio of 0.53. The results in Figs. 2.17 and 2.18 show that Section B wrinkles buried at a higher geomembrane surface temperature experienced a slightly greater percentage of dimensional change (17% more decrease in height, 5% more decrease in width on average) than Section A wrinkles. This additional size reduction can be attributed to the effects of thermal cooling upon covering leading to more geomembrane material contraction, and from greater wrinkle compression from a lower geomembrane modulus at higher burial temperatures.

Fig. 2.20 presents a cross-sectional profile of the post berm placement, immediately before backfill and post-backfill deformed wrinkle shapes experienced by Wrinkle 3 in Section A and Wrinkles 3 and 6 in Section B. Wrinkle 3 presented in Fig. 2.20a represents the typical behavior of wrinkles in Section A which experienced a small degree of thermal heating, causing a small amount of thermal growth, followed by a reduction in size upon backfill. Whereas, Wrinkles 3 and 6 detailed in Figs. 2.20b and 2.20c represent the typical response of wrinkles in Section B which experienced a larger increase in size due to thermal heating, followed by a large reduction in wrinkle size once covered.

In terms of achieving a wrinkle free installation, if wrinkles are already present in the geomembrane at the coolest time of the day, are allowed to grow by thermal heating, and are intentionally buried with 0.3 m of cool soil without the effects of equipment loading, wrinkles
will not “go away”. With regards to placing cover soil at 9am vs 2pm, no significant difference was observed in resulting height, width, or shape of buried wrinkles because they were able to thermally compress with the placement of the 0.3-m-thick layer of cooler sand. Based on this alone, one may think that wrinkle fate and leakage implications would be practically the same for cover soil placed at cooler morning temperatures and hotter mid-day temperatures. Field studies conducted by Chappel et al. (2011) and Rowe et al. (2012) have shown that not only does wrinkle height and width increase at hotter geomembrane temperatures, but frequency (% area covered with wrinkles) and interconnectivity (longest interconnected wrinkle feature) of wrinkles increase. Since time of day is generally a good proxy to air and solar conditions which are directly linked to geomembrane surface temperature, it is still best to place cover soil during the coolest part of the day when minimal wrinkles are present in the liner. In Sections A and B, there was no change in the number of wrinkles formed in either section – most likely because the berms were placed to intentionally capture wrinkles; the wrinkles present in the geomembrane after perimeter berm construction only got bigger with increasing temperature. The longest interconnected wrinkle in Section A after construction of the perimeter berms at 7:55 was 7 m and remained the longest connected feature at 9:15 before burial and post-backfill. Section B had a greater degree of wrinkle interconnectivity at 7:55 of about 19 m – largely due to the roll direction wrinkle connecting with cross-roll direction wrinkles. The longest connected wrinkle feature increased to 27 m at 13:15 before burial, and reduced to about 18 m after backfilling.
2.4 Conclusion

Three field investigations at two different sites were conducted to observe the fate of wrinkles in smooth, black, 1.5-mm-thick, high-density polyethylene geomembranes after placement of a 0.3-m-thick layer of cover soil. Geomembrane wrinkle geometry and surface temperature were monitored before and after placement of cover soil to assess the effects of thermal cooling, overburden pressures, construction equipment and placement techniques on the fate of geomembrane wrinkles. For the site specific materials and weather conditions examined, the following can be concluded:

1) Construction method: Spreading sand with a dozer at Site 1 led to extensive translation (i.e., plowing) and amalgamation of wrinkles. Despite the efforts of laborers trying to prevent wrinkle shifting by standing on the opposite side of a wrinkle during backfill, wrinkles still shifted out from beneath the cover soil into the uncovered liner by the weight of backfill material and by mechanical loading of the construction equipment. With the intent to bury small wrinkles, placing bucket loads of soil on either side of the wrinkle with an excavator was observed to eliminate wrinkle plowing and amalgamation at Site 2 as all wrinkles were backfilled in place individually and did not translate upon being covered. Similar results were found at Site 1, however in some instances, wrinkles were shifted out from beneath the backfill when sufficient soil was not placed on either side of the wrinkles to effectively trap them.

2) Fate of wrinkle after burial: A series of trenches were hand-excavated in four separate regions of Site 1 where wrinkles were believed to have been buried. Two of these regions were backfilled with an excavator and no wrinkles were found mainly due to thermal contraction of the buried wrinkles in one region, and translation of wrinkles out from under the cover soil in the other. The two other regions were backfilled with a dozer and wrinkles were found to remain in
both regions as the soil placement techniques deployed effectively trapped the wrinkles with sufficient quantities of soil, preventing them from translating upon backfill. For both the dozer and excavator techniques, the spatial sequence of cover soil placement and soil quantity used to trap wrinkles were observed to have a significant influence on size and location of wrinkles buried.

3) Wrinkle dimensions after burial: A series of nine wrinkles were monitored before and after placement of cover soil at Site 1, Trial B. There was no evidence of a wrinkle remaining for six of the wrinkles, while three of the wrinkles remained under the backfill at a reduced height and width. Wrinkles up to 100-mm-high at a temperature of 52°C prior to burial were observed to have flattened after placement of cover soil at a temperature of 10°C and a thickness of 0.3 m, while colder wrinkles that were trapped by large sand piles before covering remained post backfill (i.e., there was no thermal cooling). Fourteen wrinkles were monitored before and after placement of cover soil at two different geomembrane surface temperatures to quantify the effects of stress and thermal cooling on intentionally buried wrinkles at Site 2. Despite wrinkles buried at a hotter geomembrane surface temperature having larger sizes before backfill, all wrinkles buried while hot (50-53°C) and cooler (30-34°C) remained post-backfill within a similar range of final heights, widths, and aspect ratios. An additional 17% height and 5% width reduction was experienced by wrinkles buried at the hotter surface temperature which is believed to be the effects of geomembrane thermal contraction upon cooling by cover soil and greater wrinkle compression from a lower geomembrane modulus at higher burial temperatures.

4) Slack reduction mechanisms: If cover soil is to be placed on top of a geomembrane with wrinkles, the primary mechanisms responsible for the fate of wrinkle slack during soil cover construction are thermal contraction upon backfill placement and horizontal translation during or
after covering. Thermal cooling of a buried wrinkle with thin lifts (i.e. 0.3-m-thick) of soil that is cooler than the geomembrane may result in some recovery of thermal strains, and the addition of equipment loading on the surface of the soil cover might also be responsible for greater recovery of thermal strains. Lateral translation can be caused by cover soil self-weight and construction equipment loading which eliminates slack at one location but introduces slack at another location in the uncovered liner. If wrinkles are sufficiently buried with soil and do not undergo a thermal change, removal of slack is unachievable and burial of the slack in the form of a wrinkle is inevitable.

One approach to minimize burying wrinkles during daytime placement of soil cover may be to have geosynthetic installation and soil cover placement proceed together, rather than the current North American tendency of installing large amounts of geosynthetics followed by separate placement of larger amounts of cover soil. This way spreading of the cover soil could be used to push wrinkles towards a nearby unseamed edge of the geomembrane, allowing the geomembrane to be pressed smooth without the accumulation of a very large wrinkle in the direction of soil spreading. Final tie-in seaming and soil placement would then have to be done at cool daytime temperature with no wrinkles. This approach would require specifications at the time of project bidding and pre-construction coordination amongst the engineer, geosynthetic installer and earthworks contractor. It would also be more challenging – but still, not impossible – to conduct quality control and assurance tests on geomembrane welds. This approach would have an impact on construction costs but could result in a wrinkle free liner installation – at least for the conditions examined at Site A – while still allowing cover soil placement during most daytime hours.
For the site specific materials and conditions tested, it is clear that wrinkles can persist after the installation of a sand cover layer and the reported data provides some guidance on the possible size of wrinkles that remain. Additional field studies featuring different site conditions and construction practice would be useful to understand the fate of geomembrane wrinkles under a greater variety of conditions (e.g., with a geosynthetic protection layer and a gravel drainage layer).
2.5 References


Table 2.1: Summary of investigation trenching details from Site 1, Trial B

<table>
<thead>
<tr>
<th>Trench</th>
<th>Method of Backfill</th>
<th>Date Covered</th>
<th>Air temp. (°C)</th>
<th>GMB temp. (°C)</th>
<th>Date Trenched</th>
<th>Total Length of Trenches (m)</th>
<th>Wrinkles Found</th>
<th>Final Wrinkle Height/Width (mm/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A &amp; 1B</td>
<td>Exc.</td>
<td>April 28&lt;sup&gt;th&lt;/sup&gt; 11:00 – 14:00</td>
<td>10</td>
<td>52</td>
<td>May 3&lt;sup&gt;rd&lt;/sup&gt; 12:30pm</td>
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<td>0</td>
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<td>Exc.</td>
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<td>10</td>
<td>May 1&lt;sup&gt;st&lt;/sup&gt; 5pm</td>
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<tr>
<td>3</td>
<td>Dozer</td>
<td>May 1&lt;sup&gt;st&lt;/sup&gt; 10:30 – 12:30</td>
<td>12</td>
<td>28</td>
<td>May 3&lt;sup&gt;rd&lt;/sup&gt; 1:00pm</td>
<td>23</td>
<td>W8&lt;sup&gt;a&lt;/sup&gt;</td>
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<tr>
<td>4</td>
<td>Dozer</td>
<td>May 2&lt;sup&gt;nd&lt;/sup&gt; 10:00 - 11:30</td>
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<td></td>
<td></td>
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</tbody>
</table>

<sup>a</sup> = Monitored Wrinkle 8 – see Table 2.2.
Table 2.2: Summary of monitored wrinkles at Site 1, Trial B

| Detail                          | Wrinkle | 1A<sup>a</sup> | 1B<sup>a</sup> | 2 | 3 | 4 | 5 | 6 | 7 | 8<sup>b</sup> |
|--------------------------------|---------|----------------|----------------|---|---|---|---|---|---|---|---|
| Orientation                    |         | XRD            | RD             | RD<sup>c</sup> | XRD | XRD | XRD | XRD | XRD | RD |
| Just prior to soil placement   |         |                |                |     |     |     |     |     |     |     |
| Air temp. (°C)                 | 12      | 12             | 12             | 15   | 15   | 15   | 7    | 7    | 7    | 14   |
| GMB temp. (°C)                 | 50      | 52             | 52             | 52   | 52   | 52   | 9    | 9    | 9    | 31   |
| Height (mm)                    | 100     | 80             | 100            | 125  | 50   | 50   | 85   | 52   | 71   |       |
| Width (mm)                     | 450     | 350            | 400            | 350  | 220  | 220  | 370  | 320  | 360  |       |
| Length (m)                     | 3       | 8              | 5+             | 4+   | 2    | 2    | 3+   | 2.5  | 2.5  |       |
| Just after trench excavation   |         |                |                |     |     |     |     |     |     |     |
| Date (mo./day)                 | 5/3     | 5/3            | 5/3            | 5/3  | 5/3  | 5/3  | 5/3  | 5/3  | 5/3  | 5/3  |
| Time                           | 12:20   | 12:20          | 11:00          | 12:00 | 12:10 | 12:10 | 11:10 | 13:00 | 15:20 |       |
| Air temp. (°C)                 | 9       | 9              | 9              | 9    | 9    | 9    | 9    | 9    | 12   |       |
| GMB temp. (°C)                 | 11      | 11             | 11             | 11   | 11   | 11   | 11   | 11   | 11   |       |
| Height (mm)                    | 0       | 0              | 0              | 17   | 0    | 0    | 0    | 15   | 12   |       |
| Width (mm)                     | 0       | 0              | 0              | 50   | 0    | 0    | 0    | 55   | 50   |       |
| Length (m)                     | 0       | 0              | 0              | –<sup>d</sup> | –   | –   | 0    | –   | 7    |       |

Notes: XRD = cross-roll direction; RD = roll direction; Exc. = excavator; GMB = geomembrane

<sup>a</sup> = Backfilled in Trench 1 region – see Fig. 2.6.

<sup>b</sup> = Intersected by Trench 4 – see Fig. 2.9.

<sup>c</sup> = At roll direction blown-film remnant crease.

<sup>d</sup> = Entire length not excavated for Wrinkles 3-5 & 7.
Table 2.3: Summary of wrinkles monitored before and after backfill at Site 2, Section A

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<th>Wrinkle #</th>
<th>After Berm Placement, Sept 26, 7:55 (GMB 13°C)</th>
<th>Immediately Before Backfilled Sept 26, 9:15 (GMB 30-34°C)</th>
<th>After Backfilled Sept 27, 7:00 (GMB 20°C)</th>
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<td>Height (mm) Width (mm) Length (m)</td>
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Table 2.4: Summary of wrinkles monitored before and after backfill at Site 2, Section B

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<th>Wrinkle #</th>
<th>After Berm Placement, Sept 26, 7:55 (GMB 13°C)</th>
<th>Immediately Before Backfilled Sept 26, 13:15 (GMB 50-55°C)</th>
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\(^a\) = Wrinkle present but unmeasurable due to shape
Fig. 2.1. Photograph of Site 1 Trial A base liner showing plowed wrinkle features surrounding a 1.2-m-high sand road, taken June 3, 2013 at 8:21, air temperature 9°C, GMB 30°C
Fig. 2.2. Photograph of a large wrinkle feature, estimated 300-mm-high and 500-mm-wide, formed through plowing and amalgamation of slack from the sand placement process using a dozer at Site 1 Trial B
Fig. 2.3. Photograph showing sequence of dozer sand placement technique a) attempting to bury a wrinkle beneath the cover soil b) advancing sand cover causing lateral shifting of wrinkles; at Site 1, Trial B, taken May 1, 2014 at 9:20, air temperature 9.5°C, GMB
Fig. 2.4. Photograph demonstrating an excavator sand placement technique to bury geomembrane wrinkles at Site 1, Trial A, taken June 4, 2013 at 10:08, air temperature 14.5°C, GMB 45°C
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Fig. 2.7. Photograph taken at Site 1 Trial B of a) Trench 1A looking along the cross-roll direction trench where Wrinkle 1B was backfilled and did not remain post-backfill b) Trench 1B where Wrinkle 1A was backfilled and did not remain post-backfill
Fig. 2.8. a) Wrinkles prior to sand placement and eventual location of inspection Trench 2; b) wrinkles backfilled within the Trench 2 region; c) final soil placement near inspection Trench 2 (Site 1)
Fig. 2.9. a) Wrinkles prior to sand placement and eventual location of inspection Trench 3; b) location of Wrinkle 8 prior to burial; c) final soil placement near inspection Trench 3 (Site 1)
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Fig. 2.14. Variation in (a) solar radiation; (b) air temperature; (c) geomembrane surface temperature with time of day at Site 2 (September 26th)
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Fig. 2.17. Initial wrinkle height pre-backfill ($H_o$) vs final wrinkle height post-backfill ($H_f$) for monitored wrinkles in Sections A and B (Site 2)
Fig. 2.18. Initial wrinkle width pre-backfill ($W_o$) vs final wrinkle width post-backfill ($W_f$) for monitored wrinkles in Sections A and B (Site 2)
Fig. 2.19. Initial height-to-width ratio (pre-backfill) vs final height-to-width ratio (post-backfill) for monitored wrinkles in Sections A and B (Site 2)
Fig. 2.20. Inferred cross-sectional profiles of wrinkle geometry after berm placement, immediately before backfill, and after backfilling with cover soil for a) Wrinkle 3 in Section A; b) Wrinkle 3 in Section B; c) Wrinkle 6 in Section B, at Site 2 (exaggerated vertical scale)
Chapter 3

Physical response of small HDPE geomembrane wrinkles present after cover soil placement

3.1 Introduction

Leakage through holes in geomembrane liners used in water and waste containment applications can be minimized by placing a low permeable material beneath the geomembrane to create a composite liner and by reducing wrinkles that develop in the geomembrane during construction (Giroud and Bonaparte 2001; Rowe et al. 2004; Rowe et al. 2012). Geomembrane wrinkles are out-of-plane deformations caused by material expansion from solar heating (Giroud and Morel 1992; Giroud 2005; Rowe et al. 2004). As illustrated in Fig. 3.1a, if a wrinkle remains after placement of overlying materials like a protective soil cover or soil drainage layer, and after subsequent additional overburden stress from burial beneath waste in a landfill application or crushed rock in a heap leach pad, then the gap beneath the buried wrinkle creates a preferential flow path that can result in greater leakage if there is a hole in the geomembrane at or near the wrinkle (Rowe 1998). Hence, there is a need to understand the fate of a wrinkle when buried, i.e., the extent to which it may flatten out or ‘go away’.

Results from physical experiments have shown that wrinkles can experience a decrease in height and width when buried but the preferential flow path within the wrinkle gap remained despite vertical applied pressures up to 1100 kPa when there was sand above and below the geomembrane (Soong and Koerner 1998). In a composite liner configuration, Gudina and Brachman (2006a) showed that the gap was greatly reduced and could be eliminated with compacted clay beneath the geomembrane depending on applied pressure and clay
compressibility, while Brachman and Gudina (2008) showed the gap remained with a geosynthetic clay liner (GCL) and sand foundation layer beneath the geomembrane. The initial wrinkle dimensions for these composite liner experiments (pre-backfill height = 60 mm and width = 240 mm) were selected from field observations of Pelte et al. (1994) for a 1.5-mm-thick, black, HDPE geomembrane made prior to placement of any cover soil. This choice is consistent with additional wrinkle dimensions when uncovered (with heights between 40-60 mm and widths 200-300 mm), also measured for 1.5-mm-thick, black, HDPE geomembranes by Rowe et al. (2012). However, in Chapter 2 smaller and different shaped wrinkles were measured also for a 1.5-mm-thick, black, HDPE geomembrane but after placement of a 0.3-m-thick sand cover. For example, post-backfill wrinkle heights between 10 to 60 mm and widths of 50 to 80 mm were observed. A typical wrinkle remaining after sand cover placement is shown in Fig. 3.1b.

The objective of this chapter is to present results from short-term physical experiments to examine the fate of geomembrane wrinkles found to exist in the field after construction of a soil protection layer when subjected to overburden pressure. The influence of field cover soil placement technique, applied pressure, and subgrade material on wrinkle deformations and the fate of the gap beneath the wrinkle are examined.

3.2 Method and materials

3.2.1 Test cell and boundary conditions

Fig. 3.2 shows a cross section through the cylindrical steel test cell used in this laboratory study to evaluate the behaviour of small HDPE geomembrane wrinkles. The test cell has an inside diameter of 590 mm and a height of 500 mm. Vertical pressure was applied across the top soil boundary through a rubber bladder inflated with fluid pressure. Horizontal stresses
corresponding to zero lateral strain conditions were developed by limiting the outward deflection of the stiff cell walls. To reduce pressure loss due to boundary friction, the side walls were treated with a double layer of 0.1-mm-thick polyethylene sheets lubricated with silicone grease. Tognon et al. (1999) showed that this configuration reduces the sidewall friction angle to less than 5°. For the size of the test cell and friction treatment applied, it was calculated that this level of friction reduces the vertical stresses reaching the geomembrane by less than 5% (Brachman and Gudina 2002). Krushlenitzky and Brachman (2009) showed with physical testing and detailed numerical analysis that boundary conditions of this test cell were sufficient to simulate deep burial conditions for applied vertical pressures up to 3000 kPa.

The boundary conditions of the geomembrane were as follows: i) Cement grout was used to create lateral restraints at the edges of the cell wall \((X = \pm 295 \text{ mm})\) to ensure zero lateral displacement in the \((X)\) direction without restraining the vertical \((Z)\) direction, and ii) A 5 mm gap was left where the ends of the wrinkle met the cell wall \((Y = \pm 295 \text{ mm})\) to allow the geomembrane to freely deform in the vertical direction without binding against the cell wall and to obtain known stress conditions of zero axial \((Y)\) restraint (Gudina and Brachman, 2006b). Brachman and Gudina (2002) examined the possible effects of this gap using three-dimensional finite element analysis. They showed that the stress free boundary condition results in negligible effects in vertical deflection for the central 20% of the wrinkle (where all results were reported) relative to axial plane strain conditions expected for a geomembrane wrinkle in a landfill.

3.2.2 Materials

A summary of materials and configurations tested is given in Tables 3.1 and 3.2. Three different subgrade materials were tested to investigate the effects of subgrade compressibility on wrinkle deformations and the fate of the wrinkle gap. A 200-mm-thick foundation layer of dry,
poorly graded medium sand (SP) was placed beneath a dry GCL in Tests 1-11 to simulate the case of a firm foundation layer. The sand used was similar to that used by Brachman and Gudina (2008) and had a mean grain size of 0.65 mm, a uniformity coefficient of 5.8 and a coefficient of curvature of 0.7. It was compacted to a dry density of 1.9 g/cm$^3$ (obtained by taking a known mass and compacting it to a known volume) and had a water content between 0.4 and 0.8%, resulting in an initial density index of 85%. A 200-mm-thick silty sand (SM) subgrade was placed beneath a hydrated GCL in Tests 12-15. The silty sand had 42% by mass passing the 0.075 mm sieve and these fines were found to be non-plastic. To investigate the effects of a more compressible foundation, a silty clay acquired from a landfill in Milton Ontario was used for the 200-mm-thick compacted clay liner (CCL) in Test 16. The clay had a liquid limit of 26% and a plastic limit of 16% (Brachman and Sabir 2010).

The GCL tested consisted of sodium bentonite (4755 g/m$^2$) between a scrim-reinforced, nonwoven carrier geotextile (252 g/m$^2$) and a nonwoven, needle-punched cover geotextile (226 g/m$^2$), with the needle-punched fibres thermally fused to the carrier geotextile. The GCL was installed with the carrier geotextile in contact with the subgrade. In all tests, a 1.5-mm-thick, smooth, black, HDPE geomembrane was installed above the subgrade. The index stress-strain properties of the geomembrane are summarized in Table 3.3. A 300-mm-thick sand cover soil, the same poorly-graded medium sand as that used for the subgrade in Tests 1-11, and similar to the sand protection layer used at the field site studied in Chapter 2 was placed above the geomembrane to a dry density of 1.8 g/cm$^3$ at a water content between 5 and 6%.

3.2.3 Procedure

Once the subgrade was placed, a wrinkle was manually formed in the cross-roll direction of the geomembrane by using a test specimen longer than the inner diameter of the test cell. To
analyze the geomembrane behaviour during wrinkle deformations, in most tests, stainless steel pin heads were lightly pressed into the top surface of the geomembrane to track as the wrinkle deformed in the X-Z plane. The targets had a diameter of 1.75 mm, a height of 0.6 mm and a diameter and depth of penetration of 0.65 mm and 0.6 mm respectively. In order to acquire the post-backfill wrinkle geometry, a narrow vertical observation trench was temporarily excavated through the sand cover at the centre of the cell, perpendicular to the wrinkle, to measure the initial target locations and wrinkle geometry with minimal geomembrane rebound effects due to overburden stress relief. The measurements made at this time are denoted as the initial wrinkle heights and widths (Ho and Wo) in Tables 3.1 and 3.2. All measurements were acquired using a line-laser scanner to an accuracy of ±0.05 mm.

Once all materials were placed in the test cell, vertical pressures were applied in 50 kPa increments every 10 minutes for tests to 250 kPa, and 100 kPa increments every 10 minutes for tests up to 1000 kPa and greater. Each test was held at constant pressure for 100 hours at a temperature of 22 ± 1°C. This choice of duration selected allows for the analysis of the short term immediate physical response of the materials used, without considering the time dependent effects of creep and stress relaxation in the geomembrane. Prior to releasing the pressure at the end of each test, a liquid dye was injected into any remaining gap beneath the wrinkle (see Fig. 3.3a), followed by a low shrinkage grout to preserve the final wrinkle geometry (see Fig. 3.3b). The dye and grout were injected through a 10 mm diameter pipe that extended from the bottom of the test cell to the top surface of the GCL as shown in Fig. 3.2b. After setting of the grout, a narrow vertical observation trench was again excavated through the sand backfill to acquire the final deformed geomembrane surface. Once the sand backfill and geomembrane were removed
from the test cell, an insitu measurement of the underlying GCL with the preserved wrinkle shape in grout (if any) and the underlying subgrade was acquired with the laser scanner.

Small differences (0.5-2 mm) were consistently found between the final bottom geomembrane surface and final top GCL and grout surface which is the result of the geomembrane wrinkle vertically rebounding due to overburden pressure relief within the observation trench excavated to measure the final geomembrane. As a result, the final geomembrane heights and widths (Hf and Wf) reported in Tables 3.1 and 3.2 were acquired from the final deformed GCL and grout surface profiles which best represent the geomembrane shape under loading conditions.

3.3 Results and discussion

3.3.1 Effect of field cover soil placement

In Chapter 2, field measurements of wrinkle widths between 70 and 110 mm were reported for wrinkles that were intentionally buried beneath 0.3 m of sand cover soil. In this case, cover soil was placed by the bucket of an excavator without any construction vehicles driving on the cover soil surface prior to hand excavation of narrow inspection trenches and measurement of the wrinkles. The fate of such wrinkles when subjected to an additional vertical pressure of 250 kPa is shown in Fig. 3.4. These wrinkles had a width of approximately 95 mm after burial beneath 0.3 m of sand, but prior to application of the additional pressure, which corresponds to the post-backfilled mean wrinkle width measured without construction equipment loading (Chapter 2).

These experiments were conducted with a dry GCL (initial gravimetric water content of 7% and initial thickness of 7 mm) and sand foundation beneath the geomembrane wrinkle, and hence mainly serve as a reference case for later comparison with more compressible foundations.
These conditions could correspond to field scenarios where the GCL is isolated from moisture for hydration, or where vertical pressure is applied prior to significant hydration (e.g., where the rate of waste placement is rapid relative to rate of GCL hydration). For reference, an applied vertical pressure of 250 kPa corresponds to burial beneath 15–20 m of municipal solid waste, assuming a unit weight between 12.5 and 16.7 kN/m$^3$ (e.g., Zekkos et al. 2005).

All tests conducted in Table 3.1 consisted of post-backfill wrinkle widths between 93 and 95 mm. For Tests 2-4 presented in Fig. 3.4, the final wrinkles reduced in size but remained in all tests at 250 kPa overburden pressure. For a 21.5-mm-high and 95-mm-wide wrinkle shown in Fig. 3.4a, representing a typical wrinkle geometry observed post-backfill in the field without the effects of equipment loading, the wrinkle height and width was reduced by 18% (17.7 mm) and 33% (64 mm) of the original size. The remaining gap beneath the wrinkle was 16.7-mm-high and 59-mm-wide. Investigating the fate of wrinkles with similar initial widths but shorter initial heights, Test 3 was conducted with a wrinkle height of 13.5 mm shown in Fig. 3.4b which resulted in a smaller, 7-mm-high gap at 250 kPa. The physical gap was only eliminated in Test 4 for a very short (4-mm-high) wrinkle as seen in Fig. 3.4c.

At a different field site examined in Chapter 2, much narrower wrinkles were observed after placement of sand cover soil for similar conditions, other than the final grading of cover soil was done with multiple passes of a low ground pressure dozer (34 kPa track pressure). In this case, wrinkle widths were between 50 and 80 mm after placement of cover soil with the mean wrinkle width being 55 mm. After several trials, special procedures were required to form these observed field wrinkle geometries after sand placement. A wrinkle width of 55 mm could not be attained by simply compacting a 300-mm-thick layer of sand above the wrinkle as illustrated in Fig. 3.5. Due to the stresses and deformations associated with the field cover soil
placement, a need to devise a procedure that produces the shapes of wrinkles measured in the field with construction loading was necessary. After casting cement blocks at the edges of the cell wall, the wrinkle was formed at the centre of the cell by placing rectangular weights parallel to the base of the wrinkle at a 55 mm spacing. A 300-mm-thick layer of sand was then placed and compacted above the geomembrane and 30 kPa vertical pressure was applied for 12 hours. A configuration of the test cell set-up during this procedure is shown in Fig. 3.6. After applying the pre-load, the backfill material above the wrinkle was temporarily removed to exhume the weights and re-compacted to a thickness of 300 mm. In order to verify that the target wrinkle dimensions were achieved, a narrow vertical observation trench was temporarily excavated at the centre of the cell perpendicular to the wrinkle to measure the post-backfill geometry of the wrinkle. The resulting shape after the inclusion of weights and 30 kPa seating stress in Fig. 3.6 was found to mimic a typical wrinkle geometry observed post-backfill with the effects of equipment loading. This procedure was repeatable, producing a mean wrinkle height of 15 mm (standard deviation = 1 mm) and mean wrinkle width of 57 mm (standard deviation = 1 mm). All tests conducted in Table 3.2, producing post-backfill wrinkle widths of 53-59 mm wide, used this procedure to simulate construction loads.

Test 5 plotted in Fig. 3.7a presents the initial and final deformed wrinkle shape of a 15-mm-high and 55-mm-wide wrinkle with a firm sand and dry GCL subgrade. The arrows in Fig. 3.7a represent the top surface of the geomembrane, GCL, and subgrade. This wrinkle represents a typical wrinkle geometry observed post-backfill with the effects of equipment loading. The plot shows that the wrinkle height and width reduced by only 9 and 14% at 250 kPa of applied pressure. Test 3 in Fig. 3.4b, conducted under the same conditions as Test 5, except with a larger post-backfill wrinkle width of 95 mm, experienced greater height and width reductions of 33%
and 29%, respectively. The smaller wrinkle size reduction for the narrower wrinkle in Test 5 compared to the wider width wrinkle in Test 3 is likely due to the higher stiffness and therefore, lower compressibility of the smaller wrinkle geometry. This is discussed in further detail later on (following section). Despite the different final shapes achieved by Tests 5 and 3, the gap remained beneath the deformed geomembrane wrinkle in both cases.

### 3.3.2 Effect of applied pressure

By increasing the vertical applied pressure above the narrow wrinkles having a width of 55 mm, only relatively small wrinkle deformations were observed, even for a very large vertical pressure of 3000 kPa, Fig. 3.7d. Vertical overburden pressures up to 3000 kPa may be encountered in very large heap-leach pads (Lupo and Morrison 2007; Rowe et al. 2013). For instance, Tests 5, 6 and 10, all involving a 15-mm-high and 55-mm-wide wrinkle overlying a stiff sand and dry GCL subgrade, experienced height and width reductions of 9 and 14% at 250 kPa, 17 and 18% at 1000 kPa, and 31 and 40% at 3000 kPa applied pressure respectively and relative to the post-backfilled geometry. These wrinkle deformations are significantly smaller than those observed by Brachman and Gudina (2008) for initial sized wrinkles of 60-mm-high and 240-mm-wide (measured prior to burial), on a hydrated GCL overlying a stiff sand subgrade, and a sand protection layer. Brachman and Gudina's experiments correspond to the case of a wrinkle backfilled without the influence of field construction equipment loading or thermal effects. They found that the final wrinkle height and width reduced by about 40 and 56% at 250 kPa, and 57 and 77% at 1000 kPa applied pressure, respectively.

The overlying soil cover plays a prominent role in the change of wrinkle geometry as deformations of the wrinkle are largely controlled by soil deflections. Generally, the lower the stiffness of a buried structure, the more willing it is to deform with deflections that occur in the
soil backfill under applied pressures. The large initial wrinkle configuration tested by Brachman and Gudina (2008), (initially having a low stiffness and high potential for compression) experienced significant deformation in height and width as it compressed with the surrounding soil especially at low pressures, also observed by Brachman and Gudina (2002). It was hypothesized that stiffening of sand under increasing applied pressures and possible arching of earth pressures around the wrinkle may have caused only smaller additional wrinkle deflections as pressures were increased. Conversely, a stiffer structure, such as a very small and narrow wrinkle with sharp changes in curvature (e.g., wrinkles tested in Tests 5, 6 and 10), was observed to undergo only small deformations due to its lower compressibility. Therefore, as the soil compresses and densifies under the applied pressure, it has a limited effect on wrinkle compression due to the stiff response of the wrinkle. As a result, small wrinkle size reductions were measured in this investigation even for 3000 kPa stresses. From a leakage perspective, the decrease in wrinkle width would proportionally decrease leakage (Rowe 1998) however in this circumstance the leakage is probably governed by wrinkle length (Rowe et al. 2004).

In terms of the fate of the wrinkle gap, a decrease in gap volume was measured as stress increased, however the gap was not eliminated even at 3000 kPa. A decrease in the gap was primarily a result of the settlement of the sand subgrade and GCL on either side of the wrinkle which can be seen by comparing initial vs final GCL and sand surfaces in Fig. 3.7. The migration of sand from the high stress region beside the wrinkle to the low stress region beneath the wrinkle in Fig. 3.7c caused heaving of sand into the gap which led to further reduction in gap volume at 3000 kPa, however a 3.5-mm-high and 16-mm-wide gap still remained beneath the deformed geomembrane.
The influence of initial wrinkle height on the fate of the wrinkle and fate of the gap at 1000 kPa is shown in Fig. 3.8. A vertical pressure of 1000 kPa could result from burial beneath 60 m of municipal solid waste and cover soil with a unit weight of 16.7 kN/m³. These tests were conducted with the rational that if the wrinkle and/or wrinkle gap was not eliminated at 1000 kPa, they would also remain at lower pressures. For the case with a dry sand and dry GCL foundation, the gap was only eliminated in Test 9 for a very small (nearly imperceptible in the field) wrinkle height of 3 mm at 1000 kPa as indicated in Fig. 3.8b which shows the final geomembrane and GCL surfaces nearly identical (with the exception of an observer effect of 1-1.5 mm of geomembrane rebound). Contact between the geomembrane and GCL was confirmed by injecting a dye through the grout pipe, prior to injecting the grout. There was no visual evidence of a preferential flow path along the direction of the remaining wrinkle as the dye showed up radially equal around the grout pipe injection point on the surface of the GCL. The long term leakage in this case would be expected to be governed not only by the long term hydraulic conductivity of the GCL, but also by the interface transmissivity between the geomembrane and GCL (Rowe and Abdelatty 2013). For this case, leakage is expected to be very low. This testing with a dry GCL beneath the geomembrane eliminated the effects of bentonite extrusion noted by Brachman and Gudina (2008) and hence the fate of the gap in Test 9 was merely a product of the downward movement of the geomembrane and wrinkle height reduction. Although the elimination of the gap was achieved in Test 9, elimination of the wrinkle feature itself was not achieved as a 1.2-mm-high and 47-mm-wide wrinkle remained. For a 10-mm-high wrinkle in Fig. 3.8a under the same conditions, a 3.5-mm-high preferential flow feature remained.
3.3.3 Effect of compressible foundation

The subgrade materials tested had distinguishable effects on geomembrane wrinkle deformations and the fate of the wrinkle gap. The effect of having a more compressible GCL and silty sand foundation layer beneath the geomembrane was examined in Tests 12-15 shown in Fig. 3.10. A 200-mm-thick layer of the silty sand was compacted to its standard proctor optimum water content of 12% to its standard proctor maximum dry density of 1.83 g/cm$^3$. Prior to loading, the GCL was hydrated for 7 days under a 2 kPa seating stress to an initial gravimetric water content of 90% ($\pm5\%$) and had an average initial thickness of 9 mm. This corresponds to the steady state water content of this particular GCL if allowed to hydrate prior to application of overburden pressure on this silty sand foundation layer at the same water content and density based on the GCL hydration experiments reported by Rayhani et al. (2011).

The deformed wrinkle shape overlying a hydrated GCL and silty sand subgrade was similar to that of a dry GCL and sand subgrade at 250 kPa (comparing Figs. 3.7a and 3.10a) and 1000 kPa (comparing Figs. 3.7b and 3.10b). However, at the higher applied pressure of 1000 kPa, the final gap was smaller for the hydrated GCL and silty sand subgrade. Fig. 3.3b shows the GCL surface and preserved grout mold of the remaining wrinkle gap in Test 13 (Fig 3.10b). A 3.5-mm-high gap remained for a 12 mm initial wrinkle height (Fig 3.10c), and no remaining gap was evident for a 10 mm initial wrinkle height (Fig. 3.10d). Contact between the geomembrane and GCL in Test 15 was confirmed by: i) the transfer of ink targets drawn on the underside of the geomembrane to the top surface of the GCL beneath the wrinkle, ii) no grout being accepted beneath the wrinkle, and iii) the matching of deformed wrinkle and GCL geometries. Although clear evidence of contact between the geomembrane and GCL was observed, a narrow linear streamline of dye, injected through the grout pipe beneath the wrinkle, appeared on the top
surface of the GCL along the length of the wrinkle as seen in Fig. 3.3a. This preferential flow path along the crest of the wrinkle suggests that, although contact between the geomembrane and GCL was achieved, the interface transmissivity was sufficiently high such that unobstructed flow at the interface was permitted. Unfortunately, the dimensions of the cell are such that they were insufficient to deduce an interface transmissivity value. The fate of the gap here was primarily a function of vertical settlement of the geomembrane combined with the effects of bentonite extrusion within the GCL into the gap and wrinkle height reduction.

The deformations observed in both the sand and silty sand subgrade materials were also very similar. For example, both subgrades in the similar test configurations of Tests 8 and 15 (Fig. 3.8a and Fig. 3.10d respectively) deformed similarly in shape and magnitude with vertical settlements adjacent to the wrinkle of 1.5 and 1.1 mm for the sand and silty sand subgrade respectively. The wrinkle deformations in both tests were also very similar. Therefore, from results observed in Test 15, it can be reasonably postulated that by inserting a hydrated GCL in Test 8, the gap beneath the 10-mm-high wrinkle could also be eliminated when subjected to a vertical pressure of 1000 kPa.

Fig. 3.11 shows the results from one particular experiment conducted with compacted silty clay beneath the geomembrane in Test 16. While more compressible than the silty sand foundation, the silty clay was compacted towards the lower bound water content (i.e. stiffer) limit for field compaction of this soil to obtain low permeability (Benson et al. 1999; Rowe et al. 2004). This corresponded to compaction at its standard proctor optimum water content of 12% to its standard proctor maximum dry density (1.9 g/cm³). Although the wrinkle height and width did not change by any significant amount (1 and 2 mm respectively), the gap was completely eliminated at an applied pressure of 250 kPa, as indicated in Fig. 3.11 which shows the final
geomembrane and GCL surfaces to be nearly identical. Unlike the small settlements observed in the sand and silty sand subgrades at 250 kPa (0.5 and 0.7 mm respectively), the silty clay settled 4.5 mm adjacent to the wrinkle. Since the clay was vertically unconfined beneath the wrinkle, the clay heaved upwards due to migration of clay from high pressure regions (areas of geomembrane and clay contact) to regions of low pressure beneath the wrinkle. As a result, the net upward movement of clay beneath the wrinkle and downward movement of the geomembrane was such that the preferential gap was completely eliminated.

Similar to observations made by Gudina and Brachman (2006a) where wrinkles were tested overlying a compacted clay liner, cracking of the clay surface was observed beneath the wrinkle in Test 16. The cracks were located along the wrinkle crest parallel to the direction of the wrinkle and were formed by tensile strains developed during clay settlement and clay extrusion into the gap beneath the wrinkle. The cracks were measured to be approximately 0.8-mm-wide, up to 120-mm-long, 5-10 mm deep, and the majority of the cracks did not appear interconnected at the surface. The impact of surface cracks on interface transmissivity between the geomembrane and compacted clay liner is currently unknown, however it is conceivable that the surface crack features could result in a higher interface transmissivity.

The rapid increments in applied pressure (50 kPa every 10 minutes) for Test 16 were such that the clay foundation experienced largely undrained loading conditions. To assess whether the adopted loading rate influenced the geomembrane and clay deformations, Gudina and Brachman (2006a) investigated smaller increments of applied pressure over a longer loading period, allowing the clay to exceed 90% consolidation for each increment. Results suggested that the deformations of the geomembrane and clay subgrade were similar regardless of whether the clay was tested in a drained or undrained manner.
3.3.4 Effect of geotextile inclusion

Test 7 was conducted on a 15-mm-high and 55-mm-wide wrinkle with a 600 g/m² nonwoven needle-punched geotextile overlying the geomembrane. Interface shear resistance developed at the cover soil and geomembrane interface can be responsible for preventing horizontal translation of the geomembrane at the interface, especially under high overburden stresses. The intent of the geotextile inclusion was to see if reducing the interface friction generated between the geomembrane and sand backfill would increase the potential for outward lateral slip of the geomembrane at the base of the wrinkle, and possibly leading to greater wrinkle size reductions. However, inclusion of the geotextile did not have any discernable influence on the wrinkle deformations as results were similar to identical Tests 6a and 6b with no geotextile.

3.3.5 Fate of largest observed wrinkle

A particularly large (60-mm-high and 50-mm-wide) wrinkle entombed beneath a field constructed soil cover layer was noted in Chapter 2. The wrinkle was detected after hand excavation of a test pit and was caused by amalgamation of wrinkles during the dozer sand spreading technique. The wrinkle was deemed unacceptable by the onsite quality control inspector resulting in removal of this particular wrinkle, however an experiment was conducted to analyze the fate of such wrinkle if it were undetected and subjected to 250 kPa of overburden stress.

Test 11 was conducted on a 65-mm-high and 55-mm-wide wrinkle overlying a dry GCL and sand subgrade shown in Fig. 3.12 at a pressure of 250 kPa. The final wrinkle height and width reduced by 4.8 mm and 15 mm respectively and the stiff sand subgrade overlain by the dry GCL prevented extrusion of bentonite into the remaining void. Fig. 3.12 clearly shows pinching
of the wrinkle width at mid-height with the wrinkle side walls sustaining an 8 mm separation at mid-height. This particular wrinkle, already having an initially high degree of curvature at the apex, deformed to create an even sharper bend. The expected large tensile stresses sustained in the wrinkle is one of the required conditions that can potentially lead to the initiation of stress cracking failure in the geomembrane over time. Consequently, it is wise to avoid entombment of such wrinkles during construction of an overlying soil protection layer to reduce the probability of developing stress concentrations in the geomembrane.

### 3.3.6 Displacement trajectory and strains

The purpose of tracking targets on the geomembrane before and after load application was primarily to understand the displacements induced at different locations along the geomembrane wrinkle under vertical loading conditions. The target trajectories allow the assessment of possible strains that could be developing in the geomembrane under loading.

Target trajectories (indicated in Figs 3.7, 3.8 and 3.10-3.12 as black symbols for the post-backfilled position and white symbols for the post-overburden pressure position) from Tests 5-6 and 8-16 show a similar response after load application. The target displacement trajectories tracked along the inclined side walls of the wrinkles show predominately downwards and slightly inward deflections (towards the centre of the wrinkle) such that wrinkle heights and widths were reduced when subjected to overburden pressures. Targets located at the base of the wrinkle (in the flat geomembrane) deformed vertically with negligible lateral displacement. These observations suggest that the zero-lateral-displacement boundary is localized near the base of the wrinkle and was found to be fairly consistent for all tests conducted regardless of initial wrinkle size and applied pressure. This is expected to be the situation in the field where frictional forces, mobilized at the geomembrane interfaces along the laterally extensive conditions
expected at the base of a landfill, are sufficient to restrain the geomembrane from horizontal movement. These results are consistent with measured displacement trajectories observed for larger wrinkles by Gudina and Brachman (2011) at 250 kPa and Soong and Koerner (1998) at 700 kPa. The measured trajectories are indicative that the flat portion of the geomembrane adjacent to the wrinkle is not undergoing compression (which one may have hypothesized to be the mechanism which could cause entombed wrinkles to flatten under overburden pressures).

Also, for the wrinkles that experience an increase in H/W ratio upon loading, the final wrinkle becomes narrower. Narrower wrinkles generally have higher curvatures, especially at the apex (X=0), and near the base where the side walls of the wrinkle bend to conform to the subgrade. Since curvature and strain are related, wrinkles can experience higher tensile and compressive stresses at the extreme fibers when assuming higher degrees of curvature (i.e., sharper bends) under elevated vertical stresses.

3.4 Conclusion

Short-term physical experiments involving a 1.5-mm-thick high-density polyethylene geomembrane were conducted on initial size wrinkles similar to those observed after field placement with sand cover (Chapter 2). The influence of field soil cover placement technique, applied pressure, and subgrade material on the fate of the gap beneath the wrinkle and wrinkle deformations was examined. For the specific materials and conditions tested, the main conclusions are:

1) Effect of cover soil placement: Wrinkles observed to exist post-backfill in the field, without experiencing construction equipment loading, were subjected to elevated overburden pressures. Theses wrinkles, involving a mean wrinkle width of 95 mm and tested above a stiff sand and dry geosynthetic clay liner (GCL) subgrade, showed minimal wrinkle size reductions
and the gap beneath the wrinkle was only eliminated for a very small 4-mm-high wrinkle at 250 kPa applied pressure. In order to recreate a wrinkle width of 55 mm, representing the observed mean width for entombed wrinkles that experienced construction equipment loading in the field, a unique procedure involving a 30 kPa pre-load for 12 hours was necessary. This effort suggests that the non-symmetrical dynamic loading of the dozer is capable of manipulating buried wrinkles into small, narrow and thus, stiff structures during soil cover placement. As a result, only relatively small wrinkle deformations were observed (less than the deformations for the 95-mm-wide wrinkles tested under additional overburden pressures).

2) Effect of applied pressure: Due to the high degree of stiffness sustained in a 55-mm-wide wrinkle post-backfilling, only relatively small wrinkle deformations were observed even for applied stresses up to 3000 kPa. A typical 15-mm-high and 55-mm-wide wrinkle overlying a stiff foundation experienced height and width reductions of only 9 and 14% at 250 kPa, 17 and 18% at 1000 kPa, and 31 and 40% at 3000 kPa applied pressure respectively. In terms of the fate of the wrinkle gap, the volume of the gap decreased with increasing stress, however was not eliminated even at 3000 kPa. At 1000 kPa applied pressure, the gap was only eliminated for a very small 3-mm-high and 55-mm-wide wrinkle, however a 1.2-mm-high and 47-mm-wide wrinkle feature still remained.

3) Effect of compressible foundation: The deformed wrinkle shape overlying a hydrated GCL and silty sand subgrade was similar to that of a dry GCL and sand subgrade at 250 and 1000 kPa. The wrinkle gap was consistently smaller for the case with a hydrated GCL, especially at higher pressures, due to extrusion of bentonite into the wrinkle gap. The gap was completely eliminated at 1000 kPa for a 10-mm-high and 55-mm-wide wrinkle overlying a hydrated GCL and silty sand subgrade. A 15-mm-high and 55-mm-wide wrinkle was tested on a more
compressible compacted clay liner. Although negligible changes in wrinkle size were observed, the physical gap was completely eliminated at an applied pressure of 250 kPa caused by geomembrane settlement and upward clay heaving into the gap.

4) Effect of geotextile inclusion: Including a geotextile between the geomembrane and sand cover did not have a discernible influence on wrinkle deformations.

5) Wrinkle deformations and geomembrane strains: Geomembrane wrinkle displacement trajectories tracked along the side walls of the wrinkle show predominately downward and slightly inward deflections (towards the centre of the wrinkle), and targets at the base of the wrinkle (in the flat geomembrane) deformed vertically with negligible lateral translation. The measured trajectories are indicative that the zero-lateral-displacement boundary is localized near the base of the wrinkle such that the flat portion of the geomembrane adjacent to the wrinkle is not undergoing compression. For the wrinkles that became narrower (increased height-to-width ratio) under elevated vertical stresses, the higher degrees of curvature assumed by their final shape can imply higher tensile and compressive stresses and strains at the extreme fibers.

These results are applicable for the specific materials and conditions tested and should not be directly used for design purposes for different conditions without experimental verification.
3.5 References


Table 3.1: Summary of test configurations and results for wrinkles having initial widths of approximately 95 mm

<table>
<thead>
<tr>
<th>Wrinkle</th>
<th>Subgrade</th>
<th>SP or SM water content (%)</th>
<th>GCL water content (%)</th>
<th>Pressure (kPa)</th>
<th>H₀ (mm)</th>
<th>W₀ (mm)</th>
<th>Hᵣ (mm)</th>
<th>Wᵣ (mm)</th>
<th>Remaining Gap H/W (mm)</th>
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Table 3.2: Summary of test configurations and results for wrinkles having initial widths of approximately 55 mm

<table>
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<tr>
<th>Test</th>
<th>Test Configuration</th>
<th>Foundation layer</th>
<th>SP or SM water content (%)</th>
<th>GCL water content (%)</th>
<th>Pressure (kPa)</th>
<th>Ho (mm)</th>
<th>Wo (mm)</th>
<th>Hf (mm)</th>
<th>Wf (mm)</th>
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<td></td>
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*600g/m² geotextile installed above geomembrane
Table 3.3: Stress-strain properties (mean ± 95% confidence interval) of the particular geomembrane tested, obtained following ASTM D 6693 (ASTM, 2001)

<table>
<thead>
<tr>
<th>Property</th>
<th>Machine Direction</th>
<th>Cross-machine direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Strength (KN/m)</td>
<td>29 ± 1.0</td>
<td>31 ± 0.4</td>
</tr>
<tr>
<td>Break yield strength (KN/m)</td>
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<td>47 ± 1.8</td>
</tr>
<tr>
<td>Yield elongation strain (%)</td>
<td>22 ± 0.8</td>
<td>18 ± 0.4</td>
</tr>
<tr>
<td>Break elongation strain (%)</td>
<td>822 ± 30</td>
<td>874 ± 46</td>
</tr>
</tbody>
</table>
Fig. 3.1. a) Illustration of leakage through a hole in a geomembrane with a buried wrinkle. b) Photograph of a wrinkle remaining after placement of a 0.3-m-thick sand cover
Fig. 3.2. Cross-section through test cell along a) $y = 0$ and b) $x = 0$ showing configurations tested under simulated landfill conditions (dimensions in millimeters)
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Chapter 4

Field monitoring of downslope displacements of a geosynthetic lined landfill side slope

4.1 Introduction

Geosynthetic lined slopes (e.g., side slopes in a municipal solid waste landfill) require stability assessment in the short-term during construction, short- to medium-term during waste placement and in the long-term of the final geometry once all of the waste is placed (e.g., see Rowe et al. 2004). It is routine geotechnical practice to assess stability in these cases by comparing disturbing forces with restoring forces in a limit equilibrium manner, where selection of site specific interface shear strength parameters (e.g., peak, residual or a factored strength) are important for the use in stability analysis (Jones and Dixon 2004).

While a slope may be deemed to be stable (i.e., have conventional factor of safety against instability > 1), there may be deformations in the downslope direction from construction effects, waste placement effects or subsequent settlement of the waste due to strain incompatibility of lining system components. Deformations could result in tensions in the geomembrane, although presumably this would be much more relevant for steep lined canyon and quarry landfills than more conventional landfills with slopes typically inclined at 3 horizontal (H) to 1 vertical (V). Of interest here, are the deformations occurring in a typical geosynthetic lined 3H:1V side slope during construction as well as during and after waste placement. This is expected to confirm that tensile strains in the geomembrane from downslope movements are acceptably low and would mean that strain assessment in the geomembrane in these cases are governed by local gravel effects (e.g., Gallagher et al. 1999, Rowe et al. 2004, Brachman and Gudina 2008). This field
investigation permits an opportunity to quantify the downslope displacements of the coarse gravel particles from the leachate collection system relative to the geomembrane, which could be relevant in the local assessment of geomembrane strain. Geomembrane strains from local gravel indentations have been well documented for the case of gravel overlying a geomembrane on a flat surface, such as at the base of a landfill (e.g., Eastman and Brachman 2013; Brachman and Gudina 2008a; Brachman and Gudina 2008b). However, it remains a question whether the impact of tangential displacement of gravel on local indentation strains in the geomembrane are exacerbated on a sloped surface. If relative displacements occur between gravel particles and the geomembrane, especially at elevated normal stresses expected near the base of a slope, geomembrane and geosynthetic clay liner protection are a concern (e.g. Dickinson and Brachman 2010).

The objective of this chapter is to report on the instrumentation installed on a geosynthetic lined municipal solid waste landfill side slope to monitor the in-service physical performance and interaction of geosynthetic materials including the geomembrane, geotextile, geogrid and gravel during construction of the gravel drainage layer and 1.6 years after partial waste placement on the slope. A section of a landfill slope was monitored using instruments to measure temperature, displacements, relative displacements, and strains within the geosynthetic lining elements.

4.2 Site details

The geosynthetic lining system was monitored on the side slope of a municipal solid waste landfill located at a latitude of 44°23’N and longitude of 79°43’W. The monitored slope has a length of 66 m and is 21 m in height with an inclination of 3H:1V (18.4°). A cross-section of the composite geosynthetic side slope lining system is depicted in Fig. 4.1. The lining system from
the bottom-up consisted of a: fine sand subgrade; geosynthetic clay liner consisting of sodium bentonite clay encapsulated between a slit-film woven and a nonwoven needle-punched geotextile (placed with its nonwoven geotextile facing up); 1.5-mm-thick, black, double-sided textured, HDPE geomembrane; 1,900 g/m², white, nonwoven, needle-punched geotextile; polypropylene biaxial geogrid (2 different types used, both having a 58 mm by 60 mm aperture size (GG-A = Terrafix BX2000-L; GG-B = Tenax LBO 270 SAMP)); and a 0.3-m-thick, poorly-graded coarse gravel for the leachate drainage layer (D₁₀₀ = 50 mm, D₆₀ = 35 mm, D₅₀ = 32 mm, D₃₀ = 27 mm, D₁₀ = 22 mm, 0.6% passing #200 sieve). Information on the tensile stress-strain behaviour of geogrids A and B are presented in Table 4.1. The GCL, GMB, GTX and GG were placed along the entire side slope length and fixed at the top of the slope in an “L” shaped anchor trench 1.3 m in depth.

The landfill, operating since the early-mid 1960s and initially constructed with no containment system in place, was undergoing a reclamation phase involving mining and processing of the in situ waste and construction of a composite geosynthetic liner to effectively contain the waste. Processing of the in situ waste involved screening the material to separate the fine grained material passing a 50 mm sieve screener (fines) from the larger material retained on the 50 mm sieve (overs). Fines from screening operations were used as daily cover over the waste screening overs and incoming municipal solid waste as required.

The composition of material landfilled in 2013 (by volume) consisted of roughly 52% processed waste that had already experienced some degree of biological degradation, 15% daily cover soil, and 33% fresh city waste (Golder, 2014). Due to the small fraction of fresh municipal solid waste being landfilled, the component of waste settlement due to degradation of the waste is expected to be less than if the majority of the landfilled material was fresh municipal solid
waste. This may have important implications on the investigation conducted since displacements of the lining components along the side slope after waste placement are expected to be largely controlled by the down-slope shear stresses from waste settlement.

4.3 Instrumentation

The requirements for instrumentation selected for side slope monitoring was based on: i) suitability for interaction with the landfill environment, ii) provision of accurate and reliable data over its intended service life (at least several years), and iii) negligible impact on liner performance. The instruments chosen were also simple to install, use, and required no maintenance after installation since access to the instruments would be difficult, if not impossible, when covered by the overlying leachate collection system and eventually waste. Instrumentation used for building the landfill side slope monitoring system and the parameters they measure are shown in the Table 4.2.

4.3.1 Location

The proposed instrumentation was installed along the north slope as illustrated in Fig. 4.2. The northern side slope of the landfill cell was chosen such that a measuring station could be installed at the slope crest with minimal disturbances from landfill operations such as equipment traffic. The instrument location on the north slope was selected to minimize impacts on liner deformation from the temporary anchor trench along the east edge of the slope and from the corner of the cell on the west side as shown in Fig. 4.2. The east slope anchor trench restricted the geomembrane from downslope and cross-slope movements during placement of gravel along the slope and therefore acted as a zero-displacement boundary condition during construction. When installing the adjacent cell to the east, after waste had already been placed in the cell
shown in Fig. 4.2, the anchor trench was removed and the geomembranes from both cells were seamed together, thereby eliminating the zero-displacement boundary condition for future waste placement. Fig. 4.3 presents the location of each instrument installed along the slope.

4.3.2 Thermocouples

The long-term geomembrane temperature profile is of interest as it is a key factor in waste degradation and predicting geomembrane service life (Rowe et al. 2004, Rowe and Islam 2009). Additionally, due to the temperature sensitivity and the range of temperatures experienced by the steel wire extensometers, there was a need to measure temperature at regular intervals along the slope. Omega Type T thermocouples rated over a temperature range of -270 to 250°C with an accuracy of ±0.5°C were selected. The entire length of the thermocouple including the sensor tips were hermetically sealed with a fluorocarbon based polymer to provide continuous protection and resistance over the measurement junction to harsh chemicals. To attain detailed spatial and progressive temperature information along the slope, thermocouples were placed on the top surface of the geomembrane at 11, 22, 33, 44, and 55 m along the slope, and one thermocouple was installed at the base of the landfill (2 m from the toe of the slope), as shown in Fig. 4.3. All 6 thermocouple wires were threaded through a 50 mm diameter PVC conduit that extended continuously from the slope crest to base. Small incisions were drilled into the side of the PVC conduit at each thermocouples location along the slope to exit the ends of the sensors and place them onto the geomembrane surface. For supplemental protection to physical damage, the sensor tips were enclosed in a 150-mm-long, 5-mm-diameter stainless steel protection tube.
4.3.3 Extensometers

A 1.5-mm-diameter, seven-strand stainless steel wire (2.1 kN breaking strength) was used for the extensometers. These extensometers monitor the movement of a specific point relative to a common measuring table and were installed at different locations along the slope on the geomembrane, geogrid, and on gravel particles located at the bottom of the leachate collection gravel layer. By attaching extensometers to different lining components at the same location along the slope, the differential displacement can be obtained at a specific location. Extensometers also allow an approximate calculation of strain between any two measurement points.

The coefficient of linear thermal expansion of the steel wire was experimentally determined to be 21 μm/m/°C. It was found by heating a 2-m-long steel wire specimen in 3°C increments from 0 to 60°C in a temperature controlled chamber while measuring the elongation of the wire with a dial gauge to an accuracy of ±0.005 mm. The relationship was linear within the temperature range tested which encompasses the majority of temperatures experienced by the extensometers in the field. In order to apply a temperature correction factor, temperature data received from thermocouples placed above the geomembrane were assumed to be close to the temperature of the extensometers above the geomembrane and therefore, were used to estimate the average temperature of each extensometer cable. At times, the extensometers were exposed to a range of different temperatures along their length including partially covered by gravel and partially covered by gravel and waste, making it difficult to quantify the actual temperature of the wire to a high degree of accuracy. Therefore, the measurement accuracy of the extensometer sensors depends on the stage of construction and the length of the sensor. During construction of the gravel drainage layer, it is estimated that the accuracy in measuring the temperature of an 11
and 55 m long extensometer wire was approximately ±3 and ±5°C respectively. These
temperature changes correspond to a change in wire length of ±0.7 and ±5.8 mm. Therefore, the
measurement error of the 11 m and 55 m long extensometer instruments (which includes the ±0.5
mm error of the measuring station scale) would be about ±1 and ±6 mm respectively. During the
waste placement phase, the estimated accuracy in measuring the temperature of an 11 and 55 m
long wire was approximately ±2 and ±4°C respectively. The ability to estimate wire temperature
to a greater accuracy during waste placement was due to greater stability in temperature readings
once the slope was covered with a layer of gravel and partly covered with waste. These
temperature changes correspond to a change in wire length of ±0.5 and ±4.6 mm, which result in
a measurement error of about ±1 and ±5 mm respectively. Other unquantifiable possible sources
of error could include measuring station shifting and horizontal shifting (e.g., swaying) of the
extensometer conduits across the slope (which would register as downslope movement).

Each extensometer cable was attached at one end to the lining system element and the
other end ran to the top of the slope through a 12-mm-diameter PVC conduit to the measuring
table. The measuring table consists of a system of pulleys that the wires were run through and
lightly tensioned by an individual 0.5 kg weight. Five geomembrane extensometers were
installed in the field at locations along the slope measured from the crest of 11, 22, 33, 44, and
55 m after the geomembrane was deployed (Fig. 4.3). A small (0.2 m cross-slope by 0.15 m
downslope) geomembrane flap was extrusion welded onto the top surface of the geomembrane
so that the extensometer could be securely fixed without damaging the primary geomembrane
liner. The extensometer wire was attached to the flap by fastening a bolt firmly onto the flap with
the wire weaving through a series of washers as shown in Fig. 4.4a. A piece of geotextile was
placed beneath each geomembrane flap to prevent puncture of the primary liner from the bolt
head. To minimize lateral shifting of the PVC conduits, thin strips of geomembrane were extrusion welded onto the liner above each conduit at approximately 10 m intervals along the slope shown in Fig. 4.4b.

Geogrid A was used across the north slope. Following deployment of the geogrid, four extensometers were installed at 5, 11, 22, and 33 m along the slope measured from the crest (Fig. 4.3). The extensometer wire was attached to the geogrid by looping the wire through the grid and closing the loop with an aluminum sleeve as shown in Fig. 4.5. The PVC conduits of the geogrid extensometers were zip-tied to the geogrid at 5 m intervals along the slope to prevent horizontal shifting of the instruments during construction of the overlying leachate collection gravel layer.

Extensometers were installed in the leachate collection gravel by coring a small hole through a single 50 mm gravel particle to slip the wire through and was secured on the other side with an aluminum sleeve as shown in Fig. 4.6. Five gravel extensometers were installed at the same locations as the geomembrane extensometers (Fig. 4.3). As the placement of gravel advanced upslope from the base, the individual gravel particles attached to the extensometer wires were placed at their respective locations on the top surface of the geogrid and were hand backfilled with a bucket of gravel to prevent shifting of the extensometer during placement of gravel by the dozer as shown in Fig. 4.6. The PVC conduits of the gravel extensometers were also zip-tied to the geogrid at 5 m intervals along the slope to prevent horizontal shifting of the instruments.

4.3.4 Cable potentiometers

Cable potentiometers were selected to provide a direct measurement of the relative displacement between the geomembrane and gravel along the side slope. The sensor consists of a robust 65-mm-diameter and 140-mm-long stainless steel drum (which houses the electrical
components) that sits on top of the geogrid as part of the leachate collection gravel and has a 254 mm draw cable that is fixed onto the geomembranes surface which measures the differential movement as the sensor translates along the slope with the gravel (Fig. 4.7). The sensors chosen had sufficient ingress protection to debris and the prolonged effects of immersion in water under pressure and was not temperature sensitive. The accuracy of the instrument is ±0.5 mm at full stroke.

Three cable potentiometers were installed at 22, 33, and 44 m from the top of the slope on the same geomembrane flaps used for the geomembrane extensometers (Fig. 4.3). Prior to deploying the geotextile above the geomembrane, a bolt was fixed onto the geomembrane flaps with a 150-mm-long wire secured to the bolt by weaving and tightening the wire through a series of washers (see Fig. 4.4 and 4.7). The cable potentiometers were installed immediately after placement of the leachate collection gravel to prevent any potential damage to the instruments from dynamic forces of the traversing dozer up and down the slope. The gravel was hand excavated following placement to expose each geomembrane flap. A small incision was made into the geotextile just enough to pull the 150 mm wire out from underneath the geotextile in order to attach the draw cable from the sensor. The sensors were placed directly at the gravel and geogrid interface before backfilling with gravel and the instrumentation wire of each sensor was run to the top of the slope through a PVC conduit as shown in Fig. 4.7.

4.3.5 Monitoring station

The extensometer measuring table was installed after the composite liner was fully constructed and the anchor trench at the slope crest was backfilled and compacted. During installation of the extensometers on the geomembrane and geogrid, the extensometer wires were temporarily tied off to a stake at the top of the slope until the measuring table was built. Fig. 4.8
shows the fully constructed extensometer measuring table, which was modelled after one constructed by Zamara et al. (2008). The measuring table was secured with 10 stakes driven to the bottom of the anchor trench. A protective cover was used above the station when readings were not being taken and the thermocouple and cable potentiometer instrumentation wires were stored beneath the measuring table.

4.4 Results during placement of leachate collection system gravel

Installation of the leachate collection gravel above the sensors on the north slope took place from July 9 to July 13, 2013. Construction across the entire north and west slope was fully completed by July 17, 2013. The leachate collection gravel was installed in one continuous layer to the top of the slope and was placed using a low ground pressure dozer (CAT D6R, 34 kPa track pressure) fitted with a global positioning system on a standard spreading blade. The dozer pushed gravel upslope in a 0.6-m-thick lift to approximately midway up the slope and then thinned the 0.6 m lift up the remainder of the slope to achieve a final thickness of 0.3 m across the entire slope length.

Monitoring of temperature and extensometer displacements began July 9, 2013 at the onset of gravel placement. Extensometers on the geomembrane and geogrid were operational prior to commencement of gravel placement and the extensometers in the gravel were installed as gravel placement progressed upslope. One observation made onsite during gravel placement was that the majority of extensometer displacements in the geogrid and within the leachate collection gravel occurred when the dozer travelled above or adjacent to the installed sensors. This was realized by visually observing large extensometer displacements on the measuring table only in the sensors that the dozer was travelling near. For instance, as the dozer traversed upslope starting from the base, displacements would first be observed in the geogrid and gravel.
extensometers located 55 m from the slope crest. As the dozer advanced to a location 44 m from the crest, only displacements in the sensors at this location experienced movement while the adjacent sensors at 55 m and 33 m were not significantly influenced. These large displacements caused by the dozer spreading technique were observed to be a function of travel speed, dynamic pressure, and spinning of the dozer tracks while travelling upslope. The grain size and angularity of the gravel used may have exacerbated the shear displacements of the geosynthetic materials as the shear stresses (caused by shearing of gravel at the surface by the dozer) could transfer more through the large interlocking granular material relative to a smaller grain size or more rounded material.

4.4.1 Displacement

Measurements from the extensometers reveal relatively small movements in the geomembrane (< 35 mm) and large movements in the geotextile, geogrid, and gravel (up to 425 mm) during gravel placement. Fig. 4.9 presents the geomembrane, geogrid and gravel extensometer movements at the sensor locations along the slope as placement of gravel progressed upslope. All extensometer data reported has been adjusted for temperature effects.

4.4.1.1 Geomembrane displacements

In Fig. 4.9a, gradual downslope movements between 1-10 mm occurred in the geomembrane once the 0.6-m-thick layer of gravel was placed on the bottom half of the slope. On July 13, 2013, gravel on the bottom half of the slope was thinned out over a 3 hour period by spreading the upper 0.3 m of gravel onto the upper half of the slope. This accelerated the downslope movement of the geomembrane along the entire slope. All of the extensometers were covered with gravel by July 13. The dozer continued to travel on and around the sensors up until
July 17 when construction of the leachate collection gravel layer on the north and west slope was fully completed. Placement of the gravel caused an overall 31 mm downslope displacement near the toe of the slope, 16-21 mm within the middle parts of the slope, and 13 mm near the crest. Fluctuations in the extensometer readings observed in Fig. 4.9a are likely due to the thermal contraction and expansion of the geosynthetic elements themselves prior to being covered, although there may also be error in measuring the exact temperature of the steel wire to account for thermal effects (e.g., for an 11 and 55 m wire, the measurement error could be approximately ±1 and ±5 mm respectively). Upslope movements in geomembrane extensometers during gravel placement were detected at times due to geomembrane slack being pushed upslope as the gravel layer progressed upslope. For instance, a large upslope movement of 10 mm was detected in the geomembrane extensometer at 44 m from the crest immediately after the gravel layer covered the instruments on July 10 as shown in Fig. 4.9a. Fig. 4.10 shows evidence of geomembrane slack propagating in front of the gravel layer (labelled as wrinkles in Fig. 4.10) just before the gravel covered the instruments at 44 m from the top of the slope. This slack could be part of the reason why upslope geomembrane displacements were generally detected the following morning when the liner cooled and contracted upslope, recovering some of the slack.

4.4.1.2 Geogrid displacements

Downslope movements between 21-42 mm occurred in the geogrid after placement of gravel on the bottom half of the slope, shown in Fig. 4.9b, with the smallest displacements occurring at the slope crest and displacements becoming progressively larger towards mid-slope. Spreading of gravel on the upper half of the slope caused a sizeable downslope displacement at all geogrid measurement locations with the smallest displacement of 88 mm recorded near the
top of the slope and largest displacement of 248 mm occurring mid-slope following completion of gravel placement on July 17.

4.4.1.3 Gravel displacements

The largest movements detected on the slope were within the leachate collection gravel as shown in Fig. 4.9c. Gravel extensometers at 55 and 44 m were installed on July 10 and July 11 as gravel was slowly pushed upslope and only small movements of 26 and 7 mm were detected respectively, up until July 13. During gravel placement on the upper half of the slope on July 13, the remaining extensometers were installed and experienced considerable downslope movements between 176-233 mm with displacements increasing from the top to the bottom of the slope. Large movements were also detected (especially on the lower portion of the slope) on July 16 as the dozer continuously travelled primarily on the bottom half of the slope, where the sensors were located, to spread gravel onto other portions of the north slope. After completion of gravel placement on July 17, extensometers near the top of the slope displaced a total of 209 mm with increasing displacements occurring downslope to a maximum of 421 mm near the base of the slope.

4.4.2 Relative displacements

4.4.2.1 Leachate collection gravel and geomembrane

During construction of the leachate collection gravel layer, relative displacements between the gravel and geomembrane were found using extensometer measurements on each of the elements at the same location along the slope. The relative downslope displacement of gravel (directly above the geogrid) over the underlying geomembrane during gravel placement is presented in Fig. 4.11a. Due to the small movements in the geomembrane and the relatively large
movements experienced by the gravel, the relative displacements between the two components were substantial. Large relative movements between 170-215 mm along the slope occurred on July 13 during placement of gravel onto the upper half of the slope and the total relative movements at the end of construction were between 200-395 mm on July 17. The smallest relative movements occurred at the top of the slope and became progressively larger towards the bottom of the slope. This seemingly large magnitude of relative movement occurred at a low normal stress of 0.3 to 0.6-m-thick of gravel and the construction equipment loading.

4.4.2.2 Leachate collection gravel and geogrid

The geogrid here was used as tensile reinforcement on the side slope to strengthen the geotextile and gravel interface and stabilize the overlying gravel from downslope displacements during construction. To assess the effectiveness of the geogrid during placement of gravel on the slope, the relative displacement between the gravel and geogrid was calculated and is presented in Fig. 4.11b. Extensometer data collected at 11, 22, and 33 m from the top of the slope show a cumulative relative displacement of gravel translating downslope over the geogrid of 137, 114 and 75 mm respectively on July 17. A conceivable explanation as to why the gravel translated further downslope relative to the geogrid instead of translating in unison is because of the construction technique used to place the gravel. The reaction force required by the dozer to push large quantities of gravel upslope is transferred through the tracks of the dozer to the top surface of the gravel layer. As the dozer pushes gravel upslope, the dozer track shoes (i.e., protruding steel track grips) were observed to sink into the top surface of the gravel and continuously slip backwards (i.e., downslope) as the dozer traversed upslope. Due to the angular shaped particles of the crushed 50 mm limestone gravel, the downslope stresses imposed by the dozer tracks are believed to transfer quite easily to the gravel directly above the geogrid (i.e., 0.3-m-deep).
causing movements at the interface. The extent of displacement experienced by gravel at the gravel and geogrid interface is believed to be a function of the track pressure, speed, number of passes, the amount of gravel pushed upslope, thickness of the gravel layer, characteristics of the gravel material and interface strength. A likely explanation for the greater differential movements between the gravel and geogrid near the top of the slope is because, by the time the gravel extensometer were installed at 11 m from the top of the slope, the geogrid had already moved 52 mm out of its total 124 mm at that same location; whereas when the gravel extensometer was installed at 33 m, the grid had only moved 66 mm of its total 248 mm at that location. Therefore, the geogrid was under a greater stress by the time the gravel was pushed up to 11 m from the top of the slope which resulted in less geogrid displacements at this stage of gravel placement.

4.4.2.3 Geotextile and geomembrane

Geotextile downslope displacements were tracked only before and after construction of the leachate collection gravel layer on the slope shown in Table 4.3. Following deployment of the geotextile, markings were made on the upper surface of the geotextile directly above the bolts that were fixed on the geomembrane flaps which were welded to the primary geomembrane liner directly beneath the geotextile. From the time of installation to before gravel placement, the geotextile moved downslope between 25-35 mm along the entire slope. Following gravel placement, the geotextile moved downslope between 100 and 285 mm between 22 and 44 m from the slope crest as measured in Table 4.3. Adjusting for the initial geotextile movements, the geotextile had travelled 45, 150 and 240 mm downslope relative to the geomembrane at 22, 33 and 44 m from the top of the slope respectively, during gravel placement. Jones and Dixon (1998) show that relative displacements under 5 mm are enough to mobilize peak friction angles
at a geotextile/textured geomembrane interface at a low stress level of 25 kPa and under 10 mm at a stress level up to 200 kPa. They also show the interface exhibits a high degree of strain softening with around 50% reduction of shear strength at displacements over 50 mm for both stress levels. Gilbert and Byrne (1996) attribute this strain softening behaviour to the mechanisms of fibre alignment (i.e., combing of the geotextile fibers by the texturing on the geomembrane) and pull-out and filament breakage of fibres in the geotextile. They also found polishing of the texturing on the geomembrane surface to have a significant strain-softening effect, however not particularly evident at the low normal stresses imposed during construction before waste placement. Therefore, the magnitude of such relative displacements measured on the slope appear to be sufficient to mobilize post-peak friction angles between the geomembrane and geotextile elements, especially along the bottom 2/3rd of the slope.

4.4.3 Geomembrane and geogrid strains

Strains in the geomembrane and geogrid, presented in Fig. 4.12, were found between each extensometer anchor point along the slope during gravel and waste placement. Following gravel placement on the slope, the maximum geomembrane strain was less than 0.2% near the bottom of the slope (Fig. 4.12a). At a location of 33 to 44 m from the crest, compression was calculated in the geomembrane which might be the result of geomembrane slack pushed upslope and/or thermal changes in the geomembrane during gravel placement as aforementioned. To date, geomembrane strains along most sections of the slope are below 0.05% with the largest strain of 0.2% occurring near the bottom of the slope, all of which are relatively low compared to the long-term allowable tensile strain limit of 3% for HDPE geomembranes proposed by Seeger and Muller (2003). Although the strains reported are crude (±0.05%) and could be compounded with
localized strain from overlying gravel indentations, they provide a sense of the global strain experienced by the material.

Strains calculated in the geogrid within the upper half of the slope during gravel and waste placement are presented in Fig. 4.12b. The geogrid developed a considerable amount of strain from placement of the overlying gravel layer, and did not change from subsequent waste placement activities to date. Strains within the geogrid ranged between 0.3 and 1.5% with the maximum strain occurring at the very top of the slope between the anchor trench and 5 m from the crest. These measured strains were well below the strain at ultimate force for geogrid A (see Table 4.1).

4.4.4 Survivability of geogrid

The impact of installation damage on geogrids in granular backfill has been shown to reduce the tensile strength of the geogrid (e.g., Lim and McCartney, 2013; Cho et al., 2001; Koerner and Koerner, 1990). The removal of geogrid specimens along the slope after gravel placement was not permitted, however an opportunity was given to excavate inspection pits to observe the condition of the geogrid. The geogrid was assessed at 6 locations on the 55-m-long west side slope after placement of the leachate collection gravel layer. 3 of the locations were located 8 m from the slope crest and 3 were located 25 m from the crest. One of the locations 25 m from the slope crest used geogrid A for reinforcement and the other five locations used geogrid B (see Table 4.1 for geogrid properties). Observation pits, approximately 0.8 m by 0.8 m were carefully hand excavated at each location to uncover the geogrid for visual inspection. The different mechanisms of physical damage visible to the naked eye are shown in Fig. 4.13. At all 6 locations, the observed physical damage included minor abrasion of the geogrid surface (i.e., scratching) and minor splitting (i.e., separation of stranded fibres) of the geogrid along the edges
of the tensile members as shown in Fig. 4.13a. At one of the geogrid-B locations 8 m from the slope crest, severe splitting of the geogrid localized around one aperture was found as shown in Fig. 4.13b. In the geogrid-A observation pit 25 m from the slope crest, two lateral warping features were observed in the geogrid (Fig. 4.13c) likely due to interlocking between the geogrid apertures and gravel particles during downslope displacement of the gravel from the construction process. All physical damage observed was assumed to be associated with the high contact stresses and particle rearrangement during gravel placement under construction equipment loading. Overall, the geogrid was effective in strengthening the interface properties and remained in relatively good condition post-backfill, thereby successfully serving its purpose as a reinforcing element during construction.

The condition of the geotextile was also visually inspected through the openings of the geogrid in each observation pit. Approximately 5-10 gravel indentations on the top surface of the geotextile were noticed at locations 8 m from the slope crest and 0-5 gravel indentations were observed at the locations 25 m from the slope crest. An example of a gravel indentation found in the geotextile is presented in Fig. 4.13d. Conceivably, the greater extent of geotextile indentations near the top of the slope could be a result of the difference in particle size distribution along the face of the slope.

Another observation made during gravel placement was the amount of fines and smaller sized gravel particles near the base of the slope compared to the top of the slope. As gravel was unloaded from rock trucks at the slope base and pushed upslope by the dozer, the vibrations and constant rearrangement of gravel particles caused the smaller sized particles to migrate downwards toward the geotextile surface. The further upslope the gravel was pushed, the less fines and smaller sized particles were carried upslope. As a result, the 3 observation pits located
near the top of the slope consisted mainly of larger sized gravel particles and minimal fines accumulated on the geotextile surface; whereas the 3 observation pits located near mid-slope contained a wider gradation of gravel particle sizes with the smaller sized particles accumulated near the surface of the geotextile. Consequently, larger sized gravel particles in contact with the geotextile near the top of the slope lead to greater contact stresses when loaded by the traversing dozer which can cause greater indentations in the geotextile at the contact points as was observed in this particular investigation.

4.5 Results during placement of waste

Waste placement began in September 2013 in lift thicknesses of 1-1.5 m and sloping towards the west at a 2H:1V incline. A chronological sequence of waste placement to date is presented in Fig. 4.14. Due to the location of the sensors on the north slope, the waste only covered the bottom 48 m of the slope, leaving 18 m of slope uncovered at the crest. By December 2013 the waste had already reached the highest part of the slope where the sensors were located (due to the east-west sloping waste mass) as seen in Fig. 4.14. Following construction of the adjacent cell to the east in May 2014, waste placement proceeded in June 2014 and has only recently reached the location of the uncovered sensors on the north slope.

4.5.1 Geomembrane temperature

Geomembrane temperatures along the slope and at the base of the landfill were recorded over the course of the field experiment and are presented in Fig. 4.15. The geomembrane temperature at 11 m from the top of the slope (Fig. 4.15a) remains uncovered with waste to date and shows the greatest fluctuations in temperature from the seasonal change from summer to winter of about 20-25°C. At 22 m from the slope crest (Fig. 4.15b), the geomembrane
temperature also experienced a seasonal change in temperature of about 25°C however did not
significantly cool in temperature during the winter of 2014 due to partial covering with waste.
The temperature of the geomembrane at the middle and bottom of the slope were not
significantly affected by seasonal ambient temperature changes, however did fluctuate between
25 and 40°C in the bottom half of the slope (Fig. 4.15d and 4.15e) possibly due to uneven
temperatures in the waste mass owing to variability of decomposition activity within the waste.
In Fig. 4.15f, the geomembrane temperature at the base of the landfill shows an increase from 20
to 40°C over a 1.6 year period, with the majority of the increase occurring after the first 6 months
of waste placement. This relatively quick increase in temperature at the base of the landfill was
an interesting finding in itself. Barone et al. (2000) reported geomembrane base liner
temperatures of up to 15°C at the Keele Valley landfill over a 7 year period at which point an
increase in leachate head to between 4.5 and 6.5 m caused a gradual increase in temperature to
between 30-40°C. At another landfill site in Pennsylvania where the geomembrane temperature
was monitored at the base of the landfill by Koerner and Koerner (2006) under 50 m of waste,
indicated that the temperature of the geomembrane was constant at 20°C over a 5 year period,
however, the temperature suddenly increased to 30°C over a hundred day period and slowly
increased to 35°C over the next 5 years. They attributed this rapid increase in temperature to the
beginning of waste degradation, resulting in warmer leachate, and thus warmer geomembrane
temperatures. Since leachate mounding at this early stage of waste placement is unlikely, the
reason for such rapid temperature increase could be due to the partially degraded waste getting
exposed to oxygen during the waste processing stages. Due to the greater efficiency of aerobic
respiration (Rowe et al., 2004), waste degradation can proceed more rapidly than the anaerobic
conditions which were more so present in the original landfill prior to mining the waste.
Therefore, since roughly half of the landfilled waste placed in the cell was already in the process of decomposition, waste decomposition almost immediately continued after placement and was likely exacerbated by the exposure to oxygen, thus, showing early signs of heat generation.

4.5.2 Displacement

Geomembrane and gravel extensometer data throughout the waste placement process is presented in Fig. 4.16. So far, the seasonal changes of temperature were observed to have more influence on material behaviour than the waste loading on the side slope, especially for sections of the slope that were not covered with waste. From August to December of 2013, when the ambient conditions began to cool, all geomembrane and gravel extensometers detected upslope movements along the entire slope with the largest upslope movements of 11 and 7 mm for the geomembrane and gravel respectively, occurring at 22 m from the top of the slope. As the waste height covered the bottom 1/3rd of the slope in November 2013, the geomembrane and gravel extensometers near the base of the slope shifted downslope in December 2013 by 10 and 2 mm respectively and have only experienced minor downslope movements since then. By December 2013, the waste location along the slope above the sensors remained constant. The warm ambient conditions in the following summer of 2014 caused minimal displacements in both the geomembrane and gravel extensometers between 11 and 44 m from the top of the slope. The following winter of 2014, only very small upslope displacements on the magnitude of 2-4 mm were detected in the geomembrane and gravel along the upper portion of the slope uncovered by waste.

The reason why upslope movements were detected mainly in parts of the geomembrane that have not been covered with waste during the cooler parts of the year (i.e., winter) could be due to the thermal contraction of the geomembrane and geogrid. This hypothesis would assume
that the anchor trench is a zero-displacement boundary, and the thermal contractive stresses upon cooling are large enough to overcome friction at the geomembrane interface, allowing upslope displacement. The gravel along the slope should not translate upslope by itself simply due to cold weather, and it is hard to imagine the waste placement operations being able to push gravel upslope against the forces of gravity. Therefore, it is a reasonable case for the contractive stresses in the geomembrane (as well as the geogrid) to be of sufficient magnitude from cooling up to 25-30°C in the winter, to generate upslope movements in the geomembrane itself as well as overlying gravel as the shear stresses are transferred through the geotextile in between. This could explain why the movements at each location along the slope are within the same range for the geomembrane and the gravel, with slightly more upslope movements consistently detected in the geomembrane.

4.5.3 Relative displacements

Relative movements between the gravel and geomembrane are of particular interest during waste placement and subsequent waste settlement as the gravel above the geomembrane will impose both normal and possibly downslope shear loading over time. To date, this relative displacement has been measured using extensometers and cable potentiometers. The cable potentiometer sensors were installed after construction of the leachate collection gravel and directly measure the relative movement between gravel particles and the geomembrane during waste placement shown in Fig. 4.17a. To date, similar results were found from the relative displacements calculated with individual extensometer readings shown in Fig. 4.17b. The cable potentiometer sensors show a 0.5, 1, and -2.5 mm relative downslope shear displacement of gravel above the geomembrane at 22, 33, and 44 m respectively, from the top of the slope over a 1.6 year period. Similarly, the extensometers calculate a 2, 3, and 0 mm relative downslope shear
displacement at 22, 33, and 44 m respectively. Although the difference in results are of a very small magnitude (within a few mm), the discrepancies might be a result of the poor accuracy of the extensometers to detect such small movements; especially for the extensometers with longer lengths as the temperature effects on the steel wire becomes difficult to account for. The measurement error should improve as the remainder of the slope gets covered with waste and the temperature along the slope stabilizes underneath the waste mass. The greater oscillation of displacement readings in the longer extensometers observed in Fig. 4.17b are a result of the lower precision achieved over such long distances. The cable potentiometers are not temperature sensitive and have shown consistent readings over the 1.6 year monitoring period.

4.5.4 Further work

The primary focus of the ongoing site investigation is to monitor insitu downslope displacements primarily in the geomembrane and gravel particles above the geomembrane. The increasing waste height and subsequent waste settlement may generate downslope shear stresses on the side slope which may generate further relative displacements between the gravel and geomembrane. If such relative displacements were to arise at high overburden stresses, tangential displacements of gravel particles above the geomembrane might impact tensile strains in the geomembrane from local gravel indentations. In terms of the geosynthetic clay liner, in addition to extrusion from non-uniform normal loading observed by Dickinson and Brachman (2010), it is hypothesized that bentonite extrusion under coarse gravel will be exacerbated by relative downslope movements. Gravel above the geomembrane imposes both normal and potentially downslope shear loading, however the magnitude of downslope loading at different intervals along the side slope remains uncertain. This data will be valuable to quantify in order to understand and assess the insitu loading conditions experienced by a composite geosynthetic
lining system on a slope. The impact of gravel indentations on a geomembrane and geosynthetic clay liner installed on a landfill based side slope is a potential concern that warrants study and development of a practical solution.

4.6 Conclusion

A 66-m-long, 3H:1V landfill side slope was successfully instrumented to monitor the in-service physical performance and interaction of geosynthetic lining elements during construction and waste placement. The ongoing field-scale experiment has provided an opportunity to quantify temperatures, tensile strains, displacements and relative displacements along the gravel, geogrid, geotextile and geomembrane interfaces using thermocouples, extensometers and cable potentiometer instrumentation.

Significant downslope displacements of the leachate collection gravel, geogrid, and geotextile lining elements have occurred in response to construction of the gravel layer with only minor displacements within the geomembrane; all of which experienced maximum displacement along the bottom portion of the slope. Placement of gravel has induced large relative displacements (up to 400 mm) between the gravel and underlying geomembrane, albeit at a low normal stress. Gravel placement has also generated large relative displacements between the geotextile and underlying geomembrane that are thought to be of sufficient magnitude to generate post peak interface shear strengths. This may have important design implications for the selection of appropriate interface strength parameters (i.e., peak or residual shear strength) used for slope stability analysis.

The integrity of the geogrid was assessed post-construction of the leachate collection gravel layer at 6 locations on the west side slope. Minor installation damage including abrasion, warping and splitting (i.e., separation of stranded fibers) was observed in the geogrid and one
severe localized tear was found. Overall, the geogrid remained in good condition and was effective in supporting the gravel along the face of the side-slope during gravel placement. To date, the waste has risen 48 m along the face of the north slope (16 m above the elevation of the base) where the sensors are located which has left 18 m of the slope surface uncovered. Placement of waste has generated only small (1-2 mm) relative displacements between the gravel and geomembrane and the maximum geomembrane tensile strain was measured to be under 0.2% after 1.6 years of monitoring. The majority of lining system movements during waste placement were mainly influenced by seasonal changes of temperature as opposed to loading from the waste. Geomembrane temperatures at the base of the landfill have reached up to 40°C over a short, 1.6 year period, which is thought to be the effect of oxygen entering the partially decomposed waste during the insitu waste mining, processing, and re-landfilling.
4.7 References


Table 4.1: Stress-strain properties of geogrids used, obtained following ASTM D6637

<table>
<thead>
<tr>
<th>Property</th>
<th>Machine direction</th>
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<th>Cross-machine direction</th>
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<td>GG-A</td>
<td>GG-B</td>
<td>GG-A</td>
<td>GG-B</td>
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<td>Aperture dimensions (mm)</td>
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<td>Ultimate tensile strength (kN/m)</td>
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<td>Tensile strength @ 5% strain (kN/m)</td>
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Table 4.2: Instrumentation and parameters measured by the side slope monitoring system

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<th>Instrument</th>
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<th>Measured Parameter</th>
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<td>Gravel</td>
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<td>Relative displacement between gravel and geomembrane</td>
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<td>geomembrane temperature along slope and base</td>
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<td></td>
<td>Waste height</td>
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Table 4.3: Geotextile displacements before and after placement of leachate collection gravel (dimensions in millimeters)

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<th>Date (dd/mm)</th>
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<th>GTX 22m</th>
<th>GTX 33m</th>
<th>GTX 44m</th>
<th>GTX 55m</th>
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<td>25</td>
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<td>195</td>
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Fig. 4.1. Cross-section of side slope liner components
Fig. 4.2. Photograph looking north at the base and side slopes of the landfill cell with the location of instrumentation taken May 14, 2013 at 1pm, air temperature 8°C
Fig. 4.3. Schematic view of instrument layout along the north slope
Fig. 4.4. a) Photograph looking upslope at geomembrane extensometer, and b) Photograph looking across the north slope at GMB extensometer PVC conduits secured with thin geomembrane strips onto the primary liner to prevent horizontal shifting.
Fig. 4.5. Photograph of geogrid extensometer
Fig. 4.6. Photograph of leachate collection gravel extensometer installation
Fig. 4.7. a) Photograph of cable potentiometer installation between geomembrane and leachate collection gravel, and b) Schematic of connection detail
Fig. 4.8. Photograph of extensometer measuring table
Fig. 4.9. Downslope displacement of a) geomembrane, b) geogrid, and c) gravel extensometers during d) construction of the leachate collection gravel layer.
Fig. 4.10. Photograph showing geomembrane slack pushed upslope as gravel placement progresses
Fig. 4.11. Relative displacement between a) gravel and geomembrane, and b) gravel and geogrid during c) construction of the leachate collection gravel layer
Fig. 4.12. a) Geomembrane strains, and b) geogrid strains calculated from extensometer displacements during c) gravel and waste placement
Fig. 4.13. Examples of physical damage including a) minor splitting, b) severe splitting, and c) warping observed in the geogrid; and d) gravel indentation in the geotextile after placement of gravel along the west slope
Fig. 4.14. Schematic view of sequential waste placement (month/year)
Fig. 4.15. Geomembrane surface temperatures recorded along the side slope and base of the landfill over a 1.6 year period
Fig. 4.16. Displacement of a) geomembrane, and b) gravel extensometers during c) gravel and waste placement.
Fig. 4.17. Relative displacement between gravel and geomembrane measured from a) cable potentiometers, and b) extensometer data during c) waste placement
Chapter 5

Summary

5.1 Summary

In this theses, two physical issues including the fate of geomembrane wrinkles and downslope shear deformations – both of which need consideration to obtain successful long-term geomembrane liner performance – were examined.

5.1.1 Geomembrane wrinkles

At the field scale, the fate of wrinkles during construction of a sand cover protection layer was investigated for a 1.5-mm-thick, black, high-density polyethylene (HDPE) geomembrane. The primary factors influencing the fate of wrinkles were found to be the different construction equipment and cover soil placement techniques deployed by the contractor, and the change in geomembrane surface temperature upon backfill. As was expected, wrinkles were found to exist post-backfill beneath the cover soil. Despite well intentioned techniques employed by the earthworks contractor to reduce wrinkling during the backfill process, wrinkles often remained entombed within the backfill. In many cases where the contractor tried to cover individual wrinkles when smaller in size, with the presumption that smaller wrinkles may “go-away”, wrinkles were often shifted out from underneath the cover soil, forming a new wrinkle and amalgamation with others in the uncovered liner.

A wrinkle free installation may be more expensive and require additional planning, but perhaps the easiest and most practical solutions to reduce the extent of wrinkles buried beneath cover soil are: i) Timely placement of cover soil during the coolest times of the day (e.g., early in the morning or late afternoon) when the extent of geomembrane wrinkling is at its lowest
(Bonaparte et al. 2002; Rowe et al. 2004; Chappel et al. 2011; Koerner and Koerner 2013). ii) Have geosynthetic installation and soil cover placement proceed together rather than installing large amounts of the geosynthetics followed by separate placement of large amounts of cover soil. This way, spreading of the cover soil could be used to push wrinkles towards a nearby unseamed edge of the geomembrane, attaining intimate contact between the geomembrane and subgrade without the accumulation of a very large wrinkle in the direction of soil spreading. Both approaches would require proper coordination amongst the engineer, geosynthetic installer and earthworks contractor.

After identifying the geometry of wrinkles found to exist beneath a soil cover layer in the field, a laboratory study was conducted to investigate the ultimate fate of the wrinkle and gap beneath the wrinkle under additional overburden pressures expected to exist at the base of a landfill after waste placement. The influence of post-backfill wrinkle size (based on field cover soil placement technique), applied pressure, and subgrade material on wrinkle deformations and the fate of the gap beneath the wrinkle were investigated. It was found that wrinkles did not return to a flat condition even for a very small 3-mm-high and 55-mm-wide post-backfill wrinkle due to the high stiffness of the geomembrane wrinkle and vertical deformations in the subgrade beside the wrinkle preventing the wrinkle feature from achieving a height of zero. For the case of a hydrated geosynthetic clay liner subgrade, the gap beneath a 10-mm-high and 55-mm-wide wrinkle was completely eliminated at 1000 kPa overburden pressure due to downward wrinkle deformations and settlement, and extrusion of bentonite into the gap. This particular wrinkle height was on the lower end of post-backfill wrinkle heights observed beneath the cover soil in the field, and therefore, for the case of a geomembrane and geosynthetic clay liner, composite liner action may not be fully realised for most of the wrinkles that remain post-backfill.
Therefore, there is a great need to reduce the amount of wrinkles buried in the field because the wrinkles that remain post-backfill will not “go away” under additional loading, and in many cases, neither will the gap beneath the wrinkle unless placed above a more compressible subgrade such as a compacted clay liner.

5.1.2 Downslope displacements of a geosynthetic lining system

A field study was initiated to quantify downslope movements in a geosynthetic lining system. A section along a 66-m-long, 3H:1V landfill side slope was monitored using instrumentation to measure displacements within and between the lining elements during construction of an overlying gravel drainage layer and subsequent waste placement. As expected, the geosynthetic lining system performed well during construction and throughout waste placement. During construction of the drainage gravel layer, relative displacements between the geotextile and geomembrane were measured between 45 and 240 mm within the middle half of the slope which is believed to be of sufficient magnitude to mobilize post-peak friction angles during construction. Large relative downslope displacements of up to 200 and 395 mm between the gravel and geomembrane were measured during gravel placement. The physical condition of the geogrid after placement of gravel was inspected and only minor damage was found. Placement of waste (to-date 2/3rd up slope) has generated only small (1-2 mm) relative displacements between the gravel and geomembrane and movements will be continuously monitored as waste placement progresses and subsequent waste settlement occurs. This data will provide insight into the insitu loading conditions experienced by the geomembrane from the overlying gravel as the gravel particles impose both normal and tangential deformations to the geomembrane. This possible loading condition has not yet been considered in geomembrane and geosynthetic clay liner protection which may be important for the coarse gravel used as a
leachate drainage layer in Ontario. Therefore the magnitude of relative displacement is of importance to quantify. The geomembrane tensile strains were measured to be under 0.2% and the temperature at the base of the landfill has reached a maximum of 40°C after 1.6 years of monitoring.
5.1.3 References


Koerner, R. M. & Koerner, G. R. 2013. The intimate contact issue of field placed geomembranes with respect to wave (or wrinkle) management. Geosynthetic Institute, GSI White Paper #27.