HYDRAULIC PERFORMANCE OF GEOSYNTHETIC LINERS IN LANDFILLS AND TAILINGS STORAGE FACILITIES

by

Prabeen Joshi

A thesis submitted to the Department of Civil Engineering
In conformity with the requirements for
the degree of Doctor of Philosophy

Queen’s University
Kingston, Ontario, Canada
(April, 2016)

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Dedication

This work is dedicated to my uncle, Late. Mr. Bamdev Joshi.
Abstract

The effects of holes in a geomembrane on leakage through the base liner of a modern municipal solid waste and mine tailings storage facilities was examined.

First, the performance of overlapped seams below a geomembrane wrinkle was evaluated for seven geosynthetic clay liners (GCLs; three requiring and four not requiring field-applied supplemental bentonite at the longitudinal seam). For seams parallel to a wrinkle, the performance depended on the width of the seam relative to the wrinkle. With both ends of the seam confined under vertical stress from the deformed wrinkle, there was no evidence of flow along the seam. For seams perpendicular to a wrinkle, it was observed that the availability and distribution of seam bentonite, needle-punching pattern of the GCL, applied vertical stress, and GCL type can all significantly affect the flow along the unstressed section of the seam. With 400 g/m of supplemental bentonite piled along the centre of the seam, the effect of having a wrinkle on flow was largely reduced to a point where the leakage was no larger than that through a single panel of GCL.

Second, leakage through geomembrane holes in a mine tailings configuration was examined for three silty-sand tailings and four underliners (underliners ranging from silty-sand to pea gravel). The effect of different tailings, different underliners, different geomembrane type and thickness, different hole sizes, different applied stresses and heads, a nonwoven geotextile cushioning layer, and gap beneath a geomembrane hole (due to a wrinkle or stone on the foundation) on leakage are reported. The hydraulic conductivity of the tailings had largest effect on flow with a maximum measured flow (without piping) of 8.5 lpd for the cases examined. Free-flowing tailings slurry or that migrating under the applied hydraulic gradient filled any gaps beneath the geomembrane hole. There was evidence of fines migration from the tailings, through the hole, and to the underliner or geotextile. Although there was no effect of geomembrane thickness on
flow, the 1-mm-thick geomembrane wrinkles were deformed to an extent that the inner sides were in contact at an applied stress of 250kPa, inducing excessive stains in the geomembrane.
Co-Authorship


R.W.I. Brachman, P. Joshi, and R.K. Rowe

Accepted for publication in ASCE's Journal of Geotechnical and Geoenvironmental Engineering.

Contributions:

R.W.I. Brachman: initiated the project; assisted in developing the test method; contributed to the selection of the geosynthetic clay liner products; supervised the laboratory tests; assisted in data analysis and interpretation; played a key role in preparing the journal paper.

P. Joshi: developed the test method; performed all laboratory experiments; organized and interpreted the test data; conducted all finite-element seepage analysis; wrote the first draft of the journal paper.

R.K. Rowe: initiated the project; assisted in developing the test method; contributed to the selection of the geosynthetic clay liner products; supervised the laboratory tests; assisted in finite-element seepage analysis; assisted in data analysis and interpretation; reviewed the final draft of the journal paper.

Chapter 3: Hydraulic performance of GCL seams without field-applied supplemental bentonite below a geomembrane wrinkle.

P. Joshi, R.W.I. Brachman, and R.K. Rowe

Under internal review by CETCO® and NAUE GmbH & Co. KG, will be submitted to Journal of Geotechnical and Geoenvironmental Engineering.

Contributions:
P. Joshi: developed the test method; performed all laboratory experiments; organized and interpreted the test data; conducted all finite-element seepage analysis; wrote the first draft of the manuscript.

R.W.I. Brachman: initiated the project; assisted in developing the test method; contributed to the selection of the geosynthetic clay liner products; supervised the laboratory tests; assisted in data analysis and interpretation; assisted in editing the manuscript.

R.K. Rowe: initiated the project; assisted in developing the test method; contributed to the selection of the geosynthetic clay liner products; supervised the laboratory tests; assisted in data analysis and interpretation; assisted in finite-element seepage analysis; reviewed the final draft of the manuscript.

Chapter 4: A new laboratory apparatus for measuring leakage through geomembrane holes beneath mine tailings.

R.W.I. Brachman, P. Joshi, and R.K. Rowe

To be submitted to the Canadian Geotechnical Journal.

Contributions:

R.W.I. Brachman: initiated the project; assisted in developing the test method; supervised the laboratory tests; assisted in data analysis and interpretation; assisted in finite-element seepage analysis; assisted in preparing the manuscript.

P. Joshi: developed the test apparatus and test method; performed all laboratory experiments; conducted all finite-element seepage analysis; organized and interpreted the test data; wrote the first draft of the manuscript.
R.K. Rowe: initiated the project; supervised the laboratory tests; reviewed the final draft of the manuscript.

**Chapter 5: Leakage through holes in geomembranes below saturated fine tailings.**

R.K. Rowe, P. Joshi, and R.W.I. Brachman

Submitted to ASCE’s *Journal of Geotechnical and Geoenvironmental Engineering*, in review.

**Contributions:**

R.K. Rowe: initiated the project; contributed to the selection of the tested materials; supervised the laboratory tests; assisted in finite-element seepage analysis; played a key role in the interpretation of the data; wrote much of the final version of the journal paper.

P. Joshi: developed the test apparatus and test method; performed all laboratory experiments; organized and interpreted the test data; conducted all finite-element seepage analysis; wrote the first draft of the journal paper; assisted in editing the journal paper.

R.W.I. Brachman: initiated the project; assisted in developing the test method; supervised the laboratory tests; assisted in data analysis and interpretation; reviewed the final draft of the journal paper.

**Chapter 6: Physical and hydraulic response of geomembrane wrinkles underlying saturated fine tailings.**

P. Joshi, R.K. Rowe, and R.W.I. Brachman

Submitted to the *Geosynthetics International*, in review.

**Contributions:**

P. Joshi: developed the test apparatus and test method; performed all laboratory experiments; organized and interpreted the test data; wrote the first draft of the journal paper.
R.K. Rowe: initiated the project; contributed to the selection of the tested materials; assisted in developing the test method; supervised the laboratory tests; played a key role in interpretation of data and writing of the final version of the journal paper.

R.W.I. Brachman: initiated the project; assisted in developing the test method; supervised the laboratory tests; assisted in data analysis and interpretation; reviewed the final draft of the journal paper.

In addition to the manuscripts that make up the thesis, the following conference papers have been published pertaining to the work described herein.


Acknowledgements

I am thankful to my supervisors, Kerry Rowe and Richard Brachman for their teaching, guidance and encouragement throughout my time at Queen’s. I started with a limited knowledge in geosynthetic liner technology and I feel I am leaving with a great deal of scientific understanding not only of geosynthetics but also of geotechnical and geoenvironmental engineering in general. The life lessons that I learnt from you will guide me throughout the rest of my life.

I thank Profs. Richard Bathurst, Heather Jamieson, Ian Moore, Kevin Mumford, Greg Siemens and Andy Take at the Geo-Engineering Centre at Queen’s-RMC for their encouragement and for sharing practical knowledge through personal communication and general course works. I am grateful for the continuous support and encouragement provided by Dr. Santosh Rimal. Thank you Dr. Simon Gudina for helping me take baby steps towards the GLLS world.

Special thanks to the industry partners from CETCO®, KCB, Naue GmbH & Co. KG, TAG Environmental Inc. and TERRAFIX® for their inputs throughout the research period which definitely added value to the work.

Thanks to the staffs of Department of Civil Engineering for assistance with the laboratory work. Special thanks to Maxine and Cory. Without my friends, Huma, Bipin, Hakan, Judi, Michael, Lauren, Ryan, Kevin, Pooneh, Yan, Hosney, Fady, Amr, Amy, Dan, Ramy, Shoaib, Ahmed, Vanessa, Anil and many others, life at Queen’s would not have been same.

The financial support provided by STEWARD, NSERC, CFI and the industry partners helped financing the research and my stay. This work would not have been possible without your support so I thank you.
I owe my utmost respect to my parents and love to my sisters who supported my every move, their strong support and motivation led me this far.

Finally to my wife Kinta whose support and encouragement has been driving me for the last number of years towards a successful and happy future together. Thank you for being there for me.
# Table of Contents

Abstract.................................................................................................................................iii
Co-Authorship ........................................................................................................................v
Acknowledgements ..............................................................................................................ix
Table of Contents ..................................................................................................................xi
List of Figures ......................................................................................................................xviii
List of Tables .........................................................................................................................xxiv
List of Abbreviations and Notations ....................................................................................xxv
Glossary .................................................................................................................................xxvii

Chapter 1 Introduction .........................................................................................................1
  1.1 Problem definition .......................................................................................................1
  1.2 Scope and objective of the thesis ..............................................................................2
    1.2.1 Leakage through overlapped GCL seams subjected to non-uniform stresses .......2
    1.2.2 Leakage through holes in geomembrane in mine tailings storage facilities .......3
  1.3 Thesis outline .............................................................................................................3
  1.4 Original contribution ...............................................................................................5
  1.5 References ................................................................................................................7

Chapter 2 Hydraulic performance of overlapped Geosynthetic Clay Liner seams requiring field-applied supplemental bentonite ................................................................................9
  2.1 Introduction ..............................................................................................................9
  2.2 Method ....................................................................................................................12
  2.3 Results and discussion .........................................................................................14
    2.3.1 GCL panel with no seam beneath a wrinkle ....................................................14
    2.3.2 GCL seam parallel to wrinkle .......................................................................16
    2.3.3 GCL seam perpendicular to the wrinkle .......................................................19
      2.3.3.1 Perpendicular base case .......................................................................19
      2.3.3.2 GCL seam without supplemental bentonite ........................................19
      2.3.3.3 150 mm wide GCL seam with piled supplemental bentonite ...............20
      2.3.3.4 300 mm wide GCL seam with piled supplemental bentonite ..........22
      2.3.3.5 Seam with evenly distributed supplemental bentonite .......................23
    2.3.4 Effect of GCL type .......................................................................................24
4.3.1.2 Silt above the geomembrane ................................................................. 98
4.3.2 Hydraulic conductivity of the tested overliner and underliner ......................... 99
4.3.3 Explaining observed flow rates using a FEM .............................................. 99
4.4 Other factors affecting flow through geomembrane hole .................................. 101
  4.4.1 Effect of underliner $k$ .............................................................................. 102
  4.4.2 Flow through larger geomembrane holes .................................................. 102
4.5 Summary and conclusions .............................................................................. 103
4.6 References ....................................................................................................... 105

Chapter 5 Leakage through holes in geomembranes below saturated fine tailings ...... 118
5.1 Introduction ....................................................................................................... 118
5.2 Experimental investigation ............................................................................... 120
  5.2.1 Materials .................................................................................................... 120
  5.2.2 Test apparatus and method ....................................................................... 121
  5.2.3 Hydraulic conductivity measurement ....................................................... 124
5.3 Results and discussion .................................................................................... 124
  5.3.1 Base case .................................................................................................. 124
  5.3.2 Effect of stress path .................................................................................. 125
  5.3.3 Influence of material properties on leakage through geomembrane hole ....... 125
    5.3.3.1 Hydraulic conductivity of tailings ....................................................... 125
    5.3.3.2 Effect of underliner hydraulic conductivity ....................................... 126
    5.3.3.3 Effect of geomembrane type and thickness ....................................... 128
  5.3.4 Effect of geomembrane hole size .............................................................. 128
  5.3.5 Effect of a transmissive layer between tailings and geomembrane ............... 129
  5.3.6 Effect of effective stress ........................................................................... 129
  5.3.7 Gap beneath a geomembrane hole due to a stone .................................... 131
  5.3.8 Migration of fines ..................................................................................... 132
5.4 Numerical modelling ....................................................................................... 133
  5.4.1 Effect of geomembrane on flow ............................................................... 133
  5.4.2 Effect of underliner $k$ .............................................................................. 133
  5.4.3 Explaining observed flow rates using a numerical model ......................... 134
  5.4.4 Predictive modelling .................................................................................. 136
    5.4.4.1 Effect of geomembrane hole size ....................................................... 138
Chapter 6 Physical and hydraulic response of geomembrane wrinkles underlying saturated fine tailings

6.1 Introduction ........................................................................................................... 159
6.2 Experimental details ................................................................................................. 162
  6.2.1 Apparatus and boundary conditions .................................................................. 162
  6.2.2 Materials and test procedure ............................................................................ 162
6.3 Results ..................................................................................................................... 166
  6.3.1 Physical response of geomembrane wrinkles under applied vertical stresses ...... 166
    6.3.1.1 1-mm-thick geomembranes ........................................................................ 166
    6.3.1.2 2-mm-thick geomembranes ........................................................................ 168
  6.3.2 Leakage through 10-mm-diameter holes on geomembrane wrinkle ................. 169
    6.3.2.1 Hole at the base of the wrinkle after tailings consolidation ......................... 169
    6.3.2.2 Hole formed on the top-side of the wrinkle after tailings consolidation ......... 169
    6.3.2.3 Hole formed on the top-side of the wrinkle prior to backfilling with tailings slurry .................................................................................................................. 170
  6.3.3 Migration of tailings into the wrinkle gap ......................................................... 170
6.4 Discussion .............................................................................................................. 172
  6.4.1 Wrinkle deformations ....................................................................................... 173
  6.4.2 Leakage through hole in the wrinkle ............................................................... 174
  6.4.3 Long term performance of the geomembrane .................................................. 174
6.5 Conclusions ........................................................................................................... 175
6.6 References ............................................................................................................ 177

Chapter 7 Conclusions and Recommendations

7.1 General ................................................................................................................ 197
7.2 Summary and main conclusions ........................................................................... 198
  7.2.1 Hydraulic performance of overlapped Geosynthetic Clay Liner seams requiring field-applied supplemental bentonite ................................................................. 198
  7.2.2 Hydraulic performance of GCL seams without field-applied supplemental bentonite below a geomembrane wrinkle ............................................................... 199
7.2.3 A new laboratory apparatus for measuring leakage through geomembrane holes beneath mine tailings .......................................................................................................................... 200
7.2.4 Leakage through holes in geomembranes below saturated fine tailings .......... 201
7.2.5 Physical and hydraulic response of geomembrane wrinkles underlying saturated fine tailings .................................................................................................................. 202
7.3 General conclusions and practical implications .................................................. 203
7.4 Recommendations for future work ...................................................................... 203
7.5 References ........................................................................................................... 206

Appendix A Supplementary materials for Chapter 2 and 3 (Chapter 2: Hydraulic performance of overlapped Geosynthetic Clay Liner seams requiring field-applied supplemental bentonite), (Chapter 3: Hydraulic performance of GCL seams without field-applied supplemental bentonite below a geomembrane wrinkle) .......................................................................................................................... 207

Appendix A.1 Grain size distribution of supplemental bentonite, foundation sand and drainage gravel used in Chapter 2 and 3 .................................................................................. 208
Appendix A.2 Steps taken while setting up and terminating permeation tests on GCL seams. ................................................................................................................................. 210
Appendix A.3 Friction treatment and bentonite based side seal details ...................... 215
Appendix A.4 Physical test results not reported in Chapter 2 and 3 ......................... 218
Appendix A.5 Submerged hydration of GCL3, 4, 5 and 6 under 2 kPa applied stress .... 231
Appendix A.6 Determination of metals in tap water used in Chapter 2 and Chapter 3 by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) method ... 233
Appendix A.7 Swell index test on bentonite hydrated with dye (Brilliant Blue G-250, Fisher BioReagents) water for 30 days ................................................................................ 235
Appendix A.8 Leakage calculation for field wrinkles based on the GLLS permeation tests . 238
Appendix A.9 Inferring the interface-transmissivity along the GCL seam using measured flow. ................................................................................................................................. 243
Appendix A.10 Evidence of leakage through GCL seam and panel in Test T11 ............ 245
Appendix A.11 Finite element modelling using SEEP/W ........................................... 252
Appendix A.12 Groove inspection of GCL3 and GCL4 ............................................. 256
Appendix A.13 Groove hydration of GCL3 and GC4 ............................................... 263
Appendix A.14 Differential settlement of sand subgrade due to pressure distribution that developed around wrinkle .................................................................................. 267
Appendix A.15 Submerged hydration of GCL4 sample with 0.5 and 1 in. edge bentonite removed. ................................................................. 269
Appendix A.16 Free swelling of GCL5 and GCL6 under submerged conditions. ............... 271
Appendix A.17 Peel strength tests on GCL5 and GCL6. .................................................. 273
Appendix A.18 Mass per unit area (MPUA) of GCL5 and GCL6 at and away from the seam area.................................................................................................................. 283
Appendix A.19 Conference paper Brachman et al. 2011. .................................................... 292
Appendix A.20 Conference paper Joshi et al. 2011. ................................................................ 307
Appendix B Supplementary materials for Chapter 4, 5 and 6 (Chapter 4: A new laboratory apparatus for measuring leakage through geomembrane holes beneath mine tailings), (Chapter 5: Leakage through holes in geomembranes below saturated fine tailings), (Chapter 6: Physical and hydraulic response of geomembrane wrinkles underlying saturated fine tailings) ............... 319
Appendix B.1 Grain size distribution of materials used in Chapter 4, 5 and 6...................... 320
Appendix B.2 Steps taken for setting up and terminating permeation tests. ....................... 322
Appendix B.3 Placing a hole in the geomembrane. ............................................................ 325
Appendix B.4 Gravel used in Test 13 (Chapter 5). ............................................................ 328
Appendix B.5 Artificially formed wrinkle and perimeter seal. ............................................ 330
Appendix B.6 Photograph showing tailings inside the gap beneath the 1-mm-thick geomembrane wrinkle backfilled with 30 cm tailings slurry at 65% solids (Test W1, Chapter 6). .................................................................................................................. 332
Appendix B.7 Granular filter design for k-test in GLLS ................................................... 334
Appendix B.8 Hydraulic conductivity tests on Silt, Tailings and Cyclone sands used in Chapter 4, 5 and 6.................................................................................................................. 340
Appendix B.9 Prototype tests to observe wrinkle deformation and test perimeter seal........ 345
Appendix B.10 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time for tests in Chapter 5. .......................... 349
Appendix B.11 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time for tests in Chapter 6. ....................... 365
Appendix B.12 Modelling of leakage through single hole in a geomembrane using SEEP/W. .................................................................................................................. 369
Appendix B.13 Filter compatibility check for the nonwoven geotextile for use as a filter beneath T-7 tailings................................................................................................. 377

xvi
Appendix B.14 Report on the in-plane transmissivity flow measurement on virgin geotextile and geotextile exhumed from Test 11 in Chapter 5 ................................................................. 379
Appendix B.15 Tensile properties of the 1-mm-thick LLDPE geomembrane tested .............. 383
Appendix B.16 Specific gravity determination of T-6, T-7, T-8 and silt used in Chapter 4 ... 386
Appendix B.17 Final density of tailings and underliner for tests in Chapter 5 and 6 .......... 391
Appendix B.18 Conference paper Joshi et al. 2014 ......................................................... 394
Appendix B.19 Whole rock analysis and water chemistry of tailings used in Chapter 5 and 6.
........................................................................................................................................ 406
Appendix C Force generated upon drying a GCL ............................................................ 410
Appendix C.1 Method ........................................................................................................ 411
Appendix C.2 Test results .................................................................................................. 414
List of Figures

Figure 2.1 Cross-section views showing geomembrane wrinkle and GCL: (a) single panel of GCL beneath a wrinkle, (b) wrinkle on top and parallel to an overlapped GCL seam, and (c) wrinkle perpendicular to a GCL seam. .................................................................................................................. 36

Figure 2.2 Schematic of the tested GCLs: (a) GCL1 with piled supplemental bentonite, (b) GCL2 with piled supplemental bentonite, (c) GCL8 with piled supplemental bentonite and (d) GCL2 with even supplemental bentonite.................................................................................................................. 37

Figure 2.3 Schematic of permeation test setup (all dimensions in mm). ............................................ 38

Figure 2.4 Flow vs time for parallel GCL2 with different seam width and base case with a single panel of GCL beneath a wrinkle. ................................................................................................................. 39

Figure 2.5 Geomembrane wrinkle and GCL seam deformation due to applied vertical stress (250 kPa): (a) Gap beneath the wrinkle partially filled with free swelling GCL and supplemental bentonite, and (b) Vertical movement of edge of the GCL seam (narrower than final geomembrane wrinkle) upon wrinkle deformation................................................................. 40

Figure 2.6 Reduction in flow due to the presence of supplemental bentonite at the seam of GCL2 in perpendicular case with 150 mm wide seams tested in 0.59 m test cell. ............................................. 41

Figure 2.7 (a) Photograph taken after termination of Test T34 with upper panel removed to show dye stains on top of the supplemental bentonite, (b) Photograph with the central piled supplemental bentonite cut and flipped to show dye stains on the bottom of the supplemental bentonite in Test T34, (c) Photograph taken after Test T12 termination with upper GCL panel lifted to show dye stains on top of the evenly distributed supplemental bentonite, and (d) Photograph showing dye on the bottom of supplemental bentonite in Test T12 (the bentonite was dry and desiccated when the picture was taken). ............................................................................................................. 42

Figure 2.8 Effect of GCL type on flow: (a) Lower flow through 150 mm wide GCL1 seam, and (b) Lower flow through 300 mm wide GCL8 seam, compared to a test with GCL2 seam. Note that in comparing leakage, allowance must be made for the larger dia. test cell used for tests in Figure 2.8b......................................................... 43

Figure 2.9 Photograph taken after test termination with upper GCL panel lifted to expose the supplemental bentonite: (a) GCL1, and (b) GCL8. No dye stains visible on top of the supplemental bentonite. Flow occurred along the bottom of the supplemental bentonite pile..... 44
Figure 2.10 Effect of applied vertical stress on flow. All tests involved a geomembrane wrinkle perpendicular to a 300 mm GCL seam with piled supplemental bentonite.

Figure 2.11 Height and width of the gap beneath the wrinkle. Width of the void space decreased with increasing pressure.

Figure 3.1 Techniques in use to introduce bentonite at the seam: (a) field-applied supplemental bentonite placed at the overlapped ends of the GCL, (b) a melted groove on a nonwoven cover geotextile allowing bentonite to extrude out upon hydration, and (c) presence of factory-applied powder bentonite on the nonwoven cover geotextile.

Figure 3.2 Plan and cross-section views showing orientation of geomembrane wrinkle with respect to GCL seam.

Figure 3.3 Cross-section of the tested GCLs. NW – Nonwoven geotextile, W – Woven geotextile, NP – Needle-punched.

Figure 3.4 Schematic of a permeation test setup in a 1 m diameter test cell (parallel test setup; all dimensions in mm).

Figure 3.5 (a) Measured flow rate through a single panel of GCL4 beneath a deformed geomembrane wrinkle, and (b) Measured flow rate through 150 mm wide overlapped seams of GCL3 and GCL4 in perpendicular case beneath a geomembrane wrinkle.

Figure 3.6 Pictures showing melted grooves of GCL3b: (a) Dry GCL sample showing well exposed panel bentonite at the melted groove, (b) Dry GCL sample showing little exposure of panel bentonite through the melted groove, (c) Well hydrated bentonite at the melted groove after 5 days of submerged hydration, (d) The hydrated GCL sample shows minimal amount of bentonite above the GCL surface after 5 days of submerged hydration.

Figure 3.7 Observed predominant flow path in all tests with leakage along the GCL seam.

Figure 3.8 Photographs taken after permeation-test-termination by lifting the upper GCL panel at the seam to expose the flow-path and melted groove of: (a) GCL4 in Test T20 with higher amount of hydrated bentonite present at the melted groove. The dye concentration was higher at the groove and a good contact between the upper and lower panel was maintained, and (b) GCL3b in Test T14, where the dye concentration is uniform throughout the seam width, the bentonite at the groove with incomplete melt had no excess bentonite. There was a formation of a hydration wave on the lower carrier woven geotextile of the upper GCL panel.
Figure 3.9 Effect of heat-tacking on 150 mm overlap of GCL4, GCL3 and GCL3b (schematic of heat-tack at upgradient seam is shown in Figure 3.7d and downgradient seam is shown in Figure 3.7g). ................................................................. 83

Figure 3.10 Recorded flow through GCL5 and GCL6 overlapped seams. ......................... 84

Figure 3.11 Photographs taken after permeation test by lifting the upper GCL panel at the seam to expose the flow-path of: (a) GCL6 after Test T38 termination. Tortuous flow path observed at the overlap and there was no sign of any washed out bentonite. (b) GCL5 after Test T40 termination. Flow is channelized and the bentonite from the overlap had been washed out. ...................... 85

Figure 3.12 X-ray images of a representative peel-strength specimen of: (a) GCL5, and (b) GCL6 after oven drying. The specimens are 100 mm wide and 200 mm long. Darker spots in the x-ray image represent the needle-punched fibres ................................................................. 86

Figure 3.13 (a) Differential swelling and hydration waves were prominent upon surface scanning of a free swelling GCL5. (b) Differential swelling was observed however no distinct flow channel is formed on the surface of GCL6 ........................................................................ 87

Figure 4.1 (a) Geomembrane hole in a typical municipal solid waste landfill configuration, and (b) Geomembrane hole in a mine tailings containment configuration ................................................. 109

Figure 4.2 (a) Geomembrane buried deep in a containment facility, and (b) Representation of earth and pore pressure action on a region of soil around a hole in the geomembrane liner. ..... 110

Figure 4.3 Flow lines and select contours of total head (in m) from axisymmetric finite-element seepage analysis for: (a) Field scale model, and (b) Laboratory scale model. The hydraulic conductivity of tailings and underliner were 5x10^{-9} m/s and 1x10^{-5} m/s respectively .......... 111

Figure 4.4 Elevation vs pore pressure distribution in two different combination of overliner and underliner examined (SEEP/W results). Due to having a low pore pressure below the geomembrane layer, effective stresses on the underliner are likely to be closer to applied vertical stress ........................................................................................................ 112

Figure 4.5 Effect of cell diameter on flow through geomembrane hole with an overliner of thickness 0.3 m for soils with hydraulic properties that of low k fine tailings overliner / sand underliner and higher k tailings overliner / sand underliner. ......................................................... 113

Figure 4.6 Schematic of the test system ............................................................................. 114

Figure 4.7 (a) Schematic of friction treatment and bentonite perimeter seal details, (b) Photograph showing the seal and friction treatment, (c) Post-test termination picture showing the presence of
blue dye restricted towards the perimeter of the seal, and (d) No evidence of leakage through the seal after the geomembrane has been removed.

Figure 4.8 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, (d) Cumulative consolidated water, and (e) Measured flow versus time for Tests P1 and P2.

Figure 4.9 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, (d) Cumulative consolidated water, and (e) Measured flow versus time for Tests P3 and P4.

Figure 5.1 Cross-section showing: (a) Geomembrane hole in a typical municipal solid waste landfill configuration, and (b) Geomembrane hole in a mine tailings containment configuration.

Figure 5.2 Schematic of apparatus (0.5 m high and 0.59 m diameter) showing 0.14 m of compacted underliner and 0.3 m of tailings slurry.

Figure 5.3 Test result for 10-mm-diameter hole: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time.

Figure 5.4 Flow through a 10-mm-diameter geomembrane hole with UL-6 underliner ($k = 6.9 \times 10^{-7}$ m/s at $p' = 1500$ kPa) but different tailings under the same applied stress of $p = 3000$ kPa, $u = 1500$ kPa, $p' = 1500$ kPa. The error bar represents the range of measured flow for multiple tests.

Figure 5.5 Flow results showing little effect of underliner with same overlying tailings. The error bar represents the range of measured flow for multiple tests.

Figure 5.6 Photograph shows the underliner after termination of Test 5 and removal of the geomembrane. The area just beneath the centrally located hole contains relatively high percentage fines (much greater than 25%) with the percentage fines decreasing with radial distance from the hole.

Figure 5.7 (a) Tailings and underliner allowed to settle in glass bottles filled with water before and after Test 5: (i) T-5 underliner before test, (ii) T-7 tailings before test, (iii) no change in underliner sample taken 10 cm away from centre, (iv) increase in fines in underliner sample from just below the hole, (v) no change in underliner sample taken from 10 cm away from centre; (b) Approximate sampling locations for samples iii, iv, and v.

Figure 5.8 Photograph showing cross-section of geotextile used in Test 12 where the geotextile was used as a filter between gravel underliner and geomembrane with hole to prevent piping failure.

Figure 5.9 Effect of geomembrane hole size. (a) Test conducted with a 1.5-mm-diameter hole in the geomembrane, and (b) Tests conducted with 10 and 20-mm-diameter holes. The error bar
represents the range of measured flow for multiple tests. Note: The vertical scales for the plots are not same.

Figure 5.10 Photograph showing cross-section through the virgin and exhumed geotextile from Test 11. Pore spaces in the exhumed geotextile are filled with tailings.

Figure 5.11 Effect of applied effective stresses on flow for (a) 1.5-mm-diameter hole, and (b) 10-mm-diameter hole. The error bars represent the range of measured flow for multiple tests.

Figure 5.12 Photograph taken after termination of Test 13. The geomembrane has been removed to expose the 25 mm gravel particle placed near the hole and the initial gap between the geomembrane and underliner has been filled with tailings. The blue dye shows where the flow predominately went into the underliner after passing through the hole.

Figure 5.13 Hydraulic conductivity of silty-sand with corresponding percentage fines (particles passing sieve No. 200).

Figure 5.14 Calculated leakage through a 10-mm-diameter hole in a 1-mm-thick geomembrane backfilled with different tailings over a UL-6 underliner under different head above the liner. Tailings were submerged beneath a 0.3 m pressure head in all simulations.

Figure 6.1 (a) Stress distribution on the surface of a geomembrane wrinkle covered by gravel drainage layer in a municipal solid waste landfill configuration. Magnitude of horizontal component of the stresses is smaller than the vertical component due to interlocking of gravel particles and positive arching. (b) Stress distribution on the surface of a geomembrane wrinkle in a mine tailings containment configuration. Vertical and horizontal components of the applied stresses are equal due to isotropic or near isotropic conditions.

Figure 6.2 Cross-section of the test apparatus and test configurations.

Figure 6.3 An artificially formed geomembrane wrinkle (200 mm wide and 60 mm high) with a 10-mm-diameter hole on the side (1-mm-thick LLDPE; Test W1). Steel weights were used to form the shape of the wrinkle and were removed during backfilling.

Figure 6.4 Cross-section showing the initial and final shape of the wrinkle with tailings inside the gap beneath the wrinkle (Test W1). The wrinkle was covered with 300 mm tailings slurry (with 65% solids) and left for 24 hours.

Figure 6.5 (a) Underside of the 1-mm-thick LLDPE geomembrane before Test W2 with white paint on one side of wrinkle crest line and ink marks on the opposite side. A double-sided tape is attached on one side to prevent the geomembrane from relaxing after the applied stress is removed. (b) Post-test photograph showing underside of the geomembrane after the termination
of Test W2. (c) Enlarged view of inset in Figure 6.5b showing ink marks transferred from one side of the wrinkle to the white paint on the opposite side confirming contact between the inner sides of the wrinkle.

Figure 6.6 Photograph showing deformed geomembrane wrinkle being profiled using a line laser through a vertical observation trench. The 1-mm-thick HDPE geomembrane wrinkle was allowed to deform under 250 kPa overburden stress for 100 hours (Test W3).

Figure 6.7 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time for Test W4.

Figure 6.8 Cross-section measured with surface scanning laser through deformed 1-mm-thick geomembranes (initially 200 mm wide and 60 mm high) after being subjected to 250 kPa for 100 hours (a) LLDPE wrinkle (Test W2), (b) HDPE wrinkle (Test W3).

Figure 6.9 Deformed wrinkle from Test W2 after it had been subjected to 250 kPa overburden stress for 100 hours. Note that due to the presence of double-sided tape on the inner wall of geomembrane wrinkle, the sides are still touching even after removal of stress.

Figure 6.10 Cross-section through deformed 2-mm-thick HDPE geomembrane wrinkle (initially 200 mm wide and 60 mm high) after subjected to 250 kPa for 100 hours. There is some missing data at the location of the hole because the laser signal did not get reflected along the width of the hole.

Figure 6.11 Cross-section through deformed 2-mm-thick geomembrane wrinkles subjected to a total stress of 1000 kPa. In Test W4, the hole was placed after consolidation of tailings under 250 kPa for 100 hours. In Test W5, the hole was placed prior to backfilling with tailings. The different shape of deformed wrinkle in Test W5 is due to the gap beneath the wrinkle being partially filled with tailings prior to wrinkle deformation under externally applied stresses.

Figure 6.12 Hole being placed on the top-side of the exposed wrinkle (Test W4). The wrinkle was painted white to have a reflecting surface for laser scanning.

Figure 6.13 Photographs taken after removing the deformed geomembrane wrinkle followed by permeation test termination. (a) After Test W4 with 2 mm HDPE geomembrane where the hole was placed after tailings consolidation (see Figure 6.12). (b) In Test W5 with 2-mm-thick LLDPE geomembrane where the hole was placed before placement of tailing.

Figure 6.14 Post-test evaluated percentage fines (passing US sieve #200) from different locations on a vertical plane perpendicular to the geomembrane wrinkle at the centre of the test cell in, (a) Test W4 with 2-mm-thick HDPE wrinkle, (b) Test W5 with 2-mm-thick LLDPE wrinkle.
List of Tables

Table 2.1. Properties of GCLs tested........................................................................................................34
Table 2.2. Summary of permeation tests.................................................................................................35
Table 3.1 Properties of GCLs used for the study .....................................................................................73
Table 3.2 Summary of permeation tests.................................................................................................74
Table 4.1 Summary of test parameters and results .................................................................................107
Table 4.2 Index properties of overliner and underliner after test termination ......................................108
Table 5.1 Properties of materials used in the test ..................................................................................143
Table 5.2 Summary of permeation tests .................................................................................................144
Table 6.1 Index stress-strain properties (measured in machine (MD) and cross-machine (X-MD) direction) of the HDPE and LLDPE geomembranes studied (Tested according to ASTM 2015). ........................................................................................................................................180
Table 6.2 Initial and final wrinkle dimensions of geomembrane wrinkles subjected to different stresses. ..................................................................................................................................................181
Table 6.3 Summary of permeation tests conducted at 22°C. Materials used in all tests are (a) Silty-sand underliner with ~ 12% fines (passing US sieve #200), (b) Tailings with ~ 27% fines. Initial dimensions of geomembrane wrinkle: 200 mm wide and 60 mm high (see Figure 6.4). Hole diameter 10 mm..................................................................................................................................................182
### List of Abbreviations and Notations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AOS</td>
<td>Apparent Opening Size</td>
</tr>
<tr>
<td>ASCE</td>
<td>American Society of Civil Engineers</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>Avg.</td>
<td>Average</td>
</tr>
<tr>
<td>B.C</td>
<td>British Columbia</td>
</tr>
<tr>
<td>Bent.</td>
<td>Bentonite</td>
</tr>
<tr>
<td>$C_c$</td>
<td>Coefficient of curvature</td>
</tr>
<tr>
<td>CCL</td>
<td>Compacted Clay Liner</td>
</tr>
<tr>
<td>CQC</td>
<td>Construction Quality Control</td>
</tr>
<tr>
<td>$C_u$</td>
<td>Coefficient of uniformity</td>
</tr>
<tr>
<td>$d_s$</td>
<td>Particle diameter at which #% of the sample is less than (m)</td>
</tr>
<tr>
<td>GCD</td>
<td>Geocomposite drain</td>
</tr>
<tr>
<td>GCL</td>
<td>Geosynthetic Clay Liner</td>
</tr>
<tr>
<td>GLLS</td>
<td>Geosynthetic Liner Longevity Simulator</td>
</tr>
<tr>
<td>GM / GMB</td>
<td>Geomembrane</td>
</tr>
<tr>
<td>GP</td>
<td>Poorly graded gravel</td>
</tr>
<tr>
<td>GTX</td>
<td>Geotextile</td>
</tr>
<tr>
<td>$h_p$</td>
<td>Pressure head (m)</td>
</tr>
<tr>
<td>H</td>
<td>Height of a wrinkle (m)</td>
</tr>
<tr>
<td>ha</td>
<td>Hectares</td>
</tr>
<tr>
<td>HDPE</td>
<td>High Density Polyethylene</td>
</tr>
<tr>
<td>HP-OIT</td>
<td>High Pressure Oxidative Induction Time (mins)</td>
</tr>
<tr>
<td>ICP-OES</td>
<td>Inductively Coupled Plasma Optical Emission Spectrometry</td>
</tr>
<tr>
<td>k</td>
<td>Hydraulic conductivity (m/s)</td>
</tr>
<tr>
<td>kPa</td>
<td>kilo Pascal</td>
</tr>
<tr>
<td>l</td>
<td>Litre</td>
</tr>
<tr>
<td>LLDPE</td>
<td>Linear Low Density Polyethylene</td>
</tr>
<tr>
<td>lpd</td>
<td>Litres per day</td>
</tr>
<tr>
<td>lphd</td>
<td>Litres per day per hectare</td>
</tr>
</tbody>
</table>
MD  Machine direction
MEND  The Canadian Mine Environment Neutral Drainage
min  Minute
ml  Millilitre
mm  Millimeter
MSW  Municipal Solid Waste
n  Sample number
NP  Needle-punch
NW  Nonwoven
NWSR  Nonwoven scrim reinforced
p  Total applied vertical stress (kPa)
p'  Vertical effective stress (kPa)
QA  Quality Assurance
QC  Quality Control
QUELTS  Queen’s University Experimental Liner Test Site
SD  Standard deviation
SI  Swell index (ml/2g)
SP  Poorly graded sand
Std-OIT  Standard Oxidative Induction Time (mins)
Supp.  Supplemental
TSF  Tailings Storage Facilities
u  Applied pore pressure (kPa)
W  Woven
W  Width of a wrinkle (m)
X-MD  Cross Machine Direction
XRD  X-ray diffraction
θ  Geomembrane-clay liner interface transmissivity (m²/s)
κ  Stiffness index (N/m)
Ω  Relative tensile stiffness
<table>
<thead>
<tr>
<th>Glossary</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advection</strong></td>
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<tr>
<td><strong>Bentonite</strong></td>
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<tr>
<td><strong>Bonding peel strength</strong></td>
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<tr>
<td><strong>Bulk void ratio</strong></td>
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<tr>
<td><strong>Compaction</strong></td>
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<tr>
<td><strong>Composite liner</strong></td>
</tr>
<tr>
<td><strong>Concentration</strong></td>
</tr>
<tr>
<td><strong>Construction Quality Assurance</strong></td>
</tr>
<tr>
<td><strong>Construction Quality Control</strong></td>
</tr>
<tr>
<td><strong>Contaminant</strong></td>
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</tbody>
</table>
contaminants may be beneficial or make something harmful, or otherwise unfit for use. (MEND 2009)

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cover geotextile</td>
<td>The upper geotextile which is placed above the bentonite layer during the manufacturing of the geosynthetic clay liner. It is always nonwoven for the needle-punched geosynthetic clay liner.</td>
</tr>
<tr>
<td>Cross-machine Direction</td>
<td>Direction perpendicular to the plane of its manufactured direction.</td>
</tr>
<tr>
<td>Diffusion</td>
<td>Migration of molecules or ions in air, water or a solid as a result of their own random movements from a region of higher to a region of lower concentration. Diffusion can occur in the absence of any bulk air or water movement. (Rowe et al. 2004)</td>
</tr>
<tr>
<td>Distilled water</td>
<td>Water with many of its impurities removed through distillation. Distillation involves boiling the water and then condensing the steam into a clean container. (MEND 2009)</td>
</tr>
<tr>
<td>Effluent</td>
<td>The discharge of a contaminant with water from man-made structures. Used in laboratory tests as a terminology for the outflow from conductivity tests. (MEND 2009)</td>
</tr>
<tr>
<td>Geomembrane</td>
<td>A planar, relatively impermeable, polymeric (synthetic or natural) sheet used in civil engineering applications. (IGS 2009)</td>
</tr>
<tr>
<td>Geosynthetic clay liner</td>
<td>A synthetic hydraulic barrier comprised of a layer of bentonite encapsulated between two geotextiles. The geotextile sheets are mechanically held together by needle-punching, stitch bonding, or chemical adhesive to control the swelling of bentonite and increase the shear strength of the bentonite. (IGS 2009)</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
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<tr>
<td>-----------------------------</td>
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</tr>
<tr>
<td>Geosynthetics</td>
<td>A polymeric (synthetic or natural) material used in contact with soil/rock and/or any other geotechnical material in civil engineering applications. (IGS 2009)</td>
</tr>
<tr>
<td>Geotextile</td>
<td>A planar, permeable, polymeric (synthetic or natural) textile material, which may be nonwoven, knitted or woven, used in contact with soil/rock and/or any other geotechnical material in civil engineering applications. (IGS 2009)</td>
</tr>
<tr>
<td>Hydraulic conductivity</td>
<td>The proportionality factor in Darcy’s law that represents the ability of soil to conduct water and it is equivalent to the flux under unit hydraulic gradient. (MEND 2009)</td>
</tr>
<tr>
<td>Hydraulic gradient</td>
<td>The ratio of the total head loss across the specimen to its length in the flow direction. (IGS 2009)</td>
</tr>
<tr>
<td>Interface transmissivity</td>
<td>Measure of the resistance to lateral flow in the transmissive zone between two adjacent substances. (Harpur et al. 1993)</td>
</tr>
<tr>
<td>Internal erosion (piping)</td>
<td>A process whereby particles are detached from the large mass by large hydraulic gradients and are entered into suspension to be carried away by the flowing water.</td>
</tr>
<tr>
<td>Landfill</td>
<td>A site for the disposal of waste materials in a way that keeps these materials isolated from the surrounding environment. (Rowe et al. 2004)</td>
</tr>
<tr>
<td>Needle-punched</td>
<td>A mechanical bonding of staple or filament fibres with barbed needles to form a compact fabric. (US Fabrics 2016)</td>
</tr>
<tr>
<td>Nonwoven geotextile</td>
<td>A textile structure produced by bonding or interlocking of fibres accomplished by mechanical, thermal, or chemical means. (IGS 2009)</td>
</tr>
<tr>
<td>Permeability</td>
<td>The capacity of a porous medium to transmit a liquid or gas.</td>
</tr>
</tbody>
</table>
Polyethylene  A polymer consisting of long chains of the monomer ethylene - [CH2=CH2]n.

Polymer  A substance composed of molecules of high relative molecular mass (molecular weight), the structure of which essentially comprises the multiple repetitions of units derived, actually or conceptually, from molecules of low relative molecular mass.

Polypropylene  A polymer consisting of long chains of the monomer propylene - [CH3]-n.

Porosity  The existence in a material of connected air voids. It is frequently expressed as the ratio of void volume to total volume.

Quality control  QC; the operational techniques and the activities which sustain the quality of a geomembrane material or geomembrane system, or installation; also the use of such techniques and activities.


Seepage  The movement of water into or through a porous material. (MEND 2009)

Solid waste  All solid non-hazardous solid materials that are discarded as waste and are not recyclable or reusable and includes daily and interim cover soil that is utilized as part of the landfilling operation.

Specific gravity  The ratio of the mass (density) of a sample material to the mass (density) of an equal volume of water at the same specified temperature.

Standard Proctor Compaction  A laboratory compaction procedure used to determine the relationship between water content and dry unit weight of soils.
Strain  The increase in length per unit original length when a tensile stress (or flexural stress) is applied. The elongation of the polymer when expressed as a percentage increase of the original length is a measure of the strain.

Swell index  An index for the swelling characteristics of bentonite clay. It represents the volume of 2 g of dried and finely ground bentonite clay after dispersed into a 100 mL graduated cylinder filled with DI water. (ASTM 2006)

Tailings  The ground rock waste product from a mill or process plant, the materials remaining after the economically valuable elements are removed from the ore. The tailings usually leave the mill as slurry of sand sized and/or silt sized particles in water. (MEND 2009)

Thermally treated Needle punched fibres  The needle-punched fibres bonded to carrier geotextile by heating the carrier geotextile. This process causes the fibres to fuse together and/or attached to the carrier geotextile creating a strong bond between the cover and carrier geotextiles and bentonite. (Rowe 2013)

Void ratio  Ratio of volume of void and volume of solids of a porous material.

Woven geotextile  A geotextile produced by interlacing, usually at right angles, two or more sets of yarns, fibres, filaments, tapes or other elements. (IGS 2009)

X-ray  Electromagnetic radiation with a wavelength of the order of 0.01-10 nanometers emitted when a metal target is bombarded by fast electrons. X-rays with wavelengths characteristic of the elemental composition of the metal target are emitted when an electron that has been displaced from an inner shell of an atom is replaced by another electron that falls in from an outer shell with loss of energy. This energy is detected as X-rays of a specific energy (wavelength). (Goldstein et al. 2007)
References:


Chapter 1

Introduction

1.1 Problem definition

Geomembranes (GMBs) are extensively used in the basal liner and cover systems of waste containment facilities to assist in protecting the surrounding environment (Rowe 2012). They are often used in combination with geosynthetic clay liners (GCLs) to form an effective advective-diffusive composite barrier to contaminant transport in solid waste landfills (Bonaparte et al. 2002; Rowe et al. 2004; Rowe 2012) or singly as an advective barrier in many other applications such as waste water lagoons, hydraulic dams and tailings storage facilities (TSFs). However to date, little is known about the extent of use and performance of geomembrane liners in TSFs.

A geomembrane is typically a thin (1-2.5 mm) linear-low-density polyethylene (LLDPE) or high-density polyethylene (HDPE) sheet and a GCL most commonly consists of a thin layer (5-10 mm) of bentonite clay encapsulated between two geotextiles. Both GMBs and GCLs are factory manufactured products and require good quality control (QC). During field installation, GCLs are easy to install requiring less in-situ quality assurance (QA) whereas geomembranes needs extensive quality assurance.

Two important issues to consider in regards to using geomembranes are: (i) the vulnerability of the thin polymeric material to damage both during installation and throughout the service life, and (ii) the difficulty to achieve continuous close contact between the geomembrane and the clay liner either because the geomembrane will expand and form wrinkles when heated during exposure to solar radiation (Take et al. 2012) or displace during placement of overlying materials (Waud 2015). Any damage (tears and punctures) may impact the effectiveness of the
geomembrane as a containment barrier and result in leakage of contaminants into the environment. It is often assumed that a geomembrane installed with good construction quality assurance and quality control (QA-QC) will still have 2.5-5 holes per hectare (Giroud and Bonaparte 1989, 2001). Wrinkles (sometimes called waves) formed due to the thermal expansion of the geomembrane may not flatten when subjected to overburden pressure (Soong and Koerner 1998; Gudina and Brachman 2006; Brachman et al. 2011) rather they may increase tensile strains (Brachman and Gudina 2008) from the overlying gravel drainage layer which increases the probability of a hole forming at the wrinkle. With a hole in or near a geomembrane wrinkle, the wrinkle becomes a conduit allowing fluid to flow horizontally increasing the possibility of higher leakage through the liner.

1.2 Scope and objective of the thesis

1.2.1 Leakage through overlapped GCL seams subjected to non-uniform stresses

During field installation, adjacent GCL rolls are overlapped generally by 150-300 mm and, depending on the product, supplemental bentonite is added. Estornell and Daniel (1992), Cooley and Daniel (1995), Daniel et al. (1997), Benson et al. (2004) and Kendall and Austin (2014) have all shown that overlapped GCL seams with supplemental bentonite and subjected to a uniform confining stress can perform hydraulically as well as an intact single panel of GCL.

Rowe et al. (2012) reported that GCL seams can be a geometrical imperfection that leads to the formation of wrinkles in the overlying GMB. When a large number of wrinkles are present during backfilling, it is likely that some wrinkles over the seam area remain and subject the GCL seam to non-uniform stresses. This thesis examines the hydraulic performance of those GCL seams buried below a wrinkle with a hole to evaluate the effect of wrinkle orientation, presence and distribution of supplemental bentonite, seam width, GCL type and applied vertical stress (Chapters 2 and 3).
1.2.2 Leakage through holes in geomembrane in mine tailings storage facilities

When geomembranes are installed as a single liner, concerns of leakage through the hole is much higher than when clay liners are used in conjunction (Rowe 2012). Majority of the previous studies have only considered studying leakage through defects in geomembranes used as landfill liners. The effect of size and shape of defect, type and thickness of underlying soil, applied effective stress, and hydraulic head is well understood (Brown et al. 1987; Rowe 1998; Touze-Foltz et al. 1999; Rowe et al. 2004; Rowe 2012) however the effect of having a low permeability material (soil/tailings) on top of the geomembrane such as in a TSF is not well understood. Thus the objective of this research is to examine the effect on the leakage through a hole in a geomembrane in a simulated TSF. Effects of overlying tailings, underlying foundation, geomembrane type and thickness, and any gap present below the geomembrane hole were investigated (Chapters 4, 5 and 6).

1.3 Thesis outline

This thesis has been prepared in Manuscript Form as prescribed by the Queen’s University School of Graduate Studies and contains seven chapters. This, Chapter 1: Introduction, provides a general introduction to the problem, thesis objective and the methods used. Chapters 2 to 6 (described in detail below) are original manuscripts for separate publication incorporated as chapters and each comprise of an introduction, methods, results and conclusions sections. All supporting data are provided as tables and figures at the end of each manuscripts and in the appendices. Chapter 7: Conclusions and Recommendations will draw conclusions and provide recommendations for future work.

Chapter 2, “Hydraulic performance of overlapped Geosynthetic Clay Liner seams requiring field-applied supplemental bentonite”, presents the result of experiments conducted on
overlapped seams of three GCLs—all requiring field-applied supplemental bentonite—subjected to non-uniform stresses below a 1.5-mm-thick HDPE geomembrane wrinkle. The cover (top) geotextile component of all three GCLs is a nonwoven geotextile but the carrier (bottom) geotextile component are different. One is with a woven geotextile, one with a scrim reinforced nonwoven geotextile and one with a woven geotextile laminated with a thin polymer coating. The objective of this research is to examine the effects of orientation of the overlying wrinkle (parallel or perpendicular); presence and distribution (piled or even) of supplemental bentonite; seam width (50, 150 and 300 mm); GCL type and applied vertical stress (250, 500 and 1000 kPa) on the leakage through the GCL seam. The paper version of this chapter has been accepted for publication in ASCE’s Journal of Geotechnical and Geoenvironmental Engineering.

Chapter 3: “Hydraulic performance of GCL seams without field-applied supplemental bentonite below a geomembrane wrinkle”, presents the results of experiments conducted on overlapped seams of four GCLs all not requiring field-applied supplemental bentonite—two with narrow, linear, factory melted groove in the cover geotextile and two with factory-applied powder bentonite—subjected to non-uniform stresses below a 1.5-mm-thick HDPE geomembrane wrinkle. The objective of this research is to examine the effect of alternate seam sealing technique; heat-tacking; orientation of overlying wrinkle and orientation of GCL panel on leakage through the GCL seam. In addition, the seam performance issues that relates to the manufacturing of the GCLs were identified and their effect on the seam performance are discussed.

The objective of the research presented in Chapter 4: “A new laboratory apparatus for measuring leakage through geomembrane holes beneath mine tailings”, is to describe the design and development of a new apparatus and method to test geomembranes under large applied stresses. Verification of the boundary conditions using finite-element seepage analysis and details of four
prototype tests conducted using the apparatus and method to study the effect of having a lower hydraulic conductivity material on top of the geomembrane are described.

Chapter 5: “Leakage through holes in geomembranes below saturated fine tailings”, examines the performance of two geomembranes (1-mm-LLDPE and 2-mm-HDPE) with holes with respect to their potential use as a hydraulic barrier in a tailings storage facility. The effect of overlying tailings; underlying foundation; geomembrane type and thickness; and any gap present below the geomembrane hole on leakage through geomembrane holes were studied. The paper version of this chapter has been submitted to ASCE’s Journal of Geotechnical and Geoenvironmental Engineering.

The objective of Chapter 6, “Physical and hydraulic response of geomembrane wrinkles underlying saturated fine tailings”, is to provide a first understanding of wrinkle deformations of four geomembranes (1 and 2-mm-thick LLDPE and HDPE) in a mine tailings configuration (with saturated tailings slurry backfill and a firm silty-sand foundation) where isotropic or near isotropic stresses act on the geomembrane surface. The paper version of this chapter has been submitted to the Geosynthetics International.

1.4 Original contribution

The original contributions of this thesis are as follows:

- Examination of hydraulic performance of longitudinal GCL seams subjected to non-uniform stresses due to overlying geomembrane wrinkle. In addition, it is the first time to compare the products requiring field-applied supplemental bentonite to those not requiring field-applied supplemental bentonite. This research builds on identifying manufacturing quality control issues and their impact on the field performance of overlapped GCL seams and provide practical field-applicable solution.
• Development of a new perimeter seal keeping the complexity of stress distribution along the periphery of the test boundary, due to the presence of a wrinkle, under consideration and allow the flow to occur along the location with flaws in the liner.

• Design and deployment of a new 1-m-diameter, 0.7-m-high test cell to study wider GCL seams. This new test cell helps further minimize the boundary effect and allow future studies in a larger scale.

• Design and development of a new test apparatus to simulate coupled effect of large vertical stress and pore pressure on geomembranes buried under large tailings storage facilities. The new apparatus could also be used to study liner performance in other containment facilities where large hydraulic head on the liner is expected such as heap leach or large hydraulic dams.

• Quantification of leakage through geomembrane holes in a mine tailings storage facilities. This research will help the engineers to better understand and consider the effect of soil properties, stresses at the liner level and geomembrane holes while designing tailings storage facilities.

• Provide insights on the wrinkle deformation of four geomembranes in a tailings storage facility configurations. This research will encourage the mine operators and engineers conducting construction quality assurance to reduce or eliminate geomembrane wrinkles during tailings placement and minimize the likelihood of having long term issues with the liner performance.
1.5 References


Chapter 2

Hydraulic performance of overlapped Geosynthetic Clay Liner seams requiring field-applied supplemental bentonite

2.1 Introduction

A composite liner consisting of a geomembrane and a geosynthetic clay liner (GCL) can be very effective at limiting leakage (Bonaparte et al. 2002; Rowe et al. 2004; Rowe 2012), where leakage is the magnitude of fluid flow through holes in the geomembrane under a hydraulic gradient. The primary role of the GCL is to reduce the amount of leakage through any holes in the geomembrane. Leakage through a composite geomembrane/GCL liner depends on: the number and size of geomembrane holes; the thickness and hydraulic conductivity of the GCL; the thickness and hydraulic conductivity of any soil beneath the GCL; the hydraulic gradient across the liner; the interface transmissivity between the geomembrane and GCL; and any geometrical imperfections that may exist in the composite liner (Giroud 1997; Rowe 1998; Rowe et al. 2004; Rowe 2012). Figure 2.1 identifies two such geometrical imperfections: geomembrane wrinkles and GCL seams.

Wrinkles are formed by thermal expansion of the geomembrane and lead to a gap between the geomembrane and the underlying material (Pelte et al. 1994; Giroud 2005; Chappel et al. 2012; Rowe et al. 2012). It has been shown that if there is a hole at or near a wrinkle, the leakage through the geomembrane, in addition to the factors mentioned earlier, also depends on the wrinkle width and length of interconnected wrinkles (Rowe 1998, 2012; Chappel et al. 2012). Geomembrane wrinkles have been reported to remain after backfilling with 0.3 m of sand (Take et al. 2012) and even after being buried for 8 years beneath municipal solid waste (Koerner et al. 1999). Laboratory studies conducted by Soong and Koerner (1998), Gudina and Brachman (2006), and Brachman and
Gudina (2008) have shown that the height and width of a geomembrane wrinkle decreases but that the gap beneath the deformed wrinkle can remain even under an applied vertical stresses of up to 1100 kPa.

GCL seams are the location where ends of the adjacent GCL rolls are physically overlapped (usually by 0.15 to 0.3 m along the sides of the GCL roll). The seam width can depend on the product, engineering application, manufacturer’s recommendation, and exposure conditions. Depending on the type of GCL, additional field applied supplemental bentonite may be required at the seam to prevent significant preferential leakage along the seam. Estornell and Daniel (1992), Cooley and Daniel (1995), Daniel et al. (1997), Benson et al. (2004) and Kendall and Austin (2014) have shown that overlapped GCL seams with supplemental bentonite (dry or as water-bentonite paste placed along the seam) and subjected to a uniform confining stress can perform as well as an intact single panel of GCL.

An overlapped GCL seam can be a geometric imperfection that leads to the formation of geomembrane wrinkles (Rowe et al. 2012). Since geomembrane wrinkles can form in both the roll and cross-roll directions (Rowe 2012), a geomembrane wrinkle can be oriented both parallel and perpendicular to a GCL seam, as illustrated in Figure 2.1b and c. Brachman et al. (2011) (Appendix A.19) reported measurements of deformed wrinkles when an initial wrinkle with height 200 mm and width 60 mm (wrinkle dimensions within the range of field wrinkle sizes reported by Pelte et al. 1994) was oriented parallel and perpendicular to a 150 mm wide GCL seam and subjected to a vertical pressure of 250 kPa. With the crest of the geomembrane wrinkle directly on top of and parallel to the centre of a 150 mm wide GCL seam, they observed that the deformed width of the wrinkle was narrower than 150 mm such that the geomembrane provided confining stress on both the upgradient and downgradient edges of the seam. For this situation, illustrated in Figure 2.1b, they noted that for there to be preferential flow through the seam, the flow would first have to pass
along the path between Points 1 and 2 (governed by the transmissivity of the interface between the geomembrane and GCL, the confining stress along this path and the distance along this path), then along the seam between Points 2 and 5 (governed by the transmissivity of the interface between the two GCLs, the presence of supplemental bentonite, and the confining stress and distance along the paths between Points 2 and 3 and 4 and 5). They hypothesized that leakage through a hole in the geomembrane above and parallel to this seam could remain low. When the wrinkle was perpendicular to the seam, Brachman et al. (2011) observed a stress free zone over the width of the wrinkle, illustrated in Figure 2.1c, where fluid could enter the upgradient edge of the seam (Point 1 in Figure 2.1c) and then flow through the seam under no normal stress because of the wrinkle (i.e. along the path between Points 1 and 2 in Figure 2.1c). They also noticed some local deformation of the GCL at the seam, where the upper GCL displaced upwards relative to the lower GCL when under stress. In the perpendicular case, seam flow could be governed by the presence and distribution of the supplemental bentonite at the seam.

While the physical test results of Brachman et al. (2011) and additional physical test results included in Appendix A.4 serve as a useful starting point to understand how a wrinkle may affect the hydraulic performance of GCL seams, the objective of this chapter is to provide the first quantification of the hydraulic performance of GCL seams requiring field-applied supplemental bentonite when oriented parallel and perpendicular to an overlying geomembrane wrinkle. Measured fluid flow from experiments simulating the geometry and physical (stress and deformation) conditions of GCL seams beneath geomembrane wrinkles are reported. The effects of wrinkle orientation, presence and distribution of supplemental bentonite, seam width, GCL type, and applied vertical stress on the leakage rate through the composite liner are investigated.
2.2 Method

Three types of geotextile-encased, needle-punched GCLs that all require field-applied supplemental bentonite were tested. Descriptions and illustrations of the GCLs are given in Table 2.1 and Figure 2.2. They are denoted as GCLs 1, 2 and 8 using the nomenclature defined by Ashe et al. (2015). In terms of the potential impact on overlapped seam flow, the principal differences between the products is that GCL1 had a woven carrier geotextile, GCL2 had a woven scrim-reinforced nonwoven carrier geotextile, while GCL8 had a (100 μm-thick nominal) polymer coating applied to its woven carrier geotextile.

Above the GCL, there was a 1.5-mm-thick high-density polyethylene geomembrane with an artificially formed wrinkle (initially 200-mm-wide and 60-mm-high) in each test, as illustrated in Figure 2.3. Nominal 50 mm coarse gravel was placed above the geomembrane, and a nonwoven needle-punched protection geotextile (580 g/m²) was placed between the gravel and geomembrane. Below the GCL, a firm, saturated, poorly-graded sand foundation layer was tested (60% of the particles were finer than 0.6 mm by mass, 10% of the particles were finer than 0.15 mm by mass as per ASTM 2009; initial dry density of 1.91 g/cm³). Grain size distribution of the gravel and sand is shown in Appendix A.1.

The coupled physical and hydraulic conditions on GCL seams beneath geomembrane wrinkles were simulated in cylindrical steel pressure vessels (Figure 2.3). The internal diameter of the apparatus was either 0.59 m or 1 m, as noted in Table 2.2. The 1-m-diameter cell was specifically developed to test 300 mm wide overlapped seams. Vertical pressures were applied to the top soil boundary using air pressure over a flexible rubber membrane, where the perimeter of the membrane was clamped between the lid and body of the test cell. Horizontal stresses developed in the soil materials by limiting the outward radial deflection of the test cell to negligible levels.
Losses in stress from boundary friction were limited by having a preferential vertical slip plane along the perimeter of the test cell, which was provided by having two thin plastic sheets lubricated with grease that was protected from damage from the gravel using the technique developed by Tognon et al. (1999). Brachman and Gudina (2002) have calculated that at least 95% of the applied pressure reaches the elevation of the geomembrane with this friction treatment in the 0.59-m-diameter cell, which has been confirmed by physical testing and nonlinear finite-element analysis up to 3,000 kPa applied vertical pressure by Krushelnitzky and Brachman (2009). Brachman and Gudina’s (2002) equation indicates even less loss in vertical stress from boundary friction (< 3%) in the larger 1-m-diameter cell.

Tests were conducted at 22°C and with low ionic strength tap water (Appendix A.6) as the hydrating and permeation fluid. Permeation was conducted under a head of 0.3 m (Figure 2.3). A 5-mm-wide gap was left between the ends of the wrinkle and the test cell walls to: (i) allow the fluid from the saturated gravel to flow into the wrinkle, and (ii) to prevent binding of the deforming wrinkle against the test cell boundary (Gudina and Brachman 2006). A hydraulic seal consisting of layers of dry and hydrated bentonite was placed along the interface between the GCL and the inner wall of the test apparatus to prevent any preferential flow (Figure 2.3; Appendix A.3). A geotextile/geonet drainage composite was placed along the base of the test cell to permit drainage through a port in the centre of the cell base (Appendix A.2).

Two GCL hydration conditions were examined. For experiments conducted in the 0.59-m-diameter cell, the GCL test specimens were first hydrated with tap water (≈ 40 ppm calcium) to an initial water content of 110-128% (under 20 kPa stress for 14 days). Once placed inside the test cell, essentially dry (initial water content < 6%) supplemental bentonite was applied between the seam, in all but Tests T8 and T10, at the manufacturer’s minimal recommended 400 g per linear m (grain size distribution of the supplemental bentonite is shown in Appendix A.1). The supplemental
bentonite was allowed to hydrate from moisture from the GCL for 4 days prior to application of vertical pressure or hydraulic head. For experiments conducted in the 1-m-diameter cell, the GCL test specimens were placed at their as-supplied low water content (≈ 8%) on top of the saturated sand foundation soil. The supplemental bentonite was immediately placed in the seam, and so the bottom GCL then started to hydrate from moisture in the underlying sand. Once the geomembrane and gravel were placed in the test cell, the wrinkle was filled with water and then the upper GCL started to hydrate from moisture along the initial width of the wrinkle. Hydration prior to stress and permeation was continued for 4 days. In both methods, the GCL and supplemental bentonite could continue to hydrate during permeation. Post-test gravimetric water content measurements of the GCL indicated no discernible difference between the two hydration methods (Table 2.2). Additionally, the final water content of the supplemental bentonite was 240-280% when hydrated using the first method versus 250 and 260% in two tests using the second.

Tap water mixed with 0.4 g/l laboratory grade dye (Brilliant Blue G-250, Fisher BioReagents) was used as the permeating fluid. The swell index (ASTM 2006) of supplemental bentonite sample submerged under the permeant for 30 days remained the same as the virgin bentonite at 30 mL/2g suggesting there was no effect of the permeant on the swelling capacity of the supplemental bentonite (Appendix A.7).

2.3 Results and discussion

2.3.1 GCL panel with no seam beneath a wrinkle

Prior to examining more complex configurations involving a geomembrane wrinkle over a GCL seam, the scenario of a single, intact GCL panel (i.e., with no seam) beneath a geomembrane wrinkle is presented as a reference case. For Test T36 conducted with a single panel of GCL2 beneath a geomembrane wrinkle with 0.3 m of water head applied on top of the GCL surface,
steady-state flow of $7.6 \times 10^{-11} \text{ m}^3/\text{s}$ was measured in a test that lasted for 80 days (Figure 2.4). Although steady-state flow conditions were attained after around 40 days, the test was allowed to run for twice that time to confirm steady-state had been reached and no discernable time-dependent effect on flow was observed after 40 days. To put the magnitude of this measured flow in a practical context, this flow would correspond to 0.1 lpd (litres per day) if there was a hole in a 10-m-long wrinkle feature or 1 lpd if it were in a 100-m-long wrinkle where here, and in all future similar calculations, it was assumed that the size of the hole does not limit the flow (all such calculations are shown in Appendix A.8). This leakage is low enough such that for many practical municipal solid waste (MSW) containment applications with no more than 5 holes per hectare and wrinkles no longer than 100 m, leakage would be reduced to the point that diffusion would be the dominant transport mechanism (e.g., see Rowe et al. 2004, Rowe 2012). In short, it is an extremely low flow.

With this measured flow, some insight can be obtained into the interface transmissivity ($\theta$) on either side of the wrinkle—where the geomembrane is in contact with the GCL—using two-dimensional finite-element steady-state seepage analysis (using SEEP/W; GeoStudio 2012; Appendix A.11) and anticipated values of hydraulic conductivity, $k$, for the GCL. A hydraulic conductivity of $3.8 \times 10^{-11} \text{ m/s}$—measured by Hosney and Rowe (2014) at a confining stress of 15 kPa for GCL2—was used for the portion of the GCL directly beneath the wrinkle (e.g., between points 1 and 2 in Figure 2.1a). This value is considered reasonable for three reasons. First, it was hydrated under a confining stress of 20 kPa. Second, since GCL2 had its needle-punching fibres thermally fused to the carrier geotextile, there is data to show this provides some internal confining stress (Lake and Rowe 2000; Rayhani et al. 2011). Third, even small wrinkle and foundation deformations under the applied vertical pressure may be expected to induce some membrane confinement of the GCL beneath the unstressed portion of the wrinkle (Dickinson and Brachman 2008). For the portion of the GCLs away from the wrinkle (e.g., on the outside, towards the cell
wall, of points 1 and 2 in Figure 2.1a), a hydraulic conductivity of $7 \times 10^{-12} \text{ m/s}$—reported by Rowe (2012) at a confining stress of 109-117 kPa—was used as a conservative estimate. For those values of $k_{GCL}$, a $\theta$ of $2.1 \times 10^{-12} \text{ m}^2/\text{s}$ would be required to explain the measured flow in Test T36. This required value of $\theta$ is quite close to, but marginally lower than, the latest value ($2.4 \times 10^{-12} \text{ m}^2/\text{s}$) obtained from an ongoing long-term experiment quantifying interface transmissivity of geomembrane/GCL1 interface at an applied vertical applied stress of 150 kPa. Using $\theta = 2.4 \times 10^{-12} \text{ m}^2/\text{s}$, the calculated flow was only 1% higher than the actual measured flow. GCL1 is a good proxy for the interface behaviour of GCL2, since it contains the same bentonite and essentially the same upper geotextile as in GCL1 (see Figure 2.2). The slightly lower deduced interface transmissivity could be because: (i) the applied vertical pressure is greater than 150 kPa, and (ii) the vertical stress at the edges of the wrinkle (i.e., at the opening of the interface, e.g., points 1 and 2 in Figure 2.1a) may locally be even larger than 250 kPa because of arching around the stress-free zone beneath the wrinkle.

### 2.3.2 GCL seam parallel to wrinkle

To evaluate the hydraulic performance of overlapped GCL seams running parallel beneath a geomembrane wrinkle, first, Test T19 was conducted with a 150 mm wide overlapped GCL seam (containing the manufacturers’ recommended amount of supplemental bentonite) beneath a geomembrane wrinkle such that the crest of the geomembrane wrinkle and centre of the GCL seam were on the same vertical plane (see Figure 2.1b). The measured steady-state flow was $1.6 \times 10^{-11} \text{ m}^3/\text{s}$. The test ran for over 100 days (Figure 2.4), although steady-state flow conditions were reached after about 50 days. In a practical context, this measured flow would be only 0.023 lpd if there is a hole in a 10 m long wrinkle or 0.23 lpd in a 100 m long wrinkle (Appendix A.8).
Post-test evaluation showed that both ends of the overlapped seam were confined beneath the deformed wrinkle and there was an unstressed seam width equal to the gap that remained after wrinkle deformation (see Figure 2.5a). During permeation, the unstressed zone experienced a head of 0.3 m.

The measured flow in Test T19 was nearly one-fifth of that for a single panel of GCL beneath a geomembrane wrinkle in Test T36 \( (\Lambda = \text{[flow in T19]} / \text{[flow in reference case T36]} = 0.21) \). The flow is lower than single panel mainly because: (i) both ends of the GCL seam were confined under stress due to wrinkle deformation allowing no easy access for flow along the seam overlap (Figure 2.5a), (ii) there is substantially more bentonite in the unstressed zone beneath the wrinkle with a layer of hydrated supplemental bentonite between two layers of GCL (Figure 2.5a), and (iii) the zone beneath the wrinkle may have been under some degree of membrane confinement due to the narrower deformed wrinkle and foundation soil deformation. Using a GCL hydraulic conductivity and geomembrane/GCL interface transmissivity the same as those needed to match the measured flow in the case with single panel of GCL, and assuming the same hydraulic conductivity for the supplemental bentonite as the adjacent GCLs, in a two-dimensional finite-element steady-state seepage analysis, the calculated flow was about 10% higher than the observed flow (Appendix A.11). Irrespective of how the flow is analyzed, the measured flow value and post-test observations suggest that as long as the edges of the overlapped seam are confined by the deformed wrinkle and the hydraulic conductivity of the GCL remains low, flow can be expected to be very low. Thus, provided that there is sufficient overlap at the seam, a wrinkle parallel to, and directly over, a seam has less impact on leakage than a wrinkle over a single panel GCL without a seam. However this begs the question, what is sufficient overlap?

Although the forgoing result was very good with a 150 mm seam, it relied on the wrinkle and seam being position such that the seam was under stress on both sides of the wrinkle. The
probability of this occurring can be substantially increased by following the recommendation of some manufacturers’ to use a 300 mm panel overlap at side seams.

To show the importance to limiting flow of having the edges of the overlapped GCL seam confined, a test was conducted for the case where width of the GCL seam was narrower than the width that remained beneath the deformed wrinkle. This situation could correspond to a field case of an improperly overlapped seam that went undetected or, more probably, an initially adequate seam width but where the composite liner was left exposed and the GCL experienced some panel shrinkage (e.g., see Thiel and Richardson 2005) such that the seam width was reduced (to 50 mm here) at the time of covering to less than the deformed width of the wrinkle (i.e., length between points 3-4 in Figure 2.1b). Although not yet reported in the archival literature, this situation was observed at QUELTS (Brachman et al. 2014) in the studies of wrinkles (Rowe et al. 2012) and down-slope bentonite erosion (Take et al. 2015).

A 50 mm wide seam was tested without any supplemental bentonite placed at the seam (Test T8; Table 2.2) to simulate the situation where shrinkage had left only a small overlap of the zone of GCL outside the area where the supplemental bentonite had been placed. The width of the seam was selected to be narrower than the minimum final width of the deformed wrinkle reported by Brachman et al. (2011) after conducting physical tests on geomembrane wrinkles overlying GCL seams at vertical applied pressure of 250 kPa. As expected, the measured flow was unacceptably large at $1.7 \times 10^{-5} \text{ m}^3/\text{s}$, a six order increase compared to Test T19. Post-test observations revealed that the increase in flow was not just because the seam edges were unstressed but also the upgradient edge actually deformed upwards (Figure 2.5b) further reducing resistance to flow. This shows the importance of the manufacturers’ minimum specified GCL seam width if a wrinkle will be present when the liner is covered.
2.3.3 GCL seam perpendicular to the wrinkle

2.3.3.1 Perpendicular base case

In a situation such as shown in Figure 2.1c, where a GCL seam is perpendicular to the geomembrane wrinkle, the total flow through a hole in a wrinkle could be comprised of: (i) vertical flow through the GCL, and (ii) lateral flow between the GCL seam along the unstressed zone beneath the wrinkle (i.e., between points 1 and 2 in Figure 2.1c). To quantify the vertical flow through the GCL alone, in Test T41 a single intact panel of GCL was tested above an additional piece of GCL with the same dimension as the lower portion of an overlap (150 mm wide x 590 mm long) to simulate double the GCL thickness at the seam. No supplemental bentonite was placed in between the GCL specimens in this reference case. The geomembrane wrinkle was then oriented on top of the intact panel where the wrinkle crest line was perpendicular to the longer dimension of the additional GCL piece with the intent of obtaining a reference flow for the perpendicular case in which there was no flow through the overlap.

Steady-state flow was measured at 6.1x10^{-11} m^3/s, which is 80% of that that with a single panel GCL beneath a wrinkle (Test T36, Λ=0.8, Table 2.2). Flow is slightly lower than with the single panel because of the additional piece of GCL beneath a portion (approx. 30%) of the tested length of the wrinkle.

2.3.3.2 GCL seam without supplemental bentonite

An upper bound measure of flow for a GCL seam perpendicular to a wrinkle was obtained by allowing flow to occur freely along the width of the seam beneath the wrinkle. In Test T10, a 150 mm wide overlapped seam of GCL2 with no supplemental bentonite was placed perpendicular to a wrinkle. This situation could correspond to accidental field omission of supplemental bentonite over a length of the overlapped seam where a geomembrane wrinkle is intersecting the seam. A
A steady-state flow of $2.8 \times 10^{-8}$ m$^3$/s was measured, which is almost 500 times higher than the perpendicular base case (Test T41; Figure 2.6) and 370 times the reference case of a single GCL panel below the wrinkle ($\Lambda=370$). Because of the high-flow, steady-state permeation was attained within 4 days. Comparing the measured flow with the perpendicular base case suggests that 99.8% of the total flow occurred along the unstressed portion of the overlapped seam beneath the wrinkle.

The back-calculated interface transmissivity between the two GCLs at the seam beneath the wrinkle was $2 \times 10^{-7}$ m$^2$/s (Appendix A.9), which is lower than the range of $1 \times 10^{-5}$ and $2 \times 10^{-6}$ m$^2$/s for nonwoven needle-punched geotextiles (e.g., Koerner and Bove 1983). This suggests that upon hydration, bentonite in the GCL swelled into some of the voids of the nonwoven geotextiles along the unstressed seam width, thereby reducing the geotextile transmissivity compared to virgin geotextiles.

### 2.3.3.3 150 mm wide GCL seam with piled supplemental bentonite

Test T34 was conducted with a 150 mm wide GCL2 seam with supplemental bentonite piled along the centre of the seam at the manufacturer’s recommended rate of 400 grams per linear metre (e.g., see Figure 2.2a for an illustration of piled supplemental bentonite). Supplemental bentonite was piled along the centre of the seam with an intention to simulate a field condition where bentonite is poured out of a bag or through a hole at the bottom of a pail filled with dry bentonite (as observed during construction: Brachman et al. 2007; Rowe et al. 2014). The bentonite pile was about 15-mm-thick at its peak along the middle of the pile, was typically 50-60 mm wide and over the area covered had an average mass per unit area of 7300 g/m$^2$. A steady-state flow rate of $2.1 \times 10^{-10}$ m$^3$/s was measured (T34; $\Lambda=2.7$, Figure 2.6). This flow is much closer to the perpendicular base case (Test T41) than the case with no supplemental bentonite (Test T10), which shows the importance of supplemental bentonite at the GCL seam.
To put this measured flow in a practical context, consideration of flow beneath the wrinkle through the unstressed regions of the seam and through the single GCL panel away from the seam would be required. A wrinkle that is perpendicular to the GCL seam direction and longer than the GCL panel width could intersect multiple GCL seams. The number of seams beneath the wrinkle would hence depend on the length of the wrinkle and distance between the adjacent seams. For example, if a 10 m long wrinkle (with a hole) intersected two 150 mm wide GCL seams with piled supplemental bentonite at a 4.5 m centre-to-centre spacing, then the total flow could be estimated as the sum of the flow through two wrinkle-seam intersections (twice the flow measured in Test T34) plus the flow through a single panel GCL beneath the wrinkle along the 8.8 m remaining length of the wrinkle (obtained from the measured value for a 0.59 m long wrinkle in Test T36). The resulting calculated leakage would only be 0.14 lpd. For the same scenario but with a 100 m long wrinkle, there would be 22 wrinkle/seam intersections and 86.8 m of having a single GCL panel beneath the wrinkle and the calculate leakage would be 1.4 lpd; a very low number (Appendix A.8). In either case, the flow along the unstressed portion of the seam only was less than 30% of the total flow that would occur beneath the entire length of the wrinkle. Minimizing the length of buried wrinkles and minimizing the number of holes per hectare (e.g., see Rowe 2012) as well as ensuring adequate supplemental bentonite at the GCL seams is hence essential to obtaining very low potential leakage rates.

The nature of flow along the seam is examined in the photograph shown as Figure 2.7a, taken upon termination of Test T34 and after the top GCL panel was removed for inspection. Traces of blue dye along the interface between the upper GCL and top of the supplemental bentonite pile were evident, suggesting some flow along this interface. The geotextile in contact with the supplemental bentonite along this interface was the lower geotextile component of GCL2 (a composite slit-film woven and nonwoven needle-punched geotextile, see Figure 2.2b) where most
of the nonwoven needle-punched fibres were affected by the thermal treatment process. A more pronounced flow path was observed along the bottom of the supplemental bentonite (see Figure 2.7b), where the upper nonwoven needle-punched geotextile component of GCL2 was in contact with the supplemental bentonite. This difference in flow between the upper and lower interface could be due to differences in lateral transmissivity due to differences in geotextile properties at the interface. The mass per unit area of just the nonwoven component only of the composite carrier geotextile is about 145 g/m² whereas it is about 230 g/m² for the nonwoven cover geotextile. No obvious sign of flow through the supplemental bentonite was observed which suggests that the in-plane hydraulic transmissivity of the geotextiles in contact with the supplemental bentonite controlled flow in this experiment.

2.3.3.4 300 mm wide GCL seam with piled supplemental bentonite

There was no significant effect on flow when increasing the seam width of GCL2 to 300 mm for the case with supplemental bentonite piled at the centre. The absolute magnitude recorded flow with a 300 mm wide seam perpendicular to a wrinkle of 2.2 x 10⁻¹⁰ m³/s (T28a; Table 2.2) was slightly (5%) larger than that measured for the 150 mm wide seam with piled supplemental bentonite (2.1 x 10⁻¹⁰ m³/s, Test T34; Table 2.2); however a direct comparison of the absolute magnitudes of leakage for the two cases can be misleading. Assuming no material variability between the two tests, an increase in measured leakage would be expected in T28a compared to T34 simply because of the different in size of the test apparatus. Specifically, T28a was conducted in the 1 m diameter test cell while T34 was in the 0.59 m diameter cell and hence there was a greater contribution to the measured flow from flow through the single GCL panel beneath the wrinkle on either side of the seam in T28a. Taking this into account and considering only the seam, the flow though the 300 mm wide overlap was only 70% of that through just the 150 mm overlap. Thus, even for the perpendicular case, the 300 mm overlap recommended by some manufactures has
some advantage over 150 mm even without any shrinkage (the benefit will be increased further if there is some shrinkage).

2.3.3.5 Seam with evenly distributed supplemental bentonite

In some localized portions of the overlapped seams observed during construction of the Queen’s University Environmental Liner Test Site, the initial pile of supplemental bentonite was unintentionally spread out over more of the seam width (often after inspection of the seam for minimum overlap and supplemental bentonite). To explore the effect of supplemental bentonite distribution along the seam width on flow, in Test T12, the same 400 g/m of bentonite as used in Test 34 was evenly distributed along the width of the seam (see Figure 2.2d for an illustration of evenly distributed supplemental bentonite) rather than being more of a pile of supplemental bentonite (Figure 2.2b). The flow of $2.5 \times 10^{-10} \text{ m}^3/\text{s}$ measured for the 150 mm wide seam with even supplemental bentonite ($\Lambda = 3.3$; Test T12) was 20% higher than the $2.1 \times 10^{-10} \text{ m}^3/\text{s}$ measured with piled bentonite ($\Lambda = 2.7$; Test T34), suggesting that even if it were spread out over the entire seam width, 400 g/m appears to be a sufficient amount (i.e., 2700 g/m²) to provide enough supplemental bentonite to obtain low flow. The maximum thickness of hydrated supplemental bentonite at the unstressed zone was about 10 mm for the case with even distribution of supplemental bentonite and 25 mm for the piled case. Photographs taken after termination of Test T12 by removing the upper GCL panel at the seam (Figure 2.7c), and after partially removing the supplemental bentonite (Figure 2.7d) shows blue dye along the interface of both GCLs at the seam and evenly distributed supplemental bentonite suggesting flow has occurred along both interfaces. No flow through the supplemental bentonite was observed (Figure 2.7d). In Test T11 (not discussed in this chapter), tested under same conditions as in Test T12, in addition to the flow along the seam, some flow through the intact GCL panel was observed. Test T11 is discussed in Appendix A.10.
For the 300 mm wide seam, the measured flow with an even distribution of the 400 g/m of supplemental bentonite over the entire 300 mm overlap (Test T17; 9.8 × 10⁻¹⁰ m³/s) was 4.5 times larger than with piled supplemental bentonite (Test T28a; 2.2 × 10⁻¹⁰ m³/s). The higher flow in the 300-mm-even is from the much thinner layer of supplemental bentonite present at the seam (i.e., the same 400 g/m, but evenly spread out over a 300 mm wide zone to give 1300 g/m² in the covered zone). The thickness of evenly distributed hydrated supplemental bentonite at the seam for 300 mm seam was only 4 mm compared to 25 mm when piled. The thicker layer of bentonite was less sensitive to local irregularities in the foundation soil, differential swelling of the GCL beneath the wrinkle where the GCL is hydrating under zero normal stresses, or to seam deflections due to wrinkle deformations and thus resulted in a better seal at the seam.

2.3.4 Effect of GCL type

For otherwise the same test configuration (150 mm wide overlapped seam, piled supplemental bentonite), the measured flow with GCL1 in Test T26 (Λ=0.8) was only 30% of that with GCL2 in Test T34 (Λ =2.7; Table 2.2 and Figure 2.8a) and the same as for the base case Test T41 suggesting low flow through the interface between the upper and lower GCLs at the overlap in this case. Assuming Tests T26 and T34 had the same panel flow, the difference in part is from the GCL2 having an additional nonwoven geotextile as a part of its composite woven/nonwoven carrier geotextile at the seam (see Figure 2.2b). The effect of this nonwoven component on flow is evidenced by the presence of a blue dye stain along the interface between the top GCL and the supplemental bentonite (Figure 2.7a). There was no such evidence of flow along the same interface with GCL1 (Figure 2.9a). The slightly lower mass per unit area nonwoven cover geotextile on GCL1 (216 g/m² for GCL1 vs 230 g/m² for GCL2) may have also contributed to a lower in-plane transmissivity beneath the supplemental bentonite and this geotextile and hence slightly lower flow.
GCL8 is a multicomponent product with a polymer coated woven carrier geotextile (Figure 2.2c). This polymer coating both reduces the hydraulic conductivity and provides some protection to the bentonite core in cases where there are concerns about cation exchange or desiccation (Hosney and Rowe 2013). Test T33 with GCL8 was conducted to examine if this polymer coating impacts flow through the overlapped seams. The polymer coating was placed facing down (Figure 2.2c). A measured flow of $1.7 \times 10^{-10}$ m$^3$/s in Test T33 (Table 2.2) was slightly less than $2.2 \times 10^{-10}$ m$^3$/s measured for GCL2 in Test T28a (Figure 2.8b) for a comparable test configuration (300 mm overlapped seam, piled supplemental bentonite). There was no evidence of flow along the interface between the supplemental bentonite and the polymer coating (Figure 2.9b) and the small interface flow was at the interface between the nonwoven cover geotextile and the supplemental bentonite.

A direct comparison with results from GCL2 is not straightforward because of differences in potential for both panel and seam flow. With GCL8, the panel flow was presumably low through the polymer coating. If 10% of the measured flow is attributed to flow through the GCL panel and 90% along the seam (based on upper bound measurement of $k$ for GCL8 by Hosney and Rowe 2013), then the isolated seam flow would be $1.5 \times 10^{-10}$ m$^3$/s. For GCL2, the comparable seam flow is $1 \times 10^{-10}$ m$^3$/s. The only observed difference between the seams for GCL2 and GCL8 was that GCL8 had a slightly thicker nonwoven cover geotextile ($247$ g/m$^2$ for GCL8 vs $230$ g/m$^2$ for GCL2).

The overlapped seams of GCL1, GCL2 and GCL8 all performed very well. Following the earlier example, if a 100 m long wrinkle (with a hole) intersected twenty two 150 mm wide GCL seams with piled supplemental bentonite at a 4.5 m centre-to-centre spacing, then the calculated leakage would only be 1 lpd for GCL1 based on Test T26 and 1.4 lpd for GCL2 based on Test T34. For the same length of wrinkle but with a 300 mm wide seam and a 4.35 m centre-to-centre spacing
with twenty three wrinkle-seam intersections, the calculated leakage would be 1.3 lpd for GCL2 based on Test T28a and 0.4 lpd for GCL8 based on Test T33 (Appendix A.8). In all these cases the flows were very low.

2.3.5 Effect of higher applied stresses on flow

All of the tests discussed thus far were conducted at an applied vertical pressure of 250 kPa. To study the effect on leakage at a higher applied stresses arising from deeper burial, two tests were conducted at an applied pressure of 500 kPa and one test was conducted at 1000 kPa (Figure 2.10). These tests were conducted on a 300 mm wide GCL2 seam with piled supplemental bentonite. Tests T28a, b and c are essentially same test conducted at three different stresses, starting at 250 kPa and increasing the pressure to 500 and then 1000 kPa, allowing the system to reach steady-state flow conditions between each stress increment. Compared to the flow measured at 250 kPa (2.2 x 10^{-10} m^3/s), the flow reduced by about 40% to 1.3 x 10^{-10} m^3/s at 500 kPa and 50% to 1.1 x 10^{-10} m^3/s at 1000 kPa. The recorded flow from another test conducted only at 500 kPa (1.5 x 10^{-10} m^3/s; Test T18), in the 0.59 m diameter test cell was practically same as Test T28b (1.3 x 10^{-10} m^3/s), which, allowing for the larger size of the cell used for Test T28, suggests that there was relatively little effect of permeating the test under lower pressure before applying higher pressures.

The effect of the different applied stresses on the gap remaining beneath the wrinkle at the end of the test is shown in Figure 2.11. While the gap beneath the wrinkle at 250 kPa and 500 kPa—in Tests T28a and T28b—could not be measured, it is assumed to be similar to those measured in Test T41 for 250 kPa and Test T18 for 500 kPa. The reduction in area of unstressed panel beneath the wrinkle accounts for reducing the total flow by only 5% at 500 kPa and 25% at 1000 kPa. The additional reduction in flow at higher applied vertical stresses can be attributed to the effect of one or more of the following: (i) a possible increase in membrane confinement of the GCL beneath the
unstressed portion of the wrinkle, (ii) a possible increase in confining stress on the supplemental bentonite, and/or (iii) a further decrease in GCL-geomembrane interface transmissivity away from the wrinkle.

2.4 Conclusions

Coupled physical and hydraulic experiments were conducted to quantify the leakage through overlapped GCL seams under non-uniform stresses from an overlying geomembrane wrinkle. The influence of wrinkle-seam orientation, seam width, presence and distribution of supplemental bentonite, GCL type, and applied stresses were examined. For the test conditions and materials examined, the principal conclusions are:

1. Wrinkle parallel to the GCL seam:
   - When the wrinkle was aligned directly above and parallel to the seam, flow was a function of the width of the seam relative to the deformed width of the wrinkle.
   - When the seam was narrower than the wrinkle, fluid could easily enter and flow along the unstressed width of the seam resulting in very large leakage. With a wider seam, both ends of the seam were confined under vertical stress from the deformed wrinkle and there was no sign of preferential flow along the seam; flow was predominantly downward through the seam and slightly smaller than the case with just a single intact GCL panel (i.e., no seam) beneath the wrinkle.
   - Provided the width of the seam (overlap) was sufficient, wrinkles parallel to the GCL seam had no negative effect on leakage (indeed the leakage was less than it would be directly over a panel of GCL, although both were very small).
2. Wrinkle perpendicular to the GCL seam: orienting the wrinkle perpendicular to the seam introduced an unstressed width of the seam equal to the width of the deformed wrinkle. Flow along the seam was affected by the:

- presence and distribution of supplemental bentonite: 400 g per linear metre of supplemental bentonite placed in a pile between the overlapped panels at the seam decreased the flow by over two orders of magnitude compared to having no supplemental bentonite. When the same 400 g/m of bentonite was evenly distributed along the entire width of the seam (producing a thinner layer of supplemental bentonite in the seam) the seam flow increased somewhat because the same amount of bentonite was more effective when piled than spread uniformly over a larger area since it then appeared to be less sensitive to local deformations and variations in GCL thickness beneath the wrinkle.

- type of geotextile: preferential flow was observed along the interface between the supplemental bentonite and the nonwoven geotextile at the seam. There appeared to be no obvious signs of preferential flow through the supplemental bentonite or along the interface between the supplemental bentonite and the woven geotextile or a woven geotextile with polymer coating.

- applied vertical stress: increasing the applied vertical pressure slightly reduced the wrinkle width and increased the normal stress applied by the wrinkle to the GCL, which resulted in flows that were 40 and 50% lower at 500 kPa and 1000 kPa than that measured at 250 kPa.

The results reported in this chapter show that GCL seams overlapped by 150-300 mm with 400 g/m of supplemental bentonite placed in a pile between the overlapped panels at a seam can significantly reduce preferential flow along the unstressed portion of GCL seam beneath a
geomembrane wrinkle to the point where the leakage was no larger than reference cases with single intact GCL panels. In addition to reducing the number holes and minimizing the length of wrinkles, ensuring that (i) the width of the overlapped GCL seam is greater than the wrinkle width, and (ii) there is adequate supplemental bentonite, is essential to obtaining very low leakage rates with composite geomembrane / GCL liners.

The results of this study have the following practical implications:

- Recognizing that some wrinkles are likely in most practical field cases and that these wrinkles often align with or cross GCL seams, it is important (i) to have adequate bentonite between the overlapped panels, and (ii) that the overlap at the time the composite liner is covered be, at a minimum, around 150 mm (i.e., after any shrinkage).

- With piled supplemental bentonite, better performance can be expected for 300 mm overlaps than 150 mm overlaps and, in addition, the 300 mm overlap provides some protection against small deviations from the specified overlap in the field as well as some modest shrinkage of the GCL prior to covering of a composite liner. Thus, this work provides scientific support to some manufacturers’ recommendations that the overlap at the seams be 300 mm at adjacent parallel panels.

- The coated GCL examined performed very well and the specific coating examined did not appear to have any negative impact on the performance of the overlap for the coated GCL examined (additional testing would be required to generalize this observations since different coatings and laminations may perform quite differently and, potentially, not as well).

- With a suitable amount of piled bentonite (400 g/m) and overlap at the seam, the calculated leakage for a modest length of wrinkle with a hole (i.e., 100m) (either over
and parallel to, or crossing, GCL seams, the leakage was very low. This is consistent with the previously reported good performance of well-constructed composite liners in the field.

- This work provides support for previous recommendations to control the length of connected wrinkles (which run over and parallel to, or crossing, GCL seams) and to avoid shrinkage of a GCL that could reduce the overlap at the seam to less than 150 mm.
2.5 References


Table 2.1. Properties of GCLs tested.

<table>
<thead>
<tr>
<th>GCL</th>
<th>Dry mass per unit area (g/m²)</th>
<th>Cover geotextile</th>
<th>Carrier geotextile</th>
<th>Cover geotextile mass per unit area (g/m²)</th>
<th>Carrier geotextile mass per unit area (g/m²)</th>
<th>Panel bentonite swell index (ASTM 2006) (mL/2g)</th>
<th>Peel strength⁴</th>
<th>Peel strength⁴</th>
</tr>
</thead>
<tbody>
<tr>
<td>GCL¹</td>
<td>4904 (SD = 370, n = 4)</td>
<td>Nonwoven needle punched</td>
<td>Woven</td>
<td>216 (SD = 9, n = 4)</td>
<td>155 (SD = 9, n = 4)</td>
<td>26</td>
<td>662 (SD = 88)</td>
<td>94 (SD = 17)</td>
</tr>
<tr>
<td>GCL²</td>
<td>4380 (SD = 211, n = 14)</td>
<td>Nonwoven needle punched</td>
<td>Scrim reinforced nonwoven</td>
<td>230 (SD = 14, n = 14)</td>
<td>256 (SD = 12, n = 14)</td>
<td>25</td>
<td>1549 (SD = 75)</td>
<td>194 (SD = 16)</td>
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<tr>
<td>GCL³</td>
<td>5020 (SD = 178, n = 4)</td>
<td>Nonwoven needle punched</td>
<td>Woven with polymer coating</td>
<td>247 (SD = 33, n = 4)</td>
<td>359 (SD = 17, n = 4)</td>
<td>26</td>
<td>1516 (SD = 108)</td>
<td>204 (SD = 16)</td>
</tr>
</tbody>
</table>

Note: SD = standard deviation; n = number of replicates; GCLs were Bentofix™¹ NSL, ² SRNL, ³ CNSL; ⁴ values adopted from Rentz 2015.
Table 2.2. Summary of permeation tests.

<table>
<thead>
<tr>
<th>Test name</th>
<th>GCL type</th>
<th>Orientation with wrinkle</th>
<th>Seam width (mm)</th>
<th>Supp. bent.</th>
<th>Applied pressure (kPa)</th>
<th>Cell dia. (m)</th>
<th>GCL water content relative to wrinkle (%)</th>
<th>Steady state flow (m³/s)</th>
<th>Λ</th>
<th>Perm. duration (days)</th>
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<tr>
<td>T36</td>
<td>GCL2</td>
<td>Single panel (no seam) reference</td>
<td>250</td>
<td></td>
<td>0.59</td>
<td></td>
<td>130</td>
<td>86</td>
<td>7.6 x 10⁻¹¹</td>
<td>1</td>
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<td>T8</td>
<td>GCL2</td>
<td>Parallel</td>
<td>50</td>
<td>None</td>
<td>250</td>
<td>0.59</td>
<td>-</td>
<td>-</td>
<td>1.7 x 10⁻⁵</td>
<td>&gt; 200,000</td>
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<tr>
<td>T19</td>
<td>GCL2</td>
<td>Parallel</td>
<td>150</td>
<td>Piled</td>
<td>250</td>
<td>0.59</td>
<td>138</td>
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<td>1.6 x 10⁻¹¹</td>
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<td>T41</td>
<td>GCL2</td>
<td>Perpendicular base case</td>
<td>250</td>
<td></td>
<td>0.59</td>
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<td>147</td>
<td>92</td>
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<td>T10</td>
<td>GCL2</td>
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<td>150</td>
<td>None</td>
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<td>2.8 x 10⁻⁸</td>
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<td>T34</td>
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<td>2.1 x 10⁻⁹</td>
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<td>GCL2</td>
<td>Perpendicular</td>
<td>150</td>
<td>Even</td>
<td>250</td>
<td>0.59</td>
<td>145</td>
<td>-</td>
<td>2.5 x 10⁻¹⁰</td>
<td>3.3</td>
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<tr>
<td>T17</td>
<td>GCL2</td>
<td>Perpendicular</td>
<td>300</td>
<td>Even</td>
<td>250</td>
<td>0.59</td>
<td>137</td>
<td>93</td>
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<td>T26</td>
<td>GCL1</td>
<td>Perpendicular</td>
<td>150</td>
<td>Piled</td>
<td>250</td>
<td>0.59</td>
<td>161</td>
<td>72</td>
<td>6.1 x 10⁻¹¹</td>
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<tr>
<td>T33</td>
<td>GCL8</td>
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<td>300</td>
<td>Piled</td>
<td>250</td>
<td>1</td>
<td>152</td>
<td>82</td>
<td>1.7 x 10⁻¹⁰</td>
<td>1.2*</td>
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<td>T28a</td>
<td>GCL2</td>
<td>Perpendicular</td>
<td>300</td>
<td>Piled</td>
<td>250</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>2.2 x 10⁻¹⁰</td>
<td>1.5*</td>
</tr>
<tr>
<td>T28b</td>
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<td>Perpendicular</td>
<td>300</td>
<td>Piled</td>
<td>500</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>1.3 x 10⁻¹⁰</td>
<td>0.9*</td>
</tr>
<tr>
<td>T28c</td>
<td>GCL2</td>
<td>Perpendicular</td>
<td>300</td>
<td>Piled</td>
<td>1000</td>
<td>1</td>
<td>154</td>
<td>64</td>
<td>1.1 x 10⁻¹⁰</td>
<td>0.8*</td>
</tr>
<tr>
<td>T18</td>
<td>GCL2</td>
<td>Perpendicular</td>
<td>300</td>
<td>Piled</td>
<td>500</td>
<td>0.59</td>
<td>160</td>
<td>-</td>
<td>1.5 x 10⁻¹⁰</td>
<td>2.5</td>
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</table>

Note: Λ = (flow in Test T#) / (flow in reference case Test T36); * Flow from the reference test (Test T36) scaled up for 1-m-diameter test cell to calculate an equivalent Λ.
Figure 2.1 Cross-section views showing geomembrane wrinkle and GCL: (a) single panel of GCL beneath a wrinkle, (b) wrinkle on top and parallel to an overlapped GCL seam, and (c) wrinkle perpendicular to a GCL seam.
Figure 2.2 Schematic of the tested GCLs: (a) GCL1 with piled supplemental bentonite, (b) GCL2 with piled supplemental bentonite, (c) GCL8 with piled supplemental bentonite and (d) GCL2 with even supplemental bentonite.
Figure 2.3 Schematic of permeation test setup (all dimensions in mm).
Figure 2.4 Flow vs time for parallel GCL2 with different seam width and base case with a single panel of GCL beneath a wrinkle.
Figure 2.5 Geomembrane wrinkle and GCL seam deformation due to applied vertical stress (250 kPa): (a) Gap beneath the wrinkle partially filled with free swelling GCL and supplemental bentonite, and (b) Vertical movement of edge of the GCL seam (narrower than final geomembrane wrinkle) upon wrinkle deformation.
Figure 2.6 Reduction in flow due to the presence of supplemental bentonite at the seam of GCL2 in perpendicular case with 150 mm wide seams tested in 0.59 m test cell.
Figure 2.7 (a) Photograph taken after termination of Test T34 with upper panel removed to show dye stains on top of the supplemental bentonite, (b) Photograph with the central piled supplemental bentonite cut and flipped to show dye stains on the bottom of the supplemental bentonite in Test T34, (c) Photograph taken after Test T12 termination with upper GCL panel lifted to show dye stains on top of the evenly distributed supplemental bentonite, and (d) Photograph showing dye on the bottom of supplemental bentonite in Test T12 (the bentonite was dry and desiccated when the picture was taken).
Figure 2.8 Effect of GCL type on flow: (a) Lower flow through 150 mm wide GCL1 seam, and (b) Lower flow through 300 mm wide GCL8 seam, compared to a test with GCL2 seam. Note that in comparing leakage, allowance must be made for the larger dia. test cell used for tests in Figure 2.8b.
Figure 2.9 Photograph taken after test termination with upper GCL panel lifted to expose the supplemental bentonite: (a) GCL1, and (b) GCL8. No dye stains visible on top of the supplemental bentonite. Flow occurred along the bottom of the supplemental bentonite pile.
Figure 2.10 Effect of applied vertical stress on flow. All tests involved a geomembrane wrinkle perpendicular to a 300 mm GCL seam with piled supplemental bentonite.
Figure 2.11 Height and width of the gap beneath the wrinkle. Width of the void space decreased with increasing pressure.
Chapter 3

Hydraulic performance of GCL seams without field-applied supplemental bentonite below a geomembrane wrinkle

3.1 Introduction

Conventionally, geosynthetic clay liners (GCLs) require field-applied supplemental bentonite (i.e., in addition to the panel bentonite contained between geotextiles) placed along overlapped seams between adjacent panels to limit preferential flow along the seam. Figure 3.1a illustrates an overlapped GCL seam with piled supplemental bentonite placed along the centre of the seam. Estornell and Daniel (1992), Cooley and Daniel (1995) and Benson et al. (2004) have reported that addition of 400 grams per linear metre of supplemental bentonite and subjecting the seam to an uniform overburden stress can reduce any preferential flow along the seam to a point where the leakage along the seam is no larger than that would be through a single panel of GCL. Previous studies (Estornell and Daniel 1992; Cooley and Daniel 1995; Daniel et al. 1997; Benson et al. 2004; Chapter 2 in this thesis) have reported higher leakages along the seam when the: (i) seam contained less than manufacturers’ recommended amount of supplemental bentonite, (ii) recommended amount of supplemental bentonite was distributed along the entire width of the seam in a thin layer (seam more sensitive to local deformations and bentonite thickness variations), (iii) GCL panel contained a non-uniform mass of bentonite distribution causing differential swelling at the seam, (iv) overlapped seam was subjected to low to no vertical stresses, and (v) supplemental bentonite at the seam was in contact with a nonwoven needle-punched geotextile component of the GCL.
Some modern GCLs are designed and manufactured in a way that they do not require placing field-applied supplemental bentonite along the longitudinal overlapped seams to simplify installation. The performance of two such products, one containing a melted groove in its nonwoven geotextile (Figure 3.1b) and the other with factory-applied powered bentonite impregnated in the nonwoven geotextile component at the seam are investigated in this study (Figure 3.1c).

Kendall and Austin (2014) conducted permeation tests on two GCLs containing factory-applied impregnated powered bentonite on the nonwoven geotextile at the seam (Figure 3.1c). Tests were conducted with and without seams in a rectangular flow box (1-m-long x 0.5-m-wide) and the GCLs were subjected to a uniform confining stress due to the overlying 300 mm of gravel and a hydraulic head between 1.3-3.5 m. The total flow (combined flow along 300 mm wide seam and through the GCL panel) was between 1.2 to 2.7 times smaller than that only through a single panel of GCL. This work is useful in showing excellent performance of the tested seam-sealing technique under uniform overburden stresses; however, in the field it is possible that the GCL seams experience low to no overburden stresses (e.g., due to the presence of an overlying geomembrane wrinkle) and there is a paucity of data on the performance of such GCL seams under those stress conditions.

Although small in height (< 10 mm), an overlapped GCL seam can be a geometric imperfection that lead to the formation of a geomembrane wrinkle. Rowe et al. (2012) reported the formation of geomembrane wrinkles both in the roll and cross-roll directions which means those wrinkles can be oriented both parallel and perpendicular to an overlapped GCL seam (see Figure 3.2 for the illustration of orientation between geomembrane wrinkles and a GCL seam). Brachman et al. (2011) (Appendix A.19) reported results from physical tests conducted on a 1.5-mm-thick
high-density polyethylene (HDPE) geomembrane wrinkle when buried beneath a poorly graded gravel layer, oriented parallel and perpendicular to a 150 mm wide overlapped GCL seam, and subjected to a vertical pressure of 250 kPa. They reported that the geomembrane wrinkle reduced in height and width but remained, which is consistent to what Soong and Koerner (1998), Gudina and Brachman (2006), and Brachman and Gudina (2008) reported in a similar studies but not involving GCL seams. For a parallel case (i.e., the GCL overlap lies directly beneath and is aligned with a geomembrane wrinkle, Figure 3.2a), Brachman et al. (2011) anticipated a good seam performance as long as both ends of the GCL seam are confined beneath the deformed wrinkle; while, for a perpendicular case, flow along the unstressed GCL seam beneath the wrinkle was expected to be more sensitive to hydraulic performance of the seam. Consequently, a series of tests on GCL seams that required field-applied supplemental bentonite with an overlying geomembrane wrinkle were conducted and reported in Chapter 2. When the GCL seam was parallel to the geomembrane wrinkle, for a seam that was wider than the deformed geomembrane wrinkle, it was observed that the flow was predominantly downward through the GCL and five times smaller than the case with just a single intact GCL panel (i.e., no seam) beneath the wrinkle. When the geomembrane wrinkle was perpendicular to the GCL seam (Figure 3.2b), the flow along the seam depended mainly on the presence and distribution of supplemental bentonite at the seam.

In some cases, the lower geotextile from the upper GCL panel can be heat-tacked (i.e., thermally fused) to the upper geotextile from the lower GCL panel along the overlapped seam in the field. Heat-tacking has been investigated and proposed as a preventive measure against GCL panel shrinkage for some applications while the liner is exposed for an extended period of time (Thiel and Thiel 2009; Rowe et al. 2010). However, it is unknown to what extent heat-tacking may also effect the hydraulic performance of the overlapped seam.
The objective of this chapter is to provide some insight into the effect that the overlying geomembrane wrinkle may have on the hydraulic effectiveness of overlapped seams of GCL products using two different seam sealing techniques not requiring field-applied supplemental bentonite – one with a narrow, linear factory melted groove in one of the geotextiles; the other with factory applied powered Bentonite. Measured fluid flow from coupled physical and hydraulic experiments conducted under an applied vertical pressure of 250 kPa and hydraulic head of 0.3 m with a geomembrane wrinkle parallel and perpendicular to the GCL seam are reported. The effect of heat-tacking on the leakage rate through the GCL seam are also investigated.

### 3.2 Materials and method

The index characteristics of the four tested GCLs, denoted as GCLs 3, 4, 5 and 6, are shown in Table 3.1 and are illustrated in Figure 3.3 (where the nomenclature was adopted to match Ashe et al. 2015). While all of the tested products do not require placing additional bentonite at the seam during field installation, the fundamental differences between the GCLs is the seam sealing technique. GCL3 and 4 contain a narrow, linear, factory melted groove on the nonwoven cover geotextile (about 75 mm inwards from the lateral ends of the roll). This groove is intended to allow hydrated panel bentonite to extrude into the seam. Performance of these GCL seams is expected to depend on the quality of the melted groove and the amount and swelling capacity of the panel bentonite. In GCL5 and 6, a 500 mm wide strip of the nonwoven cover geotextile along the lateral edges of the GCL rolls were impregnated with factory-applied powered bentonite. This impregnated bentonite is intended to swell upon hydration and thereby seal the seam. Since the amount of bentonite along the seam area is distributed as a thin layer, the seam performance with this technique may be expected be more sensitive to local GCL deformations, if unstressed.
All GCLs at their off-the-roll moisture content (~30-39% for GCL3 and GCL4, ~10-14% for GCL3b, ~10% for GCL5 and 6), were first placed on a firm, saturated, poorly graded sand foundation. This sand had an initial dry density of 1.91 g/cc, mean grain size of 0.45 mm, and uniformity coefficient of 4 (ASTM 2009; Appendix A.1). Above the GCL, a 1.5-mm-thick high-density polyethylene (HDPE) geomembrane with an artificially formed wrinkle (initially 60-mm-high and 200-mm-wide) was placed (Figure 3.4). The geomembrane was covered by a 580 g/m² nonwoven geotextile protection layer beneath a 0.3 m thick layer of nominal 50 mm coarse gravel (grain size distribution of the coarse gravel is shown in Appendix A.1).

A cylindrical test cell with an internal diameter of 0.59 m was used to conduct all tests on 150 mm wide overlapped seams of GCL3, 3b and 4. For 300 mm wide overlapped seams of GCL5 and 6, a larger test cell with an internal diameter of 1 m was used. A cross-section of the 1-m-diameter test cell showing the test setup and materials tested is shown in Figure 3.4. The test boundary conditions are same as that described in Chapter 2 where a uniform vertical pressure was applied on top soil surface by inflating a flexible rubber bladder using fluid pressure. Outward deflection of the rigid cell wall was limited which developed horizontal stresses corresponding to zero lateral strains. Friction along the inner wall surface was minimized by applying friction treatment that involved attaching one of the two layers of 0.1-mm-thick polyethylene sheets—lubricated with grease in between—on the inner wall of the cell to allow the other layer to slide with the soil in contact (see Tognon et al. 1999 for the details of friction treatment). With this treatment, in excess of 95% of the vertical stress has been shown to be transferred at the elevation of the geomembrane (Brachman and Gudina 2002).

All GCLs were hydrated inside the test apparatus prior to permeation. The GCLs were first allowed to hydrate for four days from moisture from the saturated sand below the GCL and a 20-
40 mm deep water pond above the GCL inside the wrinkle under just the weight of 0.3 m of gravel above the geomembrane. Hydration trials conducted on GCL specimens outside of the apparatus showed the adopted hydration conditions and time allowed the GCLs to attain over 90% of their reference water content (i.e., the maximum water content attainable under the hydration conditions; Appendix A.5). The GCLs in the apparatus were then allowed to further hydrate (for the portion directly beneath the wrinkle) or to consolidate (for the GCL loaded by the gravel away from the wrinkle) for four days under an applied vertical pressure of 250 kPa (applied in five equal increments, each ten minutes apart) prior to starting the permeation phase of the experiment. The gravimetric water contents of the GCL beneath and away from the wrinkle after permeation and upon termination of each experiment are reported in Table 3.2.

The permeation phase of each experiment involved imposing a difference in hydraulic head of 0.3 m between the fluid in the wrinkle and outflow discharge point. With negligible head loss in the sand beneath the GCL, the 0.3 m head drop essentially acted over the GCL overlap. Preferential flow along the inner wall of the test cell and the GCL was prevented by applying a bentonite based perimeter seal consisting of layers of dry and wet bentonite (Appendix A.3). As a check that there was no side wall leakage and to help evaluate where the flow occurred, a laboratory-grade-dye (Brilliant Blue G-250, Fisher BioReagents) was added to the low ionic strength tap water @0.4 g/l. This dye showed no effect on the swelling capacity of bentonite (Appendix A.7) and there was no evidence of preferential flow through the seal upon inspection following completion of each experiment.

3.3 Results and discussion

3.3.1 Base case with a single panel of GCL
As a reference base case, results from Test T37 conducted in a 0.59 m diameter test cell with a single panel of GCL4 (i.e., with no seam) placed beneath a geomembrane wrinkle and permeated under a hydraulic head of 0.3 m under an applied stress of 250 kPa are presented first. GCL4 has nonwoven needle-punched geotextiles for both its upper and lower geotextiles. A steady-state flow rate of 6.6 x 10^{-11} \text{m}^3/\text{s} (0.006 lpd, litres per day) was recorded from an experiment conducted for 90 days (Test T37, Figure 3.5a). In a practical context, this measured flow would correspond to about 1 lpd if there was a hole in a 100 m long wrinkle feature overlying a single panel of GCL4. Such a flow would be so small that diffusion would likely be the dominating transport mechanism for many practical cases (e.g., see Rowe 2005, 2012). Here, and in all similar calculations, it is assumed that the hole itself does not limit the flow (e.g., see Rowe et al. 2004).

Although the entire flow occurred through the intact GCL, there may be differences in the amount of flow through the unstressed portion of the GCL immediately beneath the wrinkle and that beside the wrinkle. Flow through the GCL section beneath the deformed wrinkle is controlled by the hydraulic conductivity, \( k \), of the GCL subjected to no applied stresses. Flow through the GCL away from the wrinkle is controlled by both \( k \) and the transmissivity along the geomembrane/GCL interface, \( \theta \), and this interface is compressed by the applied stresses (locally at the edges of the wrinkle; this vertical stress is likely larger than the applied stress of 250 kPa due to stress redistribution away from the wrinkle). Due to the consolidation of the GCL under such high applied stresses, the hydraulic conductivity of the GCL away from the wrinkle is expected to be very low (< 7 x 10^{-12} \text{m/s}; Rowe 2012). The value of \( \theta \) away from the wrinkle is also expected to be low. For example, for a comparable GCL with a nonwoven cover geotextile, Rowe and Abdelatty (2012) reported \( \theta = 2.2 \times 10^{-11} \text{m}^2/\text{s} \) under 100 kPa of confining stress, while Barroso et al. (2010) reported \( \theta = 7.8 \times 10^{-12} \text{m}^2/\text{s} \) under 200 kPa. Under the test conditions, even lower \( \theta \)
could be expected because of the larger applied vertical stresses. Thus for a very low $k$ and $\theta$, away from the wrinkle, any flow occurring other than through the section of GCL immediately beneath the wrinkle is neglected. Using two dimensional finite element analysis (using SEEP/W, GeoStudio 2012) and assuming flow occurring only through the GCL section immediately beneath the wrinkle (i.e. $\theta=0$), a GCL $k = 4.8 \times 10^{-11}$ m/s is required to match the measured flow (Appendix A.11). This value of $k$ is not larger than is typical for a needle-punched GCL permeated with low ionic strength water at a low confining stress of 3-4 kPa ($5 \times 10^{-11}$ m/s; Rowe 2012). Overall, flow through a single panel of GCL beneath a wrinkle is expected to remain low as long as the GCL hydraulic conductivity remains low (Rowe 2012).

### 3.3.2 Bentonite hydration through the melted groove

The GCL3 and 4 samples studied was shipped directly to the laboratory by the manufacturer specifically for this study. The samples of GCL containing a melted groove were carefully examined for GCL3, 3b and 4. In total, 3.6 m of melted groove were inspected for GCL3, 10 m for GCL3b, and 15 m for GCL4. Based on the observed continuity of the melted groove in the geotextile, the groove was then categorized as having a complete or an incomplete melt (Appendix A.12). A complete melt groove had the entire thickness of the nonwoven geotextile melted and the panel bentonite fully exposed such that there would be no resistance to free extrusion of panel bentonite upon hydration (e.g., a complete melt groove is shown in Figure 3.6a). A groove where the panel bentonite was not well exposed, as there were still nonwoven fibers at the groove mainly due to only partial melting of the nonwoven geotextile, was categorized as an incomplete melt (e.g., an incomplete melt groove is shown in Figure 3.6b).
To observe the effect of the degree of melt at the groove on hydration and penetration of panel bentonite through the groove, complete and incomplete melted groove edge samples obtained from the GCL3b (Figure 3.6a, b) and a sample from GCL4 were allowed to hydrate when submerged in tap water with no overburden stress (Appendix A.13). As intended, the panel bentonite in samples with a complete geotextile melt (both for GCL3b and 4) swelled through the groove. The maximum height of bentonite that swelled through the groove was 8 mm for GCL3b (see Figure 3.6c) and 10 mm for GCL4 beyond the surface of the GCL as measured with a line-laser. The dry mass per linear metre of the extruded bentonite (above the GCL surface) was 7 g/m for GCL3b and 8 g/m for GCL4. However, the sample with incomplete geotextile melt showed little to no sign of bentonite penetrating the intended melt zone (see Figure 3.6d for a GCL3b sample with incomplete melt). The laser scan detected at most 2 mm of bentonite protruding above the GCL surface at only discrete and non-continuous locations of hydrated bentonite along the groove.

To assess the potential impact of bentonite penetration through the melted groove on seam flow, all GCL3b test specimens for permeation testing were selected from the continuous zones with an incomplete geotextile melt.

### 3.3.3 GCL seam parallel to the wrinkle

Test T24 was conducted with a 150 mm wide overlapped seam of GCL4 with the seam running parallel to the geomembrane wrinkle with the melted groove facing down. The seam was installed with the melted grooves of both GCL panels facing down and aligned such that the crest of the geomembrane wrinkle was on the same vertical plane of the melted groove (e.g., see Figure 3.4). A steady-state flow of $1.2 \times 10^{-10} \text{ m}^3/\text{s} (0.01 \text{ lpd})$ was measured. This flow is 1.8 times higher than that measured in the reference base case with a single panel of GCL4 beneath the wrinkle ($\Lambda = \frac{\text{[flow in T24]}}{\text{[flow in the reference case T37]}}= 1.8$). For a 100 m long field wrinkle parallel to the
seam, this flow would correspond to about 1.6 lpd. If the seam was perfect in Test T24, one would expect the flow to be smaller than that with a single panel of GCL4 (in Test 37) mainly because: (i) there were two layers of GCLs beneath the wrinkle, and (ii) both ends of the GCL seam were confined under stress due to wrinkle deformation allowing no easy access for flow along the seam. For a GCL without melted groove and tested under the same configuration as in Test T24, Chapter 2 reported a five fold decrease in flow at the seam compared to only having a single panel of the same GCL. Post-test observations conducted to understand the reason for the higher than expected flow in Test T24 showed evidence of preferential vertical flow through the unstressed melted groove lying directly below the wrinkle. Some differential movement of the subgrade directly beneath the wrinkle (where the subgrade surface beneath the wrinkle was up to 2 cm higher than that beside the wrinkle) was also observed due to the stress distribution that develops around a wrinkle (Appendix A.14). This differential movement of the subgrade may have strained the GCL at the groove and lead to preferential flow through the unstressed groove. This location with higher $k$ along the groove relative to the adjacent GCL (with confined bentonite), created a preferential flow path along the groove (see Figure 3.7a for the schematic of the observed predominant flow path). Despite of this preferential flow along the groove, the flow of 1.6 lpd/100 m is still very low, thus it appears that as long as the $k$ of groove bentonite and the GCL remains low, the flow is expected to remain low.

3.3.4 GCL seams perpendicular to the wrinkle

3.3.4.1 Permeation through 150 mm wide GCL4 seams

Test T22 was conducted with a 150 mm wide overlapped GCL4 seam with the melted groove facing down (e.g., Figure 3.3a). A flow rate of $2.2 \times 10^{-10} \text{ m}^3/\text{s}$ (0.019 lpd, $\Lambda=3.3$) was measured in a test permeated under an applied stress of 250 kPa and 0.3 m hydraulic head (Figure 3.5b). The measured
flow is the combination of the flow through the GCL panel and any preferential flow along the seam beneath the wrinkle. Based on the calculated flow through the GCL only (two layers of GCL at the seam and one layer away from the seam) using the inferred $k$ from Test T37, about 75% of the total flow measured in Test T22 can be attributed to preferential flow along the unstressed portion of the seam (see Figure 3.7b for the illustration of the observed predominant flow path; Appendix A.8 for the calculation).

In a practical context, for a longer wrinkle, the leakage will depend on the length of the wrinkle and number of wrinkle-seam intersections (controlled by the width of the GCL panel, which in this case is 4.5 m). For example, leakage through a 10 m long wrinkle perpendicular to the GCL roll direction would be the sum of the flow through two wrinkle-seam intersections (e.g., the flow measured in Test T22 for one such intersection) and through a single panel of GCL (e.g., measured in Test T37 for 0.59 m long wrinkle) through the remaining 8.8 m. The resulting leakage would be 0.13 lpd, out of which about 70% of the flow would occur through the single panel of GCL and only 30% would occur preferentially through the seams. This simple calculation suggests that for longer field wrinkles, the leakage is mostly controlled by the hydraulic conductivity of the unstressed GCL and length of the wrinkle, provided that the overlapped GCL seam is performing as well or better than that in Test T22. This also shows the benefit in reducing the amount of field wrinkles at the time when the liner is covered.

To see if there was an effect of GCL orientation on the performance of the melted groove, duplicate tests, Test T20 and T21, were conducted with the groove facing up for otherwise same test conditions as in Test T22 (where the GCL was installed with the groove facing down). Steady-state flows were measured at $1.3 \times 10^{-10}$ m$^3$/s (0.011 lpd, $\Lambda=2$) for Test T20 and $2 \times 10^{-10}$ m$^3$/s (0.017 lpd, $\Lambda=3$) for Test T21. Attributing differences in leakage rates to the GCL and groove
variability, these test results showed no discernible effect of the panel orientation on the GCL and its seam performance (Figure 3.5b).

In Tests T20-22, post permeation observations revealed evidence of flow occurring along the nonwoven geotextile at the unstressed portion of the seam beneath the wrinkle as illustrated in Figure 3.7b, c and shown in a photograph taken after termination of Test T20 (Figure 3.8a) upon lifting the upper GCL at the seam to expose the overlap. In this and the other two cases, the bentonite at the melted groove was well hydrated and the concentration of dye was higher at the groove, which likely means a higher retention period for the flow at the groove allowing the dye to concentrate. A zone of free bentonite (i.e., not contained by the geotextiles; water content = 720%) was also noticed along the entire unstressed upgradient edge of the upper GCL (Figure 3.8a). This bentonite likely came from swelling of the bentonite along the edge of the panel during hydration under no confining stress possibly combined with some extrusion from the compressed zone to unstressed edge beneath the wrinkle. Visually, it appeared that this hydrated edge bentonite sealed the opening of the GCL seam; however, the extent to which this edge bentonite may have contributed to the measured low flow in Tests T20-22 is unknown.

To examine the effect of the extrusion of edge bentonite, Test T31 was conducted by intentionally removing the panel bentonite within 2.5 cm along the outer edge of both GCL specimens at the seam (Appendix A.15). Post-test observations confirmed this prevented the appearance of bentonite extruding along the upgradient edge of the seam. The GCL specimens were installed with the melted groove facing up. The steady-state leakage in Test T31 was measured at $1.6 \times 10^{-10} \text{m}^3/\text{s}$ ($0.014 \text{lpd, } \Lambda=2.4$). This flow is not larger than that measured in tests where the free swelling bentonite along the edges of the GCL seam was observed. Test T31 was otherwise, similar in results and observations to Tests T20-22 (Figure 3.7c) and it appears that the good seam
performance in Tests T20-22 was predominately from sufficient bentonite hydration through the melted groove and not due to the extruded edge bentonite.

The measured flow with GCL4 (0.011-0.019 lpd), irrespective of the GCL panel orientation and containing only about 8 grams per linear metre of excess bentonite at the seam (based on the free hydration test) was similar to that reported in Chapter 2 for GCL2 with a nonwoven cover and a composite woven-nonwoven carrier geotextile with 400 grams per linear metre of supplemental bentonite placed at a 150 mm wide overlapped seam for otherwise same test conditions (0.018-0.022 lpd). The slightly lower flow along the GCL4 seam could be attributed to an overall lower in-plane transmissivity of the seam caused by introducing a discontinuity in the nonwoven geotextile along the seam interface by melting the geotextile. The test results show that the effectiveness of the tested complete melt groove in GCL4 with a firm and flat subgrade when subjected to non-uniform stress beneath a geomembrane wrinkle had the same potential in limiting leakage along the seam as 400 g/m of field-applied supplemental bentonite placed at the seam.

3.3.4.2 Permeation through 150 mm wide heat-tacked GCL4 seams
Factory heat-tacked samples of GCL4 obtained from the manufacturer were tested to observe the effect of heat-tacking on the hydraulic performance of the GCL seams. The heat-tacked samples were prepared by first overlapping the end of the roll GCL samples by 150 mm then applying uniform heat to the underside of the top panel along the outer edge at a rate of approximately 10 m/min and immediately applying about 2 kPa pressure to press the seam together to bond. Inspection of over 5 m long heat-tack zones, prior to the selection of test specimens, showed that the heat-tack width was uniformly between 50-75 mm. The tensile strength of the seam was similar to that reported by Joshi et al. (2011) for heat-tacked samples of GCL4 (Table 3.1; Appendix A.20).
Duplicate tests were conducted on the heat-tacked GCL4 samples. The GCL test samples were installed such that the heat-tack zone was located on the outer edge of the upper GCL panel with the melted groove facing down. The measured flow in Tests T23 and T25 were $1.1 \times 10^{-10}$ m$^3$/s (0.009 lpd; $\Lambda=1.7$) and $1.4 \times 10^{-10}$ m$^3$/s (0.012 lpd; $\Lambda=2.1$). The measured flow with heat-tacked seams were slightly lower than that recorded in tests containing non heat-tacked seams (Figure 3.9a). Post-test observations revealed that the flow had predominantly occurred along the unstressed section of the seam beneath the geomembrane wrinkle (Figure 3.7d) and there was well hydrated bentonite along the melted groove with higher dye concentration (similar to that observed at the seams without heat-tack). The slightly reduced flow in tests containing heat-tacked seams (Figure 3.9) may be from a reduction in the in-plane transmissivity of the melted nonwoven geotextiles at the seam providing additional resistance to flow.

3.3.4.3 Permeation through 150 mm wide GCL3 seams with incomplete melt

Similar to GCL4, GCL3 also has a nonwoven cover geotextile with a melted groove but has a less transmissive woven carrier geotextile (Figure 3.3b). As previously noted, tests were conducted with the GCL3b specimens intentionally selected to contain incomplete melted grooves. Test T14 was conducted with the groove facing up and Test T43 was conducted with the melted groove facing down. As expected, a larger flow of $2.2 \times 10^{-8}$ m$^3$/s (1.9 lpd, $\Lambda=333$) and $2.7 \times 10^{-8}$ m$^3$/s (2.3 lpd, $\Lambda=409$) were measured in Test T14 and Test T43 (Figure 3.5b) relative to the base case with a single panel of GCL4. The results from Tests T14 and T43 show no significant effect of GCL orientation (i.e., groove facing up or down) on flow. The recorded flow in tests with incomplete melt groove with GCL3b were about two orders of magnitude higher than that for complete melt groove with GCL4 (Test T22; Table 3.2).
Observations made after test termination showed no sign of groove hydration in Test T43 and only about 10% cumulative groove hydration in Test T14 (Figure 3.8b). The partially hydrated groove in Test T14 may have contributed to slightly reducing the flow in Test T14. In both tests, unlike in tests with GCL4, the dye concentration on both geotextiles at the seam was uniform throughout the width of the unstressed seam including the grooves (e.g., Test T14 seam in Figure 3.8b; with the lighter coloured geotextile facing up at the seam, it was easier to see the dyed zone in Test T14). In both tests, the preferential flow was predominantly along the unstressed seam (Figure 3.7e, f).

In Test T14, a 4 mm deep wave was observed in the carrier woven geotextile of the upper GCL panel at the seam centrally beneath the wrinkle (Figure 3.8b). The wave was likely formed due to the deformation of free hydrating GCL caused due to the differential settlement of the foundation beneath the wrinkle. There was no apparent effect of this wave on flow along the seam since the measured flow in Test T14 did not exceed that in Test T43 where there was no such wave.

In a practical context, for a 100 m long wrinkle perpendicular to the GCL roll direction, and with GCL3b containing an imperfectly melted groove, the measured flow would correspond to a calculated leakage rate of 40-50 lpd. The measured flow with GCL3b containing incomplete melt groove is similar to that reported in Chapter 2 for a 150 mm overlapped GCL, containing a nonwoven cover and a composite woven-nonwoven carrier geotextile, without any supplemental bentonite (2.8 x 10^-8 m^3/s = 2.4 lpd).

3.3.4.4 Hydraulic performance of heat-tacked GCL3 seams
To observe the possible best effect of heat-tacking on the hydraulic performance of the seam, tests were conducted on GCL3 seams that were heat-tacked by the manufacturer in the factory and
shipped to the Queen’s laboratory for testing. The heat-tacked seams were prepared in a similar way as described earlier for GCL4. Inspection of 3.6 m long heat-tacked zone showed a uniform width consistently between 50-75 mm and the tensile resistance to failure was also similar to that reported by Joshi et al. (2011) for heat-tacked samples of GCL3.

Two tests were conducted on the heat-tacked sample of GCL3. In the first test, Test T29, though likely an uncommon field practice, the heat-tacked zone was placed on the downgradient side of the seam with the melted groove facing up (see Figure 3.7g for the schematic of the test) to test the effect of having the heat-tacked zone along the inner edge of the seam. A flow of $1.1 \times 10^{-9} \text{ m}^3/\text{s} \ (0.1 \text{lpd}, \Lambda=16.7)$ was measured. This measured flow in Test T29 was on average 23 times lower than the flow measured in Tests T14 and T43 where the seam was installed without heat-tacking. Post-test observations from Test T29 revealed no free swelling bentonite at the melted groove, and that flow occurred laterally through the heat-tack zone and directly downward through the unhydrated groove (Figure 3.7g) however their relative contributions towards the total flow could not be determined. The second test, Test T39, was conducted with the heat-tacked zone placed on the upgradient edge of the seam with the groove facing down (Figure 3.3b). A steady-state flow rate of $6.2 \times 10^{-11} \text{ m}^3/\text{s} \ (0.005 \text{lpd}, \Lambda=0.9)$ was measured. Although steady-state flow conditions were attained within 46 days, the test was allowed to run for twice that time to confirm steady-state had been reached and no additional time-dependent effect on flow was discernable. This flow is about three orders of magnitude smaller than that measured with a non-heat-tacked GCL3b seam containing an incomplete melt, about 18 times lower than that measured in Test T29 with the heat-tacked end of the seam placed on the downgradient side (Figure 3.9b) and even slightly lower than that measured in a reference base case with a single panel of GCL4 ($6.6 \times 10^{-11} \text{ m}^3/\text{s} \ - 0.006 \text{lpd}; \text{Test T37}; \text{Figure 3.5a})$. Unlike in Test T29 and tests with heat-tacked GCL4 seams
(where there was evidence of flow beyond the heat-tacked zone; Figure 3.7), post-test observations in Test T39 revealed no sign of such flow. It appeared that the factory heat-tacking completely melted the cover nonwoven geotextile of the lower GCL panel and the carrier woven geotextile of the upper GCL panel at the seam and bonded them together creating a nearly impermeable interface, thereby forcing the flow through the GCL panel. Assuming similar hydraulic conductivities for both GCLs, the slightly lower flow in Test T39 with GCL3 may be from having two layers of GCL at the overlapped seam area compared to a single panel of GCL4 in Test T37.

All of the permeation results on heat-tacked seams reported so far were on seams prepared in a controlled factory setting and the heat tacked zone, which represented almost one-half the width of the overlap, with the two layers geotextile in contact from the upper and lower GCL fused together to create an impermeable interface. This represent a “best case” situation. To study the effect of having a narrower width of heat-tacked zone in a 150 mm overlapped seam, a single sample of heat-tacked GCL3b seam was prepared in the laboratory with a single pass of a narrow tip flame torch and pressure applied by the operator’s foot to bond the heated seam together (method as described by Joshi et al. 2011 and seen used in field applications). This created a heat-tack zone 20-30 mm wide with similar tensile strength as the manufacturer supplied heat-tacked sample (in both cases the seam strength was limited by the strength of the woven geotextile at the seam). In Test 16, the sample was tested with the heat-tacked zone placed on the upgradient edge of the seam. A flow rate of 2.8 x 10^{-8} m^3/s (2.4 lpd, A=424) was measured. There was no reduction in flow compared to the seams without heat-tack. The flow was similar to that measured in Test T43 and even slightly larger than that in Test T14. Post-test observation revealed flow predominantly occurring along the width of the unstressed seam (Figure 3.7h) and no sign of free swelling bentonite at the groove.
The extent to which heat-tacking alone should be relied upon in the field to limit preferential flow through the overlap when there is no panel bentonite hydration through the melted groove (either from incomplete geotextile melt or possible loss of panel bentonite through the groove during deployment) is left to judgement of the engineer of record for any particular case, as heat-tacking method and workmanship may affect the continuity of the heat tacking, and hence any hydraulic resistance that may arise from thermally fusing the geotextiles together. Much like a thermally fused wedge seam for a geomembrane, continuous and qualified inspection may be required to solely rely upon the hydraulic resistance of the heat-tacked geotextiles for adequate GCL seam performance.

3.3.5 Seam performance of products with carrier geotextile impregnated with powder bentonite

3.3.5.1 Permeation result on 300 mm wide GCL6 seam

In Test T38 conducted on 300 mm wide overlapped seam of GCL6 with the bentonite impregnated nonwoven geotextile component of the GCL facing up (see Figure 3.3c), a steady-state flow rate of $2.5 \times 10^{-10} \text{ m}^3/\text{s}$ ($0.022 \text{ lpd}$) was measured (Figure 3.10). This recorded flow in Test T38 is practically same as $2.2 \times 10^{-10} \text{ m}^3/\text{s}$ ($0.019 \text{ lpd}$) as that obtained for a 300 mm wide overlapped seam of a needle-punched GCL with fine-grained supplemental bentonite piled at the centre of the seam and tested under same conditions (Chapter 2). It appeared that the amount of factory-applied powered bentonite at the GCL6 seam was sufficient to hydrate, swell and effectively seal the unstressed portion of the seam beneath the wrinkle.

Post-test observation of the seam in Test T38 (Figure 3.11a) showed that the flow path along the seam was tortuous and not the entire section of the geotextile beneath the wrinkle appeared to be transmitting flow (inferred from the blue dye present at the seam). This observed
seam flow was different than that observed in Chapter 2 where the flow occurred along the entire width of the nonwoven geotextile component of the GCL beneath the wrinkle.

3.3.5.2 Permeation result on 300 mm wide GCL5 seams

In duplicate tests conducted on 300 mm wide seams of GCL5, under the same test conditions as in Test T38 for GCL6, much higher leakage rates at $8.2 \times 10^{-8}$ m$^3$/s (7.1 lpd) in Test T32 and $1.7 \times 10^{-7}$ m$^3$/s – 14.7 (lpd) in Test T40 were measured. The test results are compared with the test on GCL6 in Figure 3.10 and summarized in Table 3.2. In a practical context, the measured flow in Test T40, would correspond to a leakage of about 30 lpd if there was a hole on a 10-m-long geomembrane wrinkle perpendicular to the GCL roll direction or 300 lpd if it were on a 100 m long wrinkle.

Upon test termination and removal of the top GCL panel at the seam, distinct preferential flow channels were observed along the seam in both tests and the factory-applied bentonite along those channels was partially eroded under the applied hydraulic gradient (e.g., see Figure 3.11b showing the seam area of Test T40). These flow channels were spaced every 10-20 mm along the overlap and were 2-4 mm deep. No such features were present along the seam of GCL6 in Test T38 (Figure 3.11a).

Both GCLs 5 and 6, supplied by the same manufacturer, contained powered bentonite with similar swell indices (Table 3.1), about 50 cm wide strip of the nonwoven cover geotextile along the lateral edges of the GCLs were impregnated with factory-applied powered bentonite and the needle-punched fibres were thermally treated for effective bonding (see Figure 3.3c, d for an illustration of the impregnated bentonite). In GCL5, the nonwoven component of the carrier geotextile terminates at a nominal 20 cm from the edges of the roll hence for a 300 mm wide seam, majority of the seam contains the same geotextile components for both GCLs. The average dry
mass per unit area of the factory impregnated bentonite at the GCL5 and GCL6 seam was 900 g/m² and 1100 g/m² (Appendix A.18). This amount of bentonite at the seam is much lower than 7300 g/m² used on products requiring field-applied supplemental bentonite in Chapter 2 where manufacturers’ recommended minimum amount of bentonite was piled at the centre of the seam.

The very high leakage rates for the unstressed GCL5 seams beneath a wrinkle are attributed to the needle-punching pattern of the particular rolls that were tested. Figure 3.12a (and Appendix A.17) shows x-ray image of a off-the-roll oven-dried sample of GCL5. Concentrated cross-roll direction bands of needle-punching are visible for the samples taken from the panel (represented by darker spots in the image). For reference, x-ray image of GCL6 sample in Figure 3.12b (and in Appendix A.17) shows a more even distribution of the needle-punching. The average and the maximum peak peel strength of GCL5 was also higher compared to GCL6 (Table 3.1).

When allowed to hydrate, because of the higher density of cross-roll needle-punching concentrated in linear bands and effective thermal locking of the needle-punched fibres, the thickness of GCL5 is non-uniform with local thin bands coincident with the needle-punching bands oriented in cross-roll direction repeating every 10-20 mm (Appendix A.17). In between these bands, the GCL is locally thicker. Measurements of the top surface of GCL5 during free-swell hydration plotted in Figure 3.13a show the local depressions (around 3 mm deep) in the top surface. The variations in top surface elevation of GCL6 plotted in Figure 3.13b were not as distinct or as deep as they were for GCL5, most likely because of the more even distribution of needle-punching.

When overlapped, intersection of the two irregular surfaces of GCL5 creates linear voids that act as preferential flow pathways. Any factory-applied overlap bentonite within those voids was eroded under the applied hydraulic gradient and what remained was insufficient to swell and reduce flow through these linear voids in GCL5. With GCL6, it appears that the quantity of factory
applied seam bentonite was sufficient to swell and reduce flow through the unstressed overlap zone beneath the wrinkle.

An additional test was conducted on GCL5 seam with additional 400 grams per linear metre of powered bentonite piled at the centre of the 300 mm wide overlapped seam. The test was conducted to assure that the added supplemental bentonite at the seam would limit leakage along the seam by filling in the voids and as a check if there will be any erosion of the added bentonite under the applied hydraulic gradient. A reduced steady-state flow was measured at 5.5 x 10^{-11} m^3/s – 0.005 lpd in Test T43 (Figure 3.10; Table 3.2). Post-test observation revealed that there was no sign of bentonite erosion and the flow channels were filled by the supplemental bentonite. Using the hydraulic conductivity of the GCL5 panel as 2 x 10^{-11} m/s (Hosney 2014) the measured flow along the seam was about 1.7 x 10^{-11} m^3/s i.e., only 30% of the measured flow occurred through the seam compared to essentially 100% when no additional bentonite was added to the seam. In summary, with the addition of commonly specified amount of supplemental bentonite at the GCL5 seam, voids caused due to the non-uniform hydration features on the GCL surface were filled and flow along these channels were largely reduced. Thus, based on these tests, it appears that while GCL6 may be suitable beneath a geomembrane with wrinkles, if GCL5 is to be used below a geomembrane with wrinkles then supplemental bentonite should be added. If the geomembrane can be installed without wrinkles (as is understood to be case in Germany), then either could be used with the factory produce powdered overlaps.

3.4 Conclusions

Results from laboratory experiments examining how overlapped seams for GCLs not requiring field-applied supplemental bentonite at the seam perform under non-uniform stresses from an
overlying geomembrane wrinkle were reported. Four GCL products using two different seam sealing techniques – one with a narrow, linear factory melted groove in one of the geotextiles; the other with factory applied bentonite – were tested under a hydraulic head of 0.3 m and applied vertical pressure of 250 kPa with a geomembrane wrinkle perpendicular to the GCL seam. The wrinkle was around 40 mm high and 80 mm wide after application of the vertical pressure, thus leaving an 80-mm-wide stress free zone of the GCL overlapped seam. For the specific GCL samples and the test conditions examined, the following conclusions were reached:

1. GCL seams with a melted groove: Discontinuous melting of the groove on the nonwoven geotextile had a negative impact on the hydraulic performance of the seam. Discontinuous melt (i.e., where there were still nonwoven geotextile fibres retaining panel bentonite) hindered intrusion of panel bentonite into the overlapped seam. The flow, per geomembrane wrinkle-GCL seam intersection, recorded for GCL4 with a continuous melted groove ranged between 1.3-2.2 x 10^{-10} m^3/s (<0.02 litres per day) whereas for GCL3 specimens with discontinuous melted grooves was between 2.2-2.7 x 10^{-8} m^3/s (around 2 litres per day). The orientation of the GCL panel (i.e., with the groove either facing up or down) did not affect the flow through the seam.

2. Heat-tacked GCL seams: factory heat-tacking of a GCL seam improved the hydraulic performance of seams with a melted groove and significantly reduced the flow through the seam especially for GCL3 where the panel bentonite along the melted groove was not well exposed to extrude along the seam. The method of heat-tacking, the width of the heat-tacked zone and its positioning at the seam was found to greatly impact seam flow. The flow recorded for factory heat-tacked GCL3 and 4 seams with 50-75 mm wide heat-tacked zone located on the upgradient edge of the seam ranged between 0.6-1.4 x 10^{-10} m^3/s (<
0.012 litres per day) whereas for GCL3b seam, prepared in the laboratory, with 20-30 mm wide heat-tacked zone located on the upgradient edge of the seam was $2.8 \times 10^{-8}$ m$^3$/s (2.4 litres per day). Placing the heat-tacked zone at the downgradient edge of the seam increased the flow by about 18 times.

3. GCL seams with factory applied (impregnated) overlap bentonite: The amount of factory applied bentonite relative to size of the small voids that developed in the overlap from unrestrained hydration beneath the geomembrane wrinkle impacted GCL seam flow. GCL6 performed very well (0.22 litres per day) with 900 g/m$^2$ of factory applied bentonite in its upper nonwoven geotextile, as it was able to swell and limit preferential flow through the very small (< 1 mm) variations in free-swell thickness that developed in the particular specimens tested. However, because of concentrated needle-punching, coupled with very effective restraint of the needle-punched fibres from thermal treatment, 1100 g/m$^2$ of factory applied bentonite was insufficient to prevent preferential flow through 2-4 mm voids that developed in the particular specimens of GCL5 tested. Additional supplemental bentonite (400 g/m) placed between the overlap of GCL5 was able to limit flow to 0.005 litres per day.

These results are for the special case of having no confining pressure on top of the GCL, as occurs for the portion of the GCL beneath a wrinkle in a geomembrane. If one can ensure there are to be no wrinkles in the geomembrane upon placement of cover soil, the seam flows would be expected to be smaller than those reported in this paper.
3.5 References


Table 3.1 Properties of GCLs used for the study

<table>
<thead>
<tr>
<th>GCL</th>
<th>Seam sealing technique</th>
<th>Carrier GTX</th>
<th>Cover GTX</th>
<th>Bonding mechanism</th>
<th>Range of dry mass (g/m²)</th>
<th>Swell index of the panel bentonite (ml/2g)</th>
<th>Heat-tack strength (kN/m)</th>
<th>Peel strength (n=5)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>GTX</td>
<td>GTX</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Avg. peel strength (N/m)</td>
</tr>
<tr>
<td>GCL3b</td>
<td>Melted groove</td>
<td>W</td>
<td>NW</td>
<td>NP</td>
<td>5530-5916</td>
<td>23</td>
<td>6.7</td>
<td>1510 (SD = 256)</td>
</tr>
<tr>
<td>GCL3</td>
<td>Melted groove</td>
<td>W</td>
<td>NW</td>
<td>NP</td>
<td>3461-4346</td>
<td>24</td>
<td>6.1-7.2</td>
<td>-</td>
</tr>
<tr>
<td>GCL4</td>
<td>Melted groove</td>
<td>NW</td>
<td>NW</td>
<td>NP</td>
<td>4964-5385</td>
<td>22</td>
<td>8-9.1</td>
<td>1780 (SD = 280)</td>
</tr>
<tr>
<td>GCL5</td>
<td>Injected powered bentonite</td>
<td>SRNW</td>
<td>NW</td>
<td>NP-Thermal treatment</td>
<td>4612-4928 (Panel) 5671-6032 (Seam)</td>
<td>27</td>
<td>n.a.</td>
<td>1128.8 (SD = 194.6)</td>
</tr>
<tr>
<td>GCL6</td>
<td>Injected powered bentonite</td>
<td>W</td>
<td>NW</td>
<td>NP-Thermal treatment</td>
<td>4497-5151 (Panel) 5403-5947 (Seam)</td>
<td>26</td>
<td>n.a.</td>
<td>767.9 (SD = 69.5)</td>
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</table>

Note: GTX = geotextile; W = Woven; NW = Non-Woven; SRNW = Scrim-reinforced nonwoven; NP = Needle-punched; n = number of replicates; SD = standard deviation; GCLs were Bentomat™ 1 ST and 2 DN, Bentofix™ 3 B4000 and 4 NSP4900; 5 Tested according to ASTM (2006); 6 Tested according to ASTM (2015); 7 Values for GCL3 and GCL4 adopted from Rentz (2015).
Table 3.2 Summary of permeation tests

<table>
<thead>
<tr>
<th>Test #</th>
<th>GCL type</th>
<th>Orientation with wrinkle</th>
<th>Seam width (mm)</th>
<th>Cell diameter (m)</th>
<th>Heat-tack</th>
<th>Groove hydration (%)</th>
<th>GCL water content (%)</th>
<th>Steady-state flow (m³/s)</th>
<th>Λ</th>
<th>Test duration (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T37</td>
<td>GCL4</td>
<td>No seam</td>
<td>– a</td>
<td>0.59</td>
<td>-</td>
<td>n.a.</td>
<td>221</td>
<td>94</td>
<td>6.6 x 10⁻¹¹</td>
<td>1</td>
</tr>
<tr>
<td>T24</td>
<td>GCL4</td>
<td>Parallel</td>
<td>150</td>
<td>0.59</td>
<td>Yes</td>
<td>100</td>
<td>225</td>
<td>91</td>
<td>1.2 x 10⁻¹⁰</td>
<td>1.8</td>
</tr>
<tr>
<td>T22</td>
<td>GCL4</td>
<td>Perpendicular</td>
<td>150</td>
<td>0.59</td>
<td>No</td>
<td>100</td>
<td>209</td>
<td>105</td>
<td>2.2 x 10⁻¹⁰</td>
<td>3.3</td>
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<tr>
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<td>GCL4</td>
<td>Perpendicular</td>
<td>150</td>
<td>0.59</td>
<td>No</td>
<td>100</td>
<td>213</td>
<td>89</td>
<td>1.3 x 10⁻¹⁰</td>
<td>2</td>
</tr>
<tr>
<td>T21</td>
<td>GCL4</td>
<td>Perpendicular</td>
<td>150</td>
<td>0.59</td>
<td>No</td>
<td>100</td>
<td>218</td>
<td>99</td>
<td>2 x 10⁻¹⁰</td>
<td>3</td>
</tr>
<tr>
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<td>GCL4</td>
<td>Perpendicular</td>
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<td>0.59</td>
<td>No</td>
<td>100</td>
<td>222</td>
<td>107</td>
<td>1.6 x 10⁻¹⁰</td>
<td>2.4</td>
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<tr>
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<td>GCL4</td>
<td>Perpendicular</td>
<td>150</td>
<td>0.59</td>
<td>Yes</td>
<td>100</td>
<td>207</td>
<td>100</td>
<td>1.1 x 10⁻¹⁰</td>
<td>1.7</td>
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<tr>
<td>T25</td>
<td>GCL4</td>
<td>Perpendicular</td>
<td>150</td>
<td>0.59</td>
<td>Yes</td>
<td>100</td>
<td>191</td>
<td>104</td>
<td>1.4 x 10⁻¹⁰</td>
<td>2.1</td>
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<tr>
<td>T14</td>
<td>GCL3b</td>
<td>Perpendicular</td>
<td>150</td>
<td>0.59</td>
<td>No</td>
<td>10</td>
<td>174</td>
<td>111</td>
<td>2.2 x 10⁻⁸</td>
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<tr>
<td>T43</td>
<td>GCL3b</td>
<td>Perpendicular</td>
<td>150</td>
<td>0.59</td>
<td>No</td>
<td>0</td>
<td>181</td>
<td>113</td>
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<td>409</td>
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<tr>
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<td>GCL3</td>
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<td>Yes</td>
<td>0</td>
<td>193</td>
<td>87</td>
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<td>150</td>
<td>0.59</td>
<td>Yes</td>
<td>0</td>
<td>172</td>
<td>91</td>
<td>6.2 x 10⁻¹¹</td>
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<tr>
<td>T16</td>
<td>GCL3b</td>
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<td>150</td>
<td>0.59</td>
<td>Yes</td>
<td>0</td>
<td>163</td>
<td>97</td>
<td>2.8 x 10⁻⁸</td>
<td>424</td>
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<tr>
<td>T38</td>
<td>GCL6</td>
<td>Perpendicular</td>
<td>300</td>
<td>1</td>
<td>No</td>
<td>n.a.</td>
<td>248</td>
<td>130</td>
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<tr>
<td>T32</td>
<td>GCL5</td>
<td>Perpendicular</td>
<td>300</td>
<td>1</td>
<td>No</td>
<td>n.a.</td>
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<td>122</td>
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<td>1</td>
<td>No</td>
<td>n.a.</td>
<td>250</td>
<td>127</td>
<td>1.7 x 10⁻⁷</td>
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<tr>
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<td>GCL5</td>
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<td>n.a.</td>
<td>261</td>
<td>115</td>
<td>5.5 x 10⁻¹¹</td>
<td>n.a.</td>
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</tbody>
</table>

Note: a No seam, single panel of GCL beneath wrinkle; Λ = (flow in Test T#) / (flow in reference case Test T37).
Figure 3.1 Techniques in use to introduce bentonite at the seam: (a) field-applied supplemental bentonite placed at the overlapped ends of the GCL, (b) a melted groove on a nonwoven cover geotextile allowing bentonite to extrude out upon hydration, and (c) presence of factory-applied powder bentonite on the nonwoven cover geotextile.
Figure 3.2 Plan and cross-section views showing orientation of geomembrane wrinkle with respect to GCL seam.
Figure 3.3 Cross-section of the tested GCLs. NW – Nonwoven geotextile, W – Woven geotextile, NP – Needle-punched.
Figure 3.4 Schematic of a permeation test setup in a 1 m diameter test cell (parallel test setup; all dimensions in mm).
Figure 3.5 (a) Measured flow rate through a single panel of GCL4 beneath a deformed geomembrane wrinkle, and (b) Measured flow rate through 150 mm wide overlapped seams of GCL3 and GCL4 in perpendicular case beneath a geomembrane wrinkle.
Figure 3.6 Pictures showing melted grooves of GCL3b: (a) Dry GCL sample showing well exposed panel bentonite at the melted groove, (b) Dry GCL sample showing little exposure of panel bentonite through the melted groove, (c) Well hydrated bentonite at the melted groove after 5 days of submerged hydration, (d) The hydrated GCL sample shows minimal amount of bentonite above the GCL surface after 5 days of submerged hydration.
Figure 3.7 Observed predominant flow path in all tests with leakage along the GCL seam.
Figure 3.8 Photographs taken after permeation-test-termination by lifting the upper GCL panel at the seam to expose the flow-path and melted groove of: (a) GCL4 in Test T20 with higher amount of hydrated bentonite present at the melted groove. The dye concentration was higher at the groove and a good contact between the upper and lower panel was maintained, and (b) GCL3b in Test T14, where the dye concentration is uniform throughout the seam width, the bentonite at the groove with incomplete melt had no excess bentonite. There was a formation of a hydration wave on the lower carrier woven geotextile of the upper GCL panel.
Figure 3.9 Effect of heat-tacking on 150 mm overlap of GCL4, GCL3 and GCL3b (schematic of heat-tack at upgradient seam is shown in Figure 3.7d and downgradient seam is shown in Figure 3.7g).
Figure 3.10 Recorded flow through GCL5 and GCL6 overlapped seams.
Figure 3.11 Photographs taken after permeation test by lifting the upper GCL panel at the seam to expose the flow-path of: (a) GCL6 after Test T38 termination. Tortuous flow path observed at the overlap and there was no sign of any washed out bentonite. (b) GCL5 after Test T40 termination. Flow is channelized and the bentonite from the overlap had been washed out.
Figure 3.12 X-ray images of a representative peel-strength specimen of: (a) GCL5, and (b) GCL6 after oven drying. The specimens are 100 mm wide and 200 mm long. Darker spots in the x-ray image represent the needle-punched fibres.
Figure 3.13 (a) Differential swelling and hydration waves were prominent upon surface scanning of a free swelling GCL5. (b) Differential swelling was observed however no distinct flow channel is formed on the surface of GCL6.
Chapter 4

A new laboratory apparatus for measuring leakage through geomembrane holes beneath mine tailings

4.1 Introduction

Geomembranes can be very effective at controlling leakage for environmental containment applications, where the escape of fluid under a hydraulic gradient is limited to flow through holes in the geomembrane (Giroud 1997; Rowe et al. 2004; Rowe 2012). It is not uncommon to have holes in a geomembrane liner installed even under a strict quality assurance (e.g., Giroud and Bonaparte 1989, 2001; Colucci and Lavagnolo 1995; Beck 2014). To date, the study of leakage through geomembrane holes has mostly been done for cases similar to a modern municipal solid waste (MSW) landfill (Figure 4.1a), where generally a higher hydraulic conductivity drainage layer overlies the geomembrane liner and is underlain by a much lower hydraulic conductivity soil. However, in a tailings storage facility (TSF) lined with a geomembrane, the configuration is much different to that of a MSW landfill (Figure 4.1b). The hydraulic conductivity of the material above the geomembrane (i.e., tailings) is much lower, providing greater resistance to flow above the hole (Bonaparte et al. 1989; Giroud et al. 1997; Walton et al. 1997). The hydraulic conductivity of the material below the geomembrane is typically not as low (e.g., with much more common use of native soils), providing less resistance to flow below the hole. The pore pressures on top of the liner can be much higher thus increasing the hydraulic gradient and possibly causing migration of fine soil particles with the high local seepage stresses (Pane et al. 1983; Olsen et al. 1985). Also, the vertical stress acting on the geomembrane base liner can be much higher, possibly decreasing both the hydraulic conductivity and interface transmissivity (Rowe et al. 2004).
The coupled effect of large vertical stresses and pore pressure on flow through a geomembrane hole in a tailings storage facility is still unknown. There is a potential role for numerical seepage analysis to calculate the possible magnitude of leakage for tailings applications; however, experimental data is required to assess model assumptions and establish material parameters which may be affected by stress, head and migration of fines.

Proper simulation of the vertical effective stresses in the soil above and below the geomembrane hole is important in any laboratory idealization of this problem as they control the void ratio, and hence, the hydraulic conductivity of the soil, interface transmissivity and the mobility of fines under a hydraulic gradient. Thus leakage experiments are required to get the correct physical simulated field conditions where applied effective stresses (i.e., total stress and pore pressures) matches the effective stresses experienced by the liner in the field.

The primary objective of this chapter is to detail the development of a new experimental apparatus and procedure to measure leakage through a hole in a geomembrane with low permeable soil on top of the geomembrane. Focus is on influence of the boundary conditions in the field and how they may be simulated in the laboratory. Finite-element seepage analysis is used to evaluate the hydraulic boundary conditions and dimensions of the new apparatus. Results from four experiments are then reported to investigate the effectiveness of the new apparatus and examine how the permeability of the overlying soil (or overliner) affects the rate of flow through a geomembrane hole for effective stresses that simulate a deep tailings storage facility. Last, a finite-element seepage analysis is used to understand and interpret the measured flow from the experiments and study the effect larger geomembrane holes and lower permeability underliner have on flow in a large containment facility.
4.2 Development of a new test apparatus

4.2.1 Boundary conditions

An important consideration in the design of the test apparatus involved identifying the boundary conditions experienced by the geomembrane liner when buried deep in the field (e.g., after filling of the tailings storage facility). Figure 4.2a illustrates a geomembrane buried in a tailings storage facility and subjected to pressure from the tailings above, where: $H$ is the height of the tailings above geomembrane surface, $h_p$ is the pressure head at distance $H_T$ above the geomembrane surface, $H_T$ and $H_{UL}$ are the amount of tailings above and underliner material below the geomembrane in the laboratory simulation, and $R$ is the radial distance from the centre of the hole to an arbitrary vertical boundary. A saturated underliner with its potentiometric surface located at the same elevation as the bottom of the geomembrane is considered as the bottom hydraulic boundary condition.

A region of soil around the location of the geomembrane hole with idealized earth and pore pressures is isolated in Figure 4.2b. Vertical stress ($\sigma_v$) acting on the geomembrane liner is a function of the bulk unit weight of the tailings ($\gamma$), the tailings thickness ($H$) and the depth of any water ponding on top of the tailings surface. At-rest horizontal stress ($\sigma_h$) conditions develop from restraint against lateral movement. Pore water pressure ($u$) at some distance above the geomembrane hole ($H_T$) will not be significantly impacted by the presence of the hole and will approach hydrostatic conditions with $u \approx h_p \gamma_w$. Provided that these stresses can be simulated in a laboratory model, a reasonable idealization of field conditions should be attained.

4.2.2 Assessment of boundary conditions using a finite-element seepage model
The first step towards assessing the hydraulic boundary conditions in the laboratory model is to understand flow in a large tailings storage facility such as one shown in Figure 4.2a, where the proximity of a zero flow vertical boundary is sufficiently away from the hole to have negligible effect on flow. One dimensional flow through the facility without a geomembrane, was first calculated using Darcy’s flow equation and compared with that calculated using an axi-symmetric finite-element model using SEEP/W (GeoStudio 2012). The hydraulic conductivity of the tailings was selected to be \( k_T = 5 \times 10^{-9} \text{ m/s} \), which is towards the lower bound for fine grained tailings (Wickland et al. 2010). The hydraulic conductivity of the underliner was selected as \( k_{UL} = 1 \times 10^{-5} \text{ m/s} \) to represent field conditions where the native soil will provide little hydraulic resistance. With a tailings thickness \( (H) \) of 150 m, a radial distance to the zero flow boundary \( (R) \) of 150 m, a pressure head of 0.3 m on the tailings top surface, a 0.15-m-thick underliner and a 0.15 m pressure head applied at the bottom of the underliner, the calculated flow using Darcy’s one dimensional flow equation and finite-element model are about 30,500 lpd (litres per day) and 30,600 lpd respectively. Excellent agreement (0.3%) between the calculated and finite-element modelled output was attained.

For the case with a geomembrane, a 1-mm-thick impermeable layer between the tailings and the underliner was introduced to simulate the geomembrane. A hole in the geomembrane was modelled with the same hydraulic conductivity as the overlying tailings. No preferential lateral flow along the interface between soil and geomembrane elements was considered (i.e., flow is governed by \( k \) of the soil in contact with the geomembrane). This is a reasonable first approach for this problem given: (i) the geomembranes being considered are flat and in excellent contact with soil, (ii) high effective stress are imposed on the geomembrane surface and (iii) there is a paucity of data on the interface transmissivity for these conditions. A 10-mm-diameter hole was first
selected for study based on the survey conducted by (Colucci and Lavagnolo 1995) where the selected hole diameter represented the median area of defects found in geomembrane liners. The minimum size of the elements around the circular hole was 0.5 mm to capture the changes in the flow lines around the hole. The finite element mesh was graded getting coarser with distance away from the circular hole to a maximum size of 15 m at the top and radial model boundaries (Appendix B.12). There were a total of 87,675 three-noded elements. Further refinement of the mesh near or away from the geomembrane hole did not alter the calculated flow.

The calculated flow was 1.02 lpd and the flow lines and selected contours of total head (at 2 m interval) in the vicinity of the hole are shown in Figure 4.3a. The head loss is local and concentrated within a very small region around the hole. The flow lines are drawn such that flow through the three flow channels bounded by the flow lines are equal.

The height and width of the finite-element mesh used for the large scale field simulation was reduced by approximately a factor of 500 to a practical laboratory dimensions of height 0.45 m and radius of 0.3 m to represent a small region around the hole. With the height of tailings above the geomembrane limited to 0.3 m, other input parameters: the hydraulic properties of the tailings and the underliner, the geomembrane thickness, radius of the geomembrane hole, underliner thickness, total head on top of the tailings surface and the bottom hydraulic boundary conditions were kept same. Flow increased by only 1% compared to the large scale to 1.03 lpd. The flow lines and selected contours of total head (in m) are shown in Figure 4.3b. Like in the field scale model, the head loss is local and occurred near the hole (i.e., the shape and approximate position of the total head contour of 148 m is nearly the same in the field and laboratory model). The only visible difference with the field model is the shape of the flow channels. The middle and outer flow channels show much greater curvature to elevation 0.45 m in the laboratory model where the
pressure head is prescribed. Despite the differences in the area of flow channels and the thickness of tailings, the total amount of leakage and the heads directly around the hole appears to be simulated very well in the laboratory model.

In an additional case examined, with a tailings containing less fines and higher hydraulic conductivity than for the fine grained tailings (using $k_T = 1.1 \times 10^{-7}$ m/s) and keeping the underliner ($k_{UL} = 1 \times 10^{-5}$ m/s) and other boundary conditions same, the calculated-flow in the laboratory and field scale model were 22.7 lpd and 22.2 lpd respectively (flow 2% higher in the laboratory scale model). The head loss was local and concentrated locally near the hole. This suggests that the laboratory model can simulate field conditions well even for cases involving larger flows.

In both the field and the laboratory scale models, over 95% of the head loss occurred locally within a region ten times the radius of the hole from the centre of the hole (i.e., within 50 mm) and about 75% of the losses occurred within twice the radius of the hole (Figure 4.3b). Thus the effect of reduced laboratory dimensions on flow through a small hole is likely to be negligible. Due to having a low pore pressure below the geomembrane layer, effective stresses on the underliner are close to the applied overburden stress (Figure 4.4).

Keeping the thickness of tailings at 0.3 m, with up to four times increase in the model diameter (2.4 m dia. considered as a maximum practical size of a test cell), flow through the hole increased by less than one percent (Figure 4.5). Decrease in model diameter by half ($H:R=2:1$) decreased the flow by over two percent, decrease in model diameter to one-fourth ($H:R=4:1$), reduced the flow by over 16%. In summary, the model dimensions with $H_T = 0.3$ m, $H_{UL} = 0.15$ m and $R = 0.3$ m is sufficient to have negligible boundary effect on flow through the geomembrane.

4.2.3 Selection of laboratory apparatus
Laboratory apparatus originally developed by Brachman and Gudina (2002) was selected and modifications were made to apply overburden pressure and pore pressures simultaneously to control the applied effective stresses that then control the physical and hydraulic properties of the soil (Figure 4.6). The test cell had 0.59 m internal diameter and 0.5 m internal height.

The vertical pressure from the overburden is simulated by applying a uniformly distributed fluid pressure on top of soil surface using a rubber membrane clamped around its perimeter between the lid and body of the apparatus. Horizontal pressures corresponding to zero lateral strain conditions develop due to the rigidity of the cell limiting the outward deflection of the side walls. Boundary friction along the vertical sides of the apparatus is reduced by using friction treatment which comprises of two thin plastic sheets lubricated with grease that provides a preferential vertical slip plane along the perimeter of the test cell (Tognon et al. 1999; Appendix A.3). With this arrangement, the physical boundary conditions, as reported by Brachman and Gudina (2002) and Krushelnitzky and Brachman (2009), are sufficient enough to simulate deep burial conditions up to 3000 kPa.

Pore pressures simulating pressure head \((h_p)\) on top of the isolated region in Figure 4.2b are applied on top of the soil layer by pressurizing fluid in between two layers of a geocomposite drain (8-mm-thick geonet core with upper and lower nonwoven needle-punched geotextiles of mass per unit area 340 g/m²). Pore pressure were applied using reinforced rubber tubes capable to withstand pressures several times the maximum applied total stress. Radial distance to zero flow boundary is limited by the radius of the test cell to approximately 0.3 m. Vertical distance to the constant head boundary was set at 0.3 m. A 0.15 m head applied at the geocomposite drain placed on the bottom of the cell to achieve a known initial head bottom boundary.
A bentonite perimeter seal was developed to obtain a zero flow boundary around the outer perimeter of the geomembrane where it met with the inner wall of the test apparatus (details in Figure 4.7 and Appendix A.3). The bentonite seal was placed in dry and wet layers. The wet layer would provide an initial seal during the consolidation phase and the dry layer which would hydrate under confined conditions would: (i) provide a very low $k$ core and (ii) make up for any vertical displacement of the seal. As a check the seal performed well and to provide visual evidence of any preferential flow through the seal, blue dye solution was sprayed on top. The perimeter seal was covered with a 0.1-mm-thick polyethylene sheet to isolate the seal and prevent tailings contamination, bentonite migration and dilution of the blue dye.

4.3 Prototype tests

4.3.1 Experimental results

Results from four experiments are presented to examine the effectiveness of the new test apparatus and to gain insight on the effect of a low permeable layer on top of the geomembrane on leakage through a hole in the geomembrane. Test configurations summarized in Table 4.1. A 1-mm-thick linear low density polyethylene (LLDPE) geomembrane with a central 10-mm-diameter circular hole was used in all experiments. The geomembrane had a density of 934 kg/m$^3$, standard oxidative induction time (Std-OIT) of 162±4.5 mins, high pressure oxidative induction time (HP-OIT) of 3000 mins, yield strength of 12±0.2 kN/m, yield strain of 22.1±1.5%, break strength of 35.1±2.7 kN/m and break strain of 1200±113% (as per ASTM 2015; Appendix B.15). All tests were conducted with an underliner that was 40-60 % low plasticity silt with the balance being fine to medium sand (low end of silt range based on dry sieving and high end based on wet sieving). Grain
size distribution of the soil had \( d_{50} = 0.11 \text{ mm}, d_{10} = 0.02 \text{ mm}, C_u = 6.5 \) and \( C_c = 1.6 \) as per ASTM (2009) (Appendix B.1).

A 0.14-m-thick silt underliner layer was first compacted, over the geocomposite drain, to an initial dry density of 1830 kg/m\(^3\) at an initial gravimetric water content of 11.4%. Then it was saturated from below. The geomembrane was placed directly on top of the underliner and the perimeter seal was constructed. With the remaining setup completed as shown in Figure 4.6, the consolidation phase of the test was started. In the consolidation phase, total stress was first increased in 200 kPa increments, with a final increment of 100 kPa, to 1500 kPa with zero applied pore pressures (Figure 4.8a-c, Figure 4.9a-c) to allow the underliner and overliner to consolidate to the imposed maximum effective stress. Consolidation water was collected separately from the permeant collection system at the bottom of the cell and from the drainage port at the top of the overliner for a period of 24 ± 4 hours for each increment in stress (Figure 4.8d, Figure 4.9d). Any remaining excess pore pressure dissipated as the steady-state flow conditions were approached in the final stage of the experiment. During the permeation phase of the experiments, a 1500 kPa pore pressure was imposed on top of the overliner to maintain the effective stress at 1500 kPa at the top of the underliner; these conditions were then held constant while flow through the bottom of the apparatus was measured. The permeation phase of the experiment was continued until flow conditions were steady and were then maintained for at least a week such that for the experiments reported in this chapter had no excess pore water pressures from the increased vertical pressure.

4.3.1.1 Coarse sand above the geomembrane

Tests P1 and P2 were conducted with a coarse sand overliner placed over the geomembrane to represent a case where the overliner had minimum resistance to flow to be more like the MSW landfill situation in Figure 4.1a and to allow a comparison of results with the case with low
permeable material above the geomembrane. A poorly graded coarse sand with \( d_{50} = 1.4 \) mm, \( d_{10} = 0.9 \) mm; \( C_u = 1.7; \) \( C_c = 0.9 \) was selected (Appendix B.1). The sand overliner was loosely placed in a saturated state to an initial dry density of 1570 kg/m\(^3\). Although it appears steady-state flow conditions were reached within the first 2-3 days after the start of permeation, flow was continued to be monitored for over 20 days to examine variability of imposed total and pore pressure and to challenge the seal around the perimeter of the geomembrane over a longer period of time. Total pressure and pore pressure were maintained within ± 30 kPa. Measured flow in Tests P1 and P2 were at 0.5 and 0.63 lpd (Figure 4.8e; Table 4.1). The difference in flow from tests conducted under same conditions could be due to the variability in the silt underliner. However, the degree to which it was affected by the underliner variability could not be determined.

Post-test observations showed a relatively uniform vertical settlement of the overliner across the top surface (max. difference across the surface of 5 mm). This provides evidence that the friction treatment was effective at minimizing any physical boundary effect from the side walls as boundary friction would have resulted in much less settlement near the boundaries relative to the centre. The bentonite in the perimeter seal was dense and uniformly hydrated. The thin layer of polyethylene placed on top of the seal was able to prevent sand intrusion into the seal, free swelling of the bentonite and dilution of the blue dye that was sprayed on top (Figure 4.7c). Examination of a section taken through the seal using a sharp knife showed the blue dye was present on top of the seal only and there was no evidence of dye movement through the seal nor along the bentonite-test cell interface. Inspection of the underliner after removal of the perimeter seal and geomembrane showed no blue dye in the underliner beneath the seal and the evidence suggests that flow occurred only through the centrally located geomembrane hole (Figure 4.7d). This provided strong evidence that the bentonite based seal could prevent side wall leakage even under an applied pore pressure
of 1500 kPa. The geocomposite drain used at the bottom of the cell worked as an excellent filter and did not clog.

4.3.1.2 Silt above the geomembrane

Followed by the excavation of the coarse sand overliner in Test P2, a silt slurry prepared at 75% solid content by mass was placed on top of the geomembrane to study the effect of having a much less permeable overliner for otherwise identical conditions (Test P3). The slurry was placed at an initial dry density of 1610 kg/m$^3$. During the consolidation phase, based on the diminishing rate of additional water expelled from silt above the geomembrane (Figure 4.9d), it appears that after the first few pressure increments, pore pressure in the slurry were reduced and the initial slurry was achieving a higher degree of consolidation. The actual degree of consolidation achieved after holding the final pressure increment for 1.5 days is uncertain, but based on the volume of water expelled through the top of the cell, it is estimated that greater than 80% consolidation was reached prior to permeation.

An additional test, Test P4, was conducted under the same configuration as Test P3 however unlike the underliner in Test P3, Test P4 underliner had not experienced any applied stress other than that during compaction prior to placement of the overlying silt. The steady-state flow measured in Tests P3 and P4 were 0.16 lpd and 0.26 lpd respectively. The variability in the flow observed is likely due to the variability in the silt content of the overliner and underliner. In both cases the flow was 2-4 times lower than with a higher permeability coarse sand overliner. Post-test sampling during the excavation of the silt overliner gave an average dry density of the overliner increased to 1770-1780 kg/m$^3$ at a gravimetric water content of 18-20% and a void ratio of 0.51 (Table 4.2). The average final dry density, water content and void ratio of the silt underliner in Test P4 was 1840 kg/m$^3$, 17.6% and 0.46.
4.3.2 Hydraulic conductivity of the tested overliner and underliner

The hydraulic conductivities of the silt overliner and underliner were measured in the same test cell at the same effective stresses applied during the permeation tests to obtain the $k$ of the material under the permeation test conditions. For the silt overliner, a 0.14-m-thick graded granular filter was first placed at the bottom of the cell (Appendix B.7). A 0.3-m-thick layer of silt slurry prepared at 75% solids was then placed on top of the filter. The slurry was then consolidated to the test effective stress prior to application of hydraulic head. The $k$ of the silt overliner was measured at $4.6 \times 10^{-9}$ m/s (at $p = 1600$ kPa, $u = 100$ kPa; $p' = 1500$ kPa).

Hydraulic conductivity tests on the underliner were conducted after termination of the permeation tests, Test P1 and P2/P3. First, the overliner and geomembrane from the permeation tests were replaced by a 0.3-m-thick layer of washed poorly graded gravel ($d_{10} = 9.5$ mm, $d_{10} = 6.5$ mm, $C_u = 1.5$, $Cc = 1$) (Appendix B.1) then the underliner was subjected to effective stress applied during the permeation phase of the experiment before applying hydraulic head. The $k$ of the underliner layer was $2.6-3.1 \times 10^{-9}$ m/s at an effective stress of 1500 kPa and $1.8 \times 10^{-9}$ m/s at an effective stress of 3000 kPa (Appendix B.8).

Hydraulic conductivity of the coarse sand was estimated as 0.08 m/s using Hazen’s relationship ($k=0.1*d_{10}^2$ m/s and with $d_{10}$ in mm) and, hence, was estimated to be several orders of magnitude greater than that of the underliner.

4.3.3 Explaining observed flow rates using a FEM

The base model is the same as discussed earlier where a uniform hydraulic conductivity is assumed for both overliner and underliner and any preferential flow along the soil-geomembrane interface is neglected. The silt underliner was assigned a hydraulic conductivity of $1.8 \times 10^{-9}$ m/s based on
the measurement conducted on Test P2/P3 underliner at $p = 3100$ kPa, $u = 100$ kPa ($p' = 3000$ kPa). This effective stress was selected based on the observation from Figure 4.4 where the pore pressures in the underliner are closer to zero and hence effective stresses are nearly equal to the total stresses. The calculated flow for the case with coarse sand overlying the geomembrane ($k = 0.08$ m/s) and silt underliner ($k = 1.8 \times 10^{-9}$ m/s), was 0.5 lpd. This flow is same as that measured in Test P1 but slightly smaller than that measured in Test P2. To match the calculated flow with the measured flow in Test P2, a slightly higher $k_{UL}$ of $2.2 \times 10^{-9}$ m/s was required. This required $k_{UL}$ is slightly lower than that measured at $p' = 1500$ kPa ($2.6-3.1 \times 10^{-9}$ m/s) and higher than that measured at $p' = 3000$ kPa ($1.8 \times 10^{-9}$ m/s). While both tests were conducted under same conditions, the difference in the required $k_{UL}$ to explain the flow is likely in part due to some variability in the silt especially in the area close to the geomembrane hole.

For the configuration in Test P3 and P4, where low permeability silt was used both as an overliner and underliner, the calculated flow with $k_{OL} = 4.6 \times 10^{-9}$ m/s and $k_{UL} = 1.8 \times 10^{-9}$ m/s, uniformly assigned to the overliner and underliner, was 0.32 lpd. This calculated flow is 1.2 to 2 times higher than the actual measured flow (0.16 lpd in Test P3 and 0.26 lpd in Test P4). The smaller measured flow in the case with silt on top could also be due to: (i) the variability in the tested silt, (ii) seepage induced consolidation of the silt near the geomembrane hole and/or (iii) migration of fines from the overliner towards the hole under the applied gradient.

Due to majority of head loss occurring close to the geomembrane hole (Figure 4.3 and Figure 4.4) and with the overliner containing large amount of fines, there may have been mobilization, migration and deposition of finer particles in and around the geomembrane hole. This possible local effect was likely not captured in the bulk measurement of $k$ of the silt overliner. The magnitude of the seepage velocity generated over the area of the test cell (calculated with the
numerical model) was 42 times smaller than that generated at a distance two times the hole radius from the centre of the 10-mm-diameter hole and 225 times smaller than that generated at the hole due to flow occurring through a narrow hole under larger applied hydraulic gradient. The effect of this local $k$ reduction near the hole was simulated by assigning a reduced $k$ to a distance twice the radius of the geomembrane hole (radius of influence; where over 75% of the total head loss occurred). The value of $k$ within the radius of influence was decreased relative to the value away from the hole ($2.6-3.1 \times 10^{-9}$ m/s) by a factor of $2.6-3.1$ to $1 \times 10^{-9}$ m/s to match the flow measured in Test P3 and by a factor of $1.1-1.3$ to $2.3 \times 10^{-9}$ m/s for Test P4.

There are no measurements to support the local increase in fines causing the $k$ to reduce locally. Attempts to quantify the change in fines near the hole were unsuccessful because: (i) the amount of material involved was smaller than that required by most standards to obtain the grain size distribution of soil, (ii) there was high variability in the percentage fines in the silt, and (iii) no visual discrepancy between the region near and away from the hole was apparent.

### 4.4 Other factors affecting flow through geomembrane hole

A low hydraulic conductivity underliner is essential for controlling flow through geomembrane holes in a municipal solid waste type containment application where the high permeability overliner provides minimal resistance to flow. Typically, a geomembrane is used in conjunction with a geosynthetic clay liner (GCL; $k < 5 \times 10^{-11}$ m/s) or a compacted clay liner (CCL; $k < 1 \times 10^{-9}$ m/s) to form a composite liner. Rowe (2012) showed that a well-constructed composite liner can reduce leakages by many orders of magnitude than that expected for a single geomembrane or clay liner. The advantage of having a low $k$ underliner, with and without composite action with a geomembrane, in a tailings storage facility such as one shown in Figure 4.2a is studied using the
field scale numerical model discussed earlier. The case examined earlier with $k_T=5 \times 10^{-9}$ m/s and $k_{UL}=1 \times 10^{-5}$ m/s was remodeled with a low $k$ underliner ($k_{UL}=1 \times 10^{-9}$ m/s) to represent a case where the underliner $k$ is similar to that commonly specified for a compacted clay liner.

Additionally, the effect of having a larger diameter geomembrane hole such as those reported by Colucci and Lavagnolo (1995) in geomembrane lined landfills (largest reported equivalent hole diameter of 517 mm) and by Beck (2014) in a heap leach pad facility (largest reported equivalent hole diameter of 667 mm) are simulated by introducing a 50- and 500-mm-diameter hole for $k_T=5 \times 10^{-9}$ m/s and $k_{UL}=1 \times 10^{-5}$ and $1 \times 10^{-9}$ m/s.

4.4.1 Effect of underliner $k$

With a 10,000 times reduction in $k_{UL}$ from $1 \times 10^{-5}$ m/s to $1 \times 10^{-9}$ m/s, the flow decreased only by 8% from 30,600 lpd to 28,100 lpd in the case without geomembrane and by 66% from 1.02 lpd to 0.35 lpd for the case with geomembrane and a 10-mm-diameter hole. Although the percentage flow reduction in the case with geomembrane seems significant, the flow with high $k$ underliner was already very low.

4.4.2 Flow through larger geomembrane holes

The calculated flow through 50- and 500-mm-diameter hole for the case with $k_T=5 \times 10^{-9}$ m/s and $k_{UL}=1 \times 10^{-5}$ m/s is 6 and 80 lpd respectively. The flow further reduced for the case with $k_{UL}=1 \times 10^{-9}$ m/s to 2 and 28 lpd. Although the calculated flows through larger holes are significantly higher compared to that calculated through smaller hole, the flows are insignificant compared to the cases without geomembrane even with a high $k$ underliner.
These results show that despite of highly permeable underliner and large holes of up to half-a-metre in diameter, geomembranes can be very effective in limiting leakage through a large tailings storage facilities.

4.5 Summary and conclusions

The design and development of a new laboratory apparatus for testing geomembrane leakage for mine tailings applications under large earth and fluid pressures was presented. The apparatus is a 0.59-m-diameter and 0.5-m-high rigid test cell where vertical stresses representing the weight of the overburden material above the deeply buried geomembrane and pore pressure generated due to submerged overburden could be applied. The focus was on the influence of the boundary conditions in the new apparatus and how reasonably the apparatus measures flow through holes in the buried geomembrane. Four prototype tests conducted were presented to illustrate the use of the new apparatus at a total applied vertical pressure of 3000 kPa and applied pore pressure of 1500 kPa and to gain some insight on the effect of having a low permeable soil on top of the geomembrane. The main conclusions from the study are:

1. Calculations show that the boundary conditions applied in the test cell were able to simulate flow within 5% of that calculated in the field scale that is up to 500 times larger than the test cell dimensions.

2. With a 0.14-m-thick silt underliner ($k=1.8 \times 10^{-9}$ m/s) and a 10-mm-diameter hole on a 1-mm-thick LLDPE geomembrane, the effect of having a 0.3-m-thick layer of silt ($k=4.6 \times 10^{-9}$ m/s) was flow reduction of 3–4 times than having a coarse sand overliner with much higher $k$ (0.08 m/s).
3. The finite-element analysis gave a flow that is 1.2-2 times higher than that actually observed when a uniform hydraulic conductivity measured for the silt overliner layer was used in the analysis. To match the calculated flow with the actual measured flow it was necessary to reduce the hydraulic conductivity of the silt within a region two times the diameter of the hole from the centre of the hole where majority of head loss was observed and that possibly mobilized, migrated and deposited finer particles in and around the geomembrane hole. For the coarse sand overliner the calculated and measured flow were same.

The leakage inferred from these cases would appear to be quite small for a reasonable number of holes in a facility lined with a geomembrane with a low $k$ overliner. Flow through holes with relatively higher hydraulic conductivity tailings backfill and cyclone sand underliner are presented in Chapter 5 and 6.
4.6 References


<table>
<thead>
<tr>
<th>Test</th>
<th>Underliner</th>
<th>Geomembrane</th>
<th>Overliner</th>
<th>Applied total stress (kPa)</th>
<th>Applied pore pressure (kPa)</th>
<th>Measured leakage rate (lpd)</th>
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<td>1-mm-thick LLDPE with a centrally located 10-mm-dia. hole</td>
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Table 4.2 Index properties of overliner and underliner after test termination

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<thead>
<tr>
<th>Test</th>
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<th>Underliner</th>
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<tr>
<td></td>
<td>Average bulk density (kg/m³)</td>
<td>Average moisture content (%)</td>
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<tr>
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<td>-</td>
</tr>
<tr>
<td>P2</td>
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</tr>
<tr>
<td>P4</td>
<td>2120 (n=3)</td>
<td>19.76 (n=3)</td>
</tr>
</tbody>
</table>

Note: n - sample size, * Underliner tested for hydraulic conductivity measurement at $p=3100$ kPa, $u=100$ kPa ($p'=3000$ kPa) prior to soil sampling.
Figure 4.1 (a) Geomembrane hole in a typical municipal solid waste landfill configuration, and (b) Geomembrane hole in a mine tailings containment configuration.
Figure 4.2 (a) Geomembrane buried deep in a containment facility, and (b) Representation of earth and pore pressure action on a region of soil around a hole in the geomembrane liner.
Figure 4.3 Flow lines and select contours of total head (in m) from axisymmetric finite-element seepage analysis for: (a) Field scale model, and (b) Laboratory scale model. The hydraulic conductivity of tailings and underliner were $5 \times 10^{-9}$ m/s and $1 \times 10^{-5}$ m/s respectively.
Figure 4.4 Elevation vs pore pressure distribution in two different combination of overliner and underliner examined (SEEP/W results). Due to having a low pore pressure below the geomembrane layer, effective stresses on the underliner are likely to be closer to applied vertical stress.
Figure 4.5 Effect of cell diameter on flow through geomembrane hole with an overliner of thickness 0.3 m for soils with hydraulic properties that of low $k$ fine tailings overliner / sand underliner and higher $k$ tailings overliner / sand underliner.
Figure 4.6 Schematic of the test system.
Figure 4.7 (a) Schematic of friction treatment and bentonite perimeter seal details, (b) Photograph showing the seal and friction treatment, (c) Post-test termination picture showing the presence of blue dye restricted towards the perimeter of the seal, and (d) No evidence of leakage through the seal after the geomembrane has been removed.
Figure 4.8 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, (d) Cumulative consolidated water, and (e) Measured flow versus time for Tests P1 and P2.
Figure 4.9 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, (d) Cumulative consolidated water, and (e) Measured flow versus time for Tests P3 and P4.
Chapter 5

Leakage through holes in geomembranes below saturated fine tailings

5.1 Introduction

Tailings storage facilities (TSF) have historically relied on the in-situ soils or rock to control impacts on groundwater and surface water except where it is highly permeable. In these cases they have commonly been lined with re-compacted glacial till or other lower permeability soils (Davies et al. 2002). With increasing environmental concerns concerning the release of potential contaminants in tailings, there has been a growing interest in the use of geomembranes to line facilities (Breitenbach and Smith 2006).

Leakage through a geomembrane will depend on: the number and size of holes; the thickness and hydraulic conductivity, \( k \), of soils in contact with the geomembrane; the stresses acting on the liner; the hydraulic gradient across the liner; and, the transmissivity at the interface between geomembrane and adjacent soils, \( \theta \), (Giroud 1997; Rowe et al. 2004; Rowe 2005, 2012). It is often assumed that a geomembrane installed with good construction quality control (CQC) will have 2.5 - 5 holes per hectare (Giroud and Bonaparte 1989, 2001). However it is unlikely that this level of CQC, as used in landfill applications, would be exercised in a large tailings storage facility. This begs the question as to what leakage might be expected if a geomembrane was used and what would be the benefits of installing a geomembrane given that there likely will be some holes.

Leakage through holes in a geomembrane used as a single liner or as a part of a composite liner alongside a geosynthetic clay liner or compacted clay liner in a municipal solid-waste (MSW) landfill or in a pond application is well understood (Giroud 1997; Rowe et al. 2004; Weber 2008;
Rowe 2012). In those applications, generally a higher $k$ soil overlies the geomembrane resting on an underliner (foundation) with very low $k$ (Figure 5.1a).

A wide range of tailings gradation curves exist for various mining operations and consequently tailings may range from sand to clay-sized particles (Mittal and Morgenstern 1975). Most base metal mine tailings typically comprise 40% to 70% fines. However, some milling processes such as gold extraction may grind the ore so that 90% or more of the tailings are fines (Davies et al. 2002). Thus in many TSFs, the tailings that would overlie a geomembrane liner (Figure 5.1b) would have a large percentage of fines ($< 75\mu m$) and hence a $k$ many orders of magnitude lower than that of the drainage layers used in many other applications involving a geomembrane such as a landfill or heap leach pad (Figure 5.1a). In contrast, the underliner below the geomembrane in a TSF would be expected to have a much higher $k$ (Figure 5.1b) than the clay liner used in many other applications (Figure 5.1a). Thus, the leakage calculations used for landfill type situations (Figure 5.1a) would not appear to be relevant to TSFs and this raises the question as to what would be the leakage for reasonable TSF scenarios?

Some work has been done for the case of a permeable soil above and below a geomembrane with defects (e.g., Fukuoka 1986; Brown et al. 1987; Bonaparte et al. 1989; Giroud et al. 1997; Walton et al. 1997). Bonaparte et al. (1989) established a flow-equation by interpolating between lower and upper bound solutions in a set of laboratory experimental results. However, the proposed empirical relation can only be used when the soil overlying the geomembrane has a $k$ greater than $10^{-6} m/s$ and thickness larger than the liquid head on top of the geomembrane. Also, the equation proposed by Giroud et al. (1997) has limitations with respect to facility with larger heads. For example, for the size of the holes tested in this study, it is recommended that Bernoulli's flow equation be used for heads greater than 20 m. This would imply ignoring the role of the overlying
tailings in impeding flow through the geomembrane hole for tailings thicknesses greater than 20m. Walton et al. (1997) first derived a mathematical flow model and verified it against tests conducted at different effective stresses with permeable silica sand on top and below the geomembrane with hole. The silica sand used for the study had a high permeability of 2 x 10^{-4} m/s to justify the assumption of a fixed pressure head above and below the geomembrane defect.

No study has examined the potential leakage through a hole in a geomembrane when it is covered by material with a \( k \) representative of tailings. Although numerical modelling can be used to model this case, there is presently no experimental data to calibrate that modelling for situations representative of those that might be encountered in a TSF. Thus, the primary objective of this paper is to experimentally examine the effect on the leakage through a hole in a geomembrane used at the base of a simulated TSF of different: (i) tailings, (ii) underliners (foundations), (iii) geomembranes, (iv) hole size and, (v) applied stresses and heads. Consideration is also given to the effects of a nonwoven geotextile cushioning layer, and a small gap below the geomembrane hole. A second objective is compare the experimentally obtained leakage with that calculated using an axi-symmetric finite-element model.

5.2 Experimental investigation

5.2.1 Materials

Raw tailings and two cyclone sand samples were collected from the Highland Valley Copper mine facility in Kamloops, B. C., Canada. Three tailings with different fines and \( k \) were examined. The raw tailings (denoted as T-8, where the “-8” indicates that \( k \) was of the order of 10^{-8} m/s at \( p' = 1500 \) kPa; Table 5.1) can be classified (ASTM 2011) as a silty-sand containing 42-45% non-plastic fines (< 75 \( \mu \)m). In addition, raw tailings and cyclone sands were mixed in different proportions to
generate two other tailings (T-7 with 25-27% fines and T-6 with 12-14% fines; Table 5.1). Four underliners were studied (Table 5.1): (i) a poorly-graded pea gravel (UL-2 with <1% fines), (ii) a poorly-graded sand with silt (UL-5 with 9-10% fines), (iii) a silty-sand (UL-6 with 10-13% fines), and (iv) a blend of raw tailings and cyclone sand (UL-7 with 25-27% fines). Grain size distribution of all tailings and underliners are provided in Appendix B.1. All tailings and underliners used in this study are non-reactive to water (Appendix B.19). Thus the effect their mineral content or the pore water chemistry (when diluted with tap water; discussed later) has on their hydraulic properties was assumed insignificant. The results of the whole rock and supernatant analysis completed on the coarse fraction of the tailings are presented in Appendix B.19.

Two geomembranes were examined. The 1-mm-thick LLDPE geomembrane had a density of 934 kg/m³, standard oxidative induction time (Std-OIT) of 162±4.5 mins, high pressure oxidative induction time of 3000 minutes, yield strength of 12±0.2 kN/m, yield strain of 22.1±1.5%, break strength of 35.1±2.7 kN/m, and break strain of 1200±113% (Appendix B.15). The 2-mm-thick HDPE geomembrane had a density of 947 kg/m³, standard OIT of 175 minutes, HP-OIT of 960 minutes, yield strength of 37.8±1 kN/m, yield strain of 19.2±0.5%, break strength of 65.8±3.6 kN/m, and break strain of 842±36%.

A 4-mm-thick nonwoven, needle-punched geotextile with mass per unit area of 580 g/m² and apparent opening size (AOS) of 0.15 mm also was used in some tests.

5.2.2 Test apparatus and method

The test apparatus developed by Brachman and Gudina (2002) and the test method (Appendix B.2) developed by Joshi et al. (2014) (Appendix B.18) were used. The apparatus is a rigid cylindrical steel test cell (inside diameter 590 mm and height of 500 mm) in which a vertical pressure (p) of
up to 3000 kPa could be applied (Figure 5.2). Due to the rigidity of the 7-mm-thick cell sidewall, the horizontal stresses corresponded to zero lateral strain conditions. A friction treatment comprised of two layers of 0.1-mm-thick polyethylene sheets with a special lubricant between them (to allow the outer layer to slip with very little resistance as the soil in the cell consolidates and compresses) was applied to the cell walls. Tognon et al. (1999) showed that this arrangement reduced the sidewall friction angle to below 5°. Brachman and Gudina (2002) and Krushelnitzky and Brachman (2009) showed that these physical boundary conditions are sufficient to simulate deep burial conditions up to 3000 kPa of applied vertical stress.

In all tests (Figure 5.2), a layer of geocomposite drain (GCD) was placed on the steel base of the test cell. A 0.14 m thick layer of underliner was then compacted to an initial dry density of 1650-1700 kg/m³ at 10.5-11% water content and then saturated from below. This was followed by placement of a geomembrane specimen with a central circular defect (1.5, 10, or 20 mm in diameter). The distance from the centre of the hole to the zero flow lateral boundary was 0.295 m. To prevent any preferential flow along the sidewall of the test cell at the location of the geomembrane, a perimeter seal (involving both dry and wet layers of bentonite) was installed and blue dye was used to check for seal leakage (Joshi et al. 2014 (Appendix B.18); Appendix A.3). A 300-mm-thick layer of pumpable, non-segregating, saturated tailings slurry at 65% solids content was placed over the geomembrane. Tap water was used to prepare the tailings slurry. Two layers of geocomposite drains (connected to a tap water supply through a pressure regulator) were placed above the tailings and covered with a sand leveling layer and rubber bladder, before the top of the cell was fastened down.

A prescribed total stress was applied to the sand leveling layer and all underlying layers by pressurizing the zone between rubber bladder and the lid. A constant head boundary condition was
imposed above the tailings by pressurizing fluid in the geocomposite drains. The vertical distance from the constant head boundary to the geomembrane was 0.3 m. A constant head bottom head boundary condition of 0.15 m was applied using the bottom geocomposite drain.

The minimum hole diameter in the geomembrane (1.5 mm) was selected to be close to the minimum hole size detectable during a leak detection survey (1.4 mm; TRI 2013) using the dipole method on a water covered geomembrane (ASTM 2016).

Permeation tests were conducted at a combination of different applied stresses to simulate a tailings storage facility at various stages of development. The first case approximates a thickness of tailings applying a total stress, $p$, of 250 kPa on the lower 0.3 m of tailings where the tailings are submerged under sufficient water to generate a pore pressure, $u$, at the top of the lower 0.3 m of tailings of 200 kPa, giving an effective stress $p’=50$ kPa at the top of the lower 0.3 m of tailings. The second case had tailings applying $p=1000$ kPa, pressure head yielding $u=500$ kPa and an effective stress $p’=500$ kPa at the top of the lower 0.3 m of tailings. The third case corresponded to $p=2000$ kPa, $u=1000$ kPa, and $p’=1000$ kPa. The fourth was for $p=3000$ kPa, $u=1500$ kPa and $p’=1500$ kPa. Most of the tests were permeated at the maximum stress level $p=3000$ kPa, $u=1500$ kPa, and $p’=1500$ kPa (e.g., Figure 5.3a, b, c for the case with T-8 raw-tailings and UL-6 cyclone sand underliner).

Flow through the geomembrane hole was collected in a graduated cylinder with a known dry mass. Periodic flow measurements were taken by recording the nearest graduation on the cylinder to the lower meniscus and by taking the total mass of the cylinder with the flow that occurred between the recording intervals. The later was used for further calculations and the former was used for minimizing random error. Flow per unit time was then calculated by dividing the difference between the total mass and dry mass of the cylinder by the elapsed time between...
measurements. Since the least count of the balance used for flow measurements was 0.01 gram, measurement frequency was reduced for smaller flows.

5.2.3 Hydraulic conductivity measurement

The $k$ of the tailings and underliners were measured in the same test cell and at the same effective stresses as applied during the tests with the geomembrane and are given in Table 5.1. For the tailings, a 0.14 m thick graded granular filter was first placed at the bottom of the test cell (Appendix B.7). A 0.3 m thick layer of tailings slurry prepared at 65% solids was then placed directly on top of the filter. The tailings layer was consolidated to the test effective stresses prior to application of a hydraulic head.

Hydraulic conductivity tests on the underliner were conducted after termination of the permeation tests. First, the tailings and geomembrane from the permeation tests were replaced by a 0.3 m thick layer of washed pea gravel then the underliner was subjected to the maximum effective stress applied during the permeation phase of the experiment before applying a hydraulic head. Hydraulic conductivity measured for tailings and underliner under different effective stresses are included in Appendix B.8.

5.3 Results and discussion

5.3.1 Base case

The base case was for T-7 tailings, 1-mm-thick LLDPE geomembrane with a 10-mm-diameter ($\phi$) hole (Appendix B.3), UL-6 underliner, and subjected to $p=3000$ kPa and $u=1500$ kPa. Triplicate tests gave steady-state-flow rates of 4.5, 5 and 6 litres per day (lpd) (Tests 1A, 1B and 1D; Table...
5.2) with an average of 5.2 ±0.8 lpd. Steady-state-flow was maintained for at least one week before termination. The very similar flow rates indicates good test reproducibility (Figure 5.4).

5.3.2 Effect of stress path

To examine the effect of the path to final stress state, Test 1D was permeated to steady-state at \( p=250 \text{ kPa}, u=200 \text{ kPa} \) \((p’=50 \text{ kPa})\) and \( p=1000 \text{ kPa}, u=500 \text{ kPa} \) \((p’=500 \text{ kPa})\) before going to the base case stress \( p=3000 \text{ kPa} \) and \( u=1500 \text{ kPa} \) \((p’=1500 \text{ kPa})\). There was no notable effect of stress path and the steady-state leakage rate (6 lpd) which was larger but very similar to that for Test 1A and 1B (4.5 & 5 lpd). The results at intermediate stresses are discussed later.

5.3.3 Influence of material properties on leakage through geomembrane hole

5.3.3.1 Hydraulic conductivity of tailings

Similar tests were conducted at \( p=3000 \text{ kPa}, u=1500 \text{ kPa} \) \((p’=1500 \text{ kPa})\) with a UL-6 underliner and a 1-mm-thick LLDPE geomembrane with a 10-mm-φ hole for tailings with three different percentages of fines and \( k \). If there were no geomembrane then the change in flow should be directly proportional to the change in the harmonic mean \((k_m)\) of the tailings and underliner layer hydraulic conductivities. The steady-state flow (Figure 5.4) decreased with a decrease in \( k \) of the tailings (i.e., increasing percentage fines). The flow of 0.5 lpd (Test 2; Table 5.2) for raw tailings \((T-8 \text{ having } 45\% \text{ fines})\) with the lowest \( k=2.9 \times 10^{-8} \text{ m/s} \) \((k_m=4 \times 10^{-8} \text{ m/s})\) was an order of magnitude lower (Figure 5.3d; Figure 5.4) than the 5.2 lpd (average of recorded flow in Tests 1A, B, C at maximum applied stresses; Table 5.2) for the base case \((T-7 \text{ tailings } 25\text{-}27\% \text{ fines})\) with \( k=1.1 \times 10^{-7} \text{ m/s} \) \((k_m=1.5 \times 10^{-7} \text{ m/s})\) although \( k_m \) had only decreased by a factor of 3.7. The flow of 7 lpd for \((T-6 \text{ tailings } 12\text{-}14\% \text{ fines})\) with \( k=1.6 \times 10^{-6} \text{ m/s} \) \((k_m=1.1 \times 10^{-6} \text{ m/s})\) was only 35% more that the base case although \( k_m \) had increased by a factor of 7.3. Thus the flows were not proportional to the
change in the harmonic mean of the two layers suggesting that something in addition to the bulk $k$ was influencing the flows (to be discussed later) when the geomembrane was present.

The geomembrane had a very significant effect on reducing the flow. The calculated flow for the prescribed heads with no geomembrane (based on the $k_m$ values) for the T-8 tailings was 330 lpd (compared to 0.5 lpd with the geomembrane). For T-7 tailings and T-6 tailing the calculated flows without a geomembrane were 1240 lpd (5.2 lpd with geomembrane) and 9280 lpd (7 lpd), respectively.

5.3.3.2 Effect of underliner hydraulic conductivity

The effect of underliner $k$ was assessed by varying the underliner below the T-7 tailings ($k \sim 1.1 \times 10^{-7}$ m/s) and 1-mm-LLDPE geomembrane (10-mm-$\phi$ hole) for the base case stress ($p=3000$ kPa, $u=1500$ kPa). The lowest flow of at 3 lpd (Table 5.2 and Figure 5.5) was obtained for the silty-sand underliner (UL-7; $k \sim 1.1 \times 10^{-7}$ m/s; $k_m \sim 1.1 \times 10^{-7}$ m/s). The average flow of 5.2 lpd for the UL-6 underliner (UL-6; $k \sim 6.9 \times 10^{-7}$ m/s; $k_m \sim 1.5 \times 10^{-7}$ m/s; base case) was 73% higher, which was twice the 37% increase in harmonic mean $k$ of the two layers (applicable if there were no geomembrane), showing that the geomembrane was affecting the flow in a non-obvious manner by channeling the flow through the hole which was only 0.025% of the overall cell area. With a 17 times more permeable underliner UL-5 ($k \sim 1 \times 10^{-5}$ m/s; $k_m \sim 1.6 \times 10^{-7}$ m/s) the steady-state flow of 4 lpd was actually smaller than but essentially the same as the average flow for the 5.2±0.8 lpd for the nominally identical base case tests with UL-6 (Test 1A & 1B). The small decrease in flow appears to be related to the post-test observations of a significant increase in fines content in the underliner below and in the zone adjacent to the hole (Figure 5.6) from an initial 9% to about 25% (Figure 5.7a). The fines content of the underliner was locally similar to that of the tailings indicating that fines transport may be an important factor affecting flow as discussed later. The apparently
inconsistent trend of observed flows for the three underliners UL-7 (3 lpd), UL-6 (5.2±0.8 lpd) and UL-5 (4 lpd) is associated with the movements of fines into the tailings to be discussed more later.

For the T-7 tailings, the calculated flow for the prescribed heads with no geomembrane (based on the \( k_m \) values) for the UL-7 underliner was 910 lpd (compared to the observed 3 lpd with the geomembrane). For UL-6 and UL-5 underliners the calculated flows without a geomembrane (observed with geomembrane) were 1240 lpd (5.2 lpd) and 1330 lpd (4 lpd), respectively. With a pea gravel (UL-2) underliner the calculated flow was also 1330 lpd since for UL-5 and UL-2 underliners the harmonic mean was the same (\( k_m = 1.6 \times 10^{-7} \) m/s) to two significant digits. Experimentally, increasing the \( k \) of the underliner further with a poorly graded pea gravel (estimated \( k = 1 \times 10^{-2} \) m/s; Test 6) led to failure due to piping (internal erosion caused by seepage). Although the test was terminated soon after the failure and the steady-state-flow-conditions may not have been achieved, the leakage was greater than 2000 lpd.

To prevent piping failure and examine the effect of having a filter layer beneath the geomembrane hole, Test 6 was repeated with a nonwoven geotextile of mass per unit area 580 g/m² and apparent opening size of 0.15 mm placed below geomembrane and above the pea gravel foundation for otherwise similar conditions (Test 12). The check for filter compatibility of the geotextile with T-7 tailings is given in Appendix B.13. There was no evidence of piping and the steady-state flow of 6.5 lpd (Test 12, Figure 5.5b) was only slightly greater than that obtained in the base case test with a compacted silty-sand underliner (5.2±0.8 lpd). Post-test inspection found that the pore space of the geotextile directly below the geomembrane hole was largely filled with migrated tailings (Figure 5.8) of which approximately 40% were fines.

In summary, for the T-7 tailings (\( k \sim 1.1 \times 10^{-7} \) m/s at \( p' = 1500 \) kPa) the underliner had relatively little effect (a factor 2) on leakage through the geomembrane hole with over a more than
two order of magnitude (factor of 110) range of hydraulic conductivities ($1.1 \times 10^{-7} \text{ m/s} < k < 1.2 \times 10^{-5} \text{ m/s}$) provided that the underliner acted as a filter layer. This was attributed to migration of fines that accumulated in the foundation layer near the hole and this appears to have locally decreased the foundation $k$. However, piping must be avoided.

5.3.3.3 Effect of geomembrane type and thickness

Most tests were with a 1-mm-thick LLDPE geomembrane. To study the effect on leakage of a thicker geomembrane, a 2-mm-thick HDPE geomembrane was tested (Test 7) for conditions otherwise the same as the base case. The measured leakage rate of 4.8 lpd in Test 7 is slightly smaller than the average leakage of 5.2 lpd but within the range (4.5-6 lpd) of the three base case tests with a 1-mm-thick LLDPE geomembrane (Table 5.2). Although there was no difference in steady-state leakage rate, the test with thicker geomembrane took a week longer to reach steady-state. This increase in time is attributed to the fact that there was a larger volume of material in the hole for the thicker geomembrane and hence it took longer for sufficient fines to migrate until an equilibrium (steady-state) was achieved.

5.3.4 Effect of geomembrane hole size

To assess the effect of geomembrane hole size on flow, tests were conducted with a 1.5-mm, 10-mm (base case), and 20-mm-diameter ($\varphi$) hole in a 1-mm-thick LLDPE geomembrane. Under the same applied stresses, the steady-state flow rate (0.005 lpd) through the 1.5-mm-$\varphi$ hole was about 1000 times smaller than that measured in the base case (5.2 lpd; Figure 5.9). The flow through 20-mm-$\varphi$ hole (5 lpd) was within the range of measurements for the base cases with 10-mm-$\varphi$ hole. However, the time to reach steady-state was less than three weeks for the 10-mm-$\varphi$ hole but about
five weeks for the 20-mm-φ hole. The 2.5 times lower (calculated) seepage velocity with larger hole may have slowed the mobilization and deposition of fines in and around the hole.

### 5.3.5 Effect of a transmissive layer between tailings and geomembrane

To study the effect on flow of increasing the interface transmissivity between the tailings and the geomembrane, a 580 g/m² nonwoven needle-punched geotextile was placed over the geomembrane (Test 11). Except for the geotextile, the test was the same as the base case. With the geotextile, the steady-state-flow (8 lpd) was 60% greater than average flow (5.2 lpd) for of the base cases (Table 5.2). Although steady-state was attained within a week, the test was allowed to run for over three weeks to confirm steady-state had been achieved and no additional time-dependent change in flow was discernable. This 60% increase in flow is relevant to the dimensions of the test apparatus. However, in the field, the area potentially contributing flow through the geotextile to the hole may be larger and hence the increase in flow could be greater than reported here.

Inspection of the geotextile after test termination found that tailings had intruded into the geotextile pores (Figure 5.10). The geotextile was tested according to ASTM (2013) to assess the effect of the tailings intrusion. The in-plane transmissivity of the exhumed geotextile (0.43 x 10⁻⁶ m²/s) was one third of the off-the-roll virgin geotextile value (1.24 x 10⁻⁶ m²/s) (Appendix B.14).

### 5.3.6 Effect of effective stress

Tests were conducted for different applied stresses to simulate the conditions at various stages of TSF development. For the 10-mm-φ hole, the stress combinations examined were: (i) \( p=250 \text{ kPa}, u=200 \text{ kPa} (p'=50 \text{ kPa}) \); (ii) \( p=1000 \text{ kPa}, u=500 \text{ kPa} (p'=500 \text{ kPa}) \) and (iii) \( p=3000 \text{ kPa}, u=1500 \text{ kPa} (p'=1500 \text{ kPa}) \). For tests with a 1.5-mm-φ hole, a fourth stress combination of \( p=2000 \text{ kPa}, \)
\( u = 1000 \text{ kPa} (p' = 1000 \text{ kPa}) \) was added. All tests were conducted with T-7 tailings and UL-6 or UL-2 (pea gravel) underliners. The results are plotted in Figure 5.11 and summarized in Table 5.2.

Two tests were conducted with a 1.5-mm-\( \phi \) hole in the geomembrane with the geomembrane resting on: (i) UL-6 underliner (Test 9) and (ii) UL-2 pea gravel (Test 10). At 20 m head, the flow rate through the 1.5-mm-\( \phi \) hole was greater for the gravel underliner (0.8 lpd) than for the silty-sand underliner (0.07 lpd), but less than that for the 10-mm-\( \phi \) hole on the silty-sand underliner (1.3 lpd; Figure 5.11). As the head and effective stress increased to 50 m and \( p' = 500 \text{ kPa} \) there was a very slight increase in leakage for the 1.5-mm-\( \phi \) hole on the silty-sand underliner (to 0.09 lpd) but a decrease on the gravel underliner (to 0.03 lpd). The difference between the leakage rates for the silty-sand and gravel at 50 m head is curious; but both are small and the difference is probably due to subtle differences in how fines migrate to the small hole. For the silty-sand underliner, the flow rate decreased to 0.03 lpd going to a head of 100 m (\( p' = 1000 \text{ kPa} \)) and to 0.005 lpd on going to a head of 150 m (\( p' = 1500 \text{ kPa} \)); this decrease in flow despite a substantial increase in head is presumed to be due to consolidation of the tailings and accumulation of fines in and around the hole. In contrast, for the 1.5-mm-\( \phi \) hole on the gravel underliner, the flow rate increased slightly from 0.03 lpd at a head of 50 m (\( p' = 500 \text{ kPa} \)) to 0.04 lpd at 100 m (\( p' = 1000 \text{ kPa} \)) and to 0.08 lpd at 150 m (\( p' = 1500 \text{ kPa} \)). Although the leakages were very small at 20 m head (\( p' = 50 \text{ kPa} \)), the reduction in flow as the head increased to 150 m (\( p' = 1500 \text{ kPa} \)) is presumed to be due to consolidation of the tailings and accumulation of fines in and around the hole. For the pea gravel (UL-2) underliner, it appears that with an increase in head from 50 m to 100 m and 150 m the seepage forces were moving soil through the hole into the gravel in small amounts causing a small increase in leakage with increasing head.
In Tests 1D and 12 with a 10-mm-φ hole, the flows were similar for the silty-sand (UL-6) m and geotextile over gravel (GTX/UL-2) underliners. The flows increased by a factor of 2.7 due to a 2.5 fold increase in head from 1.3 lpd at 20 m head to about 3.5 lpd at 50 m head. However, the increase was only by a factor of about 1.8 due to the 3 fold increase in head going from 3.5 lpd at 50 m head to 6-6.5 lpd at 150 m head, indicating that there was a reduction in $k$-tailings controlling the leakage at an effective stress of 1500 kPa relative to that at 500 kPa (Figure 5.11b).

5.3.7 Gap beneath a geomembrane hole due to a stone

All previous results were for a geomembrane in direct contact with the underliner. However, there are situations where the geomembrane may not be completely flat when covered. For example, a stone on, or protruding from, the underliner may cause the geomembrane to be locally elevated above the underliner. This has the potential to create a hole when load is applied, or if near an existing hole, it has the potential to create a gap that might affect leakage. To explore this situation, a 25 mm stone was placed on the UL-6 underliner at a centre-to-centre distance of 15 mm from the 10-mm-φ hole such that there was a gap between the geomembrane and underliner but the gravel was not plugging the hole (Test 13). Otherwise, this test was same as the base case.

The steady-state leakage rate of 2.4 lpd with the stone was less than a half that for the base case (5.2±0.8 lpd) with a flat geomembrane on the silty-sand underliner (Table 5.2). The flow rate was similar to, but slightly smaller than, the case where both tailings and underliner were the base tailings material (3 lpd, Test 4, Figure 5.5; Table 5.2). The lower flow was mostly due to flow of the lower permeability slurry through the geomembrane hole into the gap below the geomembrane at the time of slurry placement. Thus, this reduced flow is associated with locally reduced $k$ below the hole, although the stone may also have affected the flow as indicted by the dye pattern which
shows the area where the greatest flow occurred below the hole and an area near the stone with higher flows than elsewhere (Figure 5.12). The dye pattern also shows the effect of subtle changes in the flow regime.

5.3.8 Migration of fines

After each test, the tailings and underliner away from the hole, near the hole, and in the hole were visually examined. There was evidence of an increase in fines in the tailings very close to the hole and in the hole. The material in the hole appeared to have more fines than the area above and below. This migration of fines likely occurred due to the high hydraulic gradients in and around the geomembrane hole. Since the volume of the soil affected was very small (less than minimum required by any standard grain size distribution test) it was not possible to establish a grain size distribution. As an alternative approach, specimens of material (~3 g) from areas: (i) in and around the hole, and (ii) various distances away from the hole, were placed in a thin cylindrical glass bottle with a flat base. The samples were submerged in tap water, shaken, and allowed to settle. The percentage of fines was estimated from the relative thickness of the fine and coarse fraction. For example, Figure 5.6 shows a visual change in underliner soil texture (percent fines) moving away from the hole after Test 5. Figure 5.7a compares virgin tailings and underliner soil samples with the underliner samples collected from different locations indicated in Figure 5.7b. An increase in fines content in the underliner at the hole and just beneath the hole was observed. The colour of fines has also changed, suggesting that fines from the underliner and fines that have migrated from the tailings were both present. It was also noted that at the same elapsed time, the supernatant in the cylinder containing sample taken from the hole area was more turbid compared to those taken away from the hole. This suggests there was mobilization and deposition of the much finer particles (those not a part of the load-carrying fabric) within the soils in the hole. This larger amount of finer
particles accumulated in the hole is thought to have significantly reduced the $k$ locally within the hole compared to its surroundings.

5.4 Numerical modelling

Axi-symmetric finite element analyses (using SEEP/W; GeoStudio 2012; Appendix B.12) were performed using the independently measured hydraulic conductivities of the overliner and underliner (Table 5.1; Appendix B.8). The model was based on the dimensions of the apparatus with a prescribed pressure head of 153.06 m along the top surface of 0.3 m thick tailings, a 0.14 m thick underliner, a prescribed pressure head of 0.15 along the bottom drainage port in the cell, and cell walls were zero flow boundaries. Any preferential flow along the soil-geomembrane interface is neglected. The mesh was refined by increasing the number of elements until there was no change in solution with further refinement.

5.4.1 Effect of geomembrane on flow

The effect of the geomembrane on flow was evaluated by simulating cases with and without the geomembrane. The base case hydraulic conductivities of tailings and underliner ($k$-tailings = $1.1 \times 10^{-7}$ m/s, and $k$-underliner = $6.9 \times 10^{-7}$ m/s measured at $p' = 1500$ kPa) were used. For the cases with geomembrane, a 10-mm-diameter hole was placed at the centre. Flow calculated for the case with and without geomembrane was 20.4 and 1280 lpd respectively. The model flow without geomembrane is 0.3% higher than the one-dimensional flow calculated using Darcy’s flow equation showing little effect of the finite element discretization.

5.4.2 Effect of underliner $k$
With an increase in the $k$-underliner ($1.2 \times 10^{-5} \text{ m/s}$; as in Test T5) for otherwise the same conditions as above, the flow increased by 5% to 1340 lpd for the case without geomembrane and by 9% to 22.7 lpd for the case with geomembrane. However, in the laboratory experiments for the conditions simulated above, the flow was lower for the case with higher $k$ underliner.

### 5.4.3 Explaining observed flow rates using a numerical model

For the base case, with a 10-mm-$\phi$ hole, the flow calculated from the finite element model (20.4 lpd) was about 4-5 times higher than the actual measured flows (4.5, 5, 6 lpd) for $p=3000$ kPa and $u=1500$ kPa ($p'=1500$ kPa). The higher flow in the model is attributed to the use of a uniform $k$ whereas in the actual tests there was clear evidence of fines migration to, and deposition in and around, the geomembrane hole that had the potential to reduce $k$ locally (e.g., see Figure 5.6). The numerical results indicated that even with a uniform $k$ in the tailings, over 80% of the applied head loss occurred within a radial distance equal to the diameter of the geomembrane hole (this distance is referred to herein as the zone of influence) and it is within this zone that fines mobilization, migration and deposition is considered most probable. This inference from the numerical results is generally consistent with the observed increased fines in this area and in the hole.

An analysis of the base case using the measured $k$ of the T-7 tailings ($k=1.1 \times 10^{-7} \text{ m/s}$) and foundation ($k=6.9 \times 10^{-7} \text{ m/s}$) except within the hole and zone of influence in the tailings where the hydraulic conductivity ($k_d$) was progressively decreased until the calculated flow matched the measured flow at $k_d=2 \times 10^{-8} \text{ m/s}$. This corresponds to a six-fold decrease in hydraulic conductivity in the local region. Based on the $k$-tests conducted on tailings in the small and larger diameter permeameters, $k_d=2 \times 10^{-8} \text{ m/s}$ corresponds to a material having about 40-45% fines as compared
to 27% in the tailings before the flow started (Figure 5.13). This percentage of fines is close to that found in the tailings that were migrated to the geotextile in Test 12.

For Test 8 with a 20-mm-φ geomembrane hole but otherwise the same conditions as the base case, the zone of influence was 20 mm and the local reduction in $k_d$ needed to match the measured flow was $9 \times 10^{-9}$ m/s which corresponds to tailings with about 50% fines. It is possible that since a larger hole draws fines from a larger volume of soil, there is potential for a greater percentage of fines accumulating within the zone of influence (at least for the range of hole sizes examined) thereby locally reducing the flow.

The value of $k_d$ within the zone of influence needed to match observed flows was decreased relative to the value away from the hole ($2.9 \times 10^{-8}$ m/s) by a factor of 2 (to $2 \times 10^{-9}$ m/s) for T-8 tailings and by a factor of 60 (from $1.6 \times 10^{-6}$ m/s to $2.7 \times 10^{-8}$ m/s) for T-6 tailings. The corresponding increase in the local fines content is from initially 45% to about 70% for T-8 tailings and from initially about 13% to about 40% for T-6 tailings. Thus, it appears that the fines have a different effect on $k_d$ for otherwise similar conditions based on starting percentage fines present in the tailings.

Although it is convenient to assume uniform fines content throughout the zone of influence in a numerical model, the actual observed increase fines in the hole and away from the hole was not the same. The thin film of accumulated fines at the hole in Figure 5.6 appears to have had more fines that the surrounding area, with a potentially highly reduced local $k_{hole}$ and consequently flow through the hole. This suggest further discretization of the zone of influence into regions: (i) within, and (ii) away, from the hole each with different hydraulic properties. Unfortunately, it was not possible to accurately estimate the percentage fines and hence the reduced $k$ of the material within the hole relative to that in the rest of the zone of influence. There was no way to definitively estimate
the \( k \) values in either location independently and, hence, there would be an infinite number of combinations that would match the flow. The constant \( k \) in the entire zone of influence represents one limit and gives the \( k_d \) values of \( 2 \times 10^{-9} \) m/s for T-8 tailings (70% fines), \( 2 \times 10^{-8} \) m/s for T-7 tailings (40-45% fines), and \( 2.7 \times 10^{-8} \) m/s for T-6 tailings (40% fines) as discussed above for a 10-mm-hole. A second limit is to deduce the \( k_{\text{hole}} \) required to match the measured flow with the rest of the zone of influence having similar properties as the parent materials. For this idealization, the calculated \( k_{\text{hole}} \) was \( 1 \times 10^{-9} \) m/s for T-8 tailings (85% fines), \( 8 \times 10^{-9} \) m/s for T-7 tailings (50% fines), and \( 9 \times 10^{-9} \) m/s for T-6 tailings (48% fines). The reality is likely between these two limits but the \( k \) may also be a little higher since the foregoing has only considered fines migration affecting the hole and tailings in the zone of influence and did not consider any change in the underliner which also likely contributed to a reduction in flow compared to the uniform \( k \) case.

### 5.4.4 Predictive modelling

The calculated leakage in the base case configuration (T-7 tailings; UL-6 underliner; 1-mm-thick LLDPE geomembrane with 10-mm-\( \phi \) hole; 153.06 m pressure head on top of the tailings surface) modelled using the actual test cell dimensions (radius = 0.295 m, depth of tailings = 0.3 m) and a uniform \( k \) assigned to the tailings (1.1 \( \times 10^{-7} \) m/s) and the underliner (6.9 \( \times 10^{-7} \) m/s) and neglecting any effect of local reduction in \( k \) in and around the hole was 20.4 lpd. Remodeling with the same parameters except for larger test cell diameters, the increase in flow was insignificant (less than 0.4%) with up to eight-fold increase in the diameter of the cell. Similar simulations for a 20-mm-\( \phi \) hole showed less than 0.9% increase in flow suggesting that there were negligible boundary effects of the cell for the conditions examined in the study. This suggest that the cell size had no significant effect on the results without a geotextile above the geomembrane.
The base model (neglecting the effect of having a zone of influence with reduced $k$) was then scaled up to predict flow through a tailings storage facility containing T-6, T-7 or T-8 tailings and UL-6 underliner. The ratio of thickness of tailings and distance from the centre of the geomembrane hole to the boundary were kept equal at unity (based on a parametric study that showed that more distant boundaries had no effect on the calculated flow). Tailings heights of 0.3, 1, 5, 10, 20, 50, 100 and 150 m were simulated with a pressure head of 0.3 m above the tailings to simulate submerged conditions. The calculated flows are plotted in Figure 5.14. For a submerged tailings storage facility, the predicted flow rate is higher than when an equivalent (e.g., 20, 50 or 150 m) high pressure head is directly applied on top of 0.3-m-thick tailings in the experiments. The higher calculated flow, compared to that measured for the same applied head, is attributed to the neglect in the modelling of any local reduction in $k$ in and around the hole that was observed in the experiments.

The calculated flow in the case where 0.3 m pressure head was applied on top of 150 m thick tailings was practically same as the case where 153.06 m pressure head was directly applied on top of 0.3 m thick tailings which suggests that the 0.3 m thick tailings layer examined in the experiments with the pressure head applied above the tailings was adequate to simulate the more complex case. This is likely true even if there was a variation in hydraulic conductivity with depth since the lower 0.3 m would be expected to have the lowest $k$.

These results also suggest that the leakage observed in the laboratory tests at different effective stresses and heads provide a good approximation of the actual flow in a larger scale. For a larger facility, the true flow is expected to lie between the laboratory results and the calculated flow (without considering local reduction in $k$) but probably closer to the lower values.
5.4.4.1 Effect of geomembrane hole size

The scaled up model with 150 m thick tailings under submerged condition was used to study the effect of different geomembrane hole sizes on flow. The flow through 50 and 500-mm-φ holes (for the base case with T-7 tailings and UL-6 underliner) was 120 and 1400 lpd respectively. For the T-8 tailings these flows reduced to 55 and 610 lpd. Although calculated flow through larger holes are much larger than with the smaller holes examined in the experiments, the flows were negligible compared to the cases without any geomembrane where a flow of more than 670,000 lpd was calculated. Thus even with a few very large holes (500-mm-φ), the geomembrane would appear to be very effective in limiting leakage compared to the case without a geomembrane for the cases examined as long as piping is avoided.

5.5 Summary and conclusions

Coupled physical and hydraulic experiments were conducted to quantify the leakage through geomembrane holes under large applied stresses from overlying tailings. The influence of different tailings, different underliners, different geomembrane type and thickness, different hole sizes, different applied stresses and heads, a nonwoven geotextile cushioning layer and a gap beneath the geomembrane hole were examined. For the specific conditions and materials examined, the following conclusions were reached:

1. Effect of tailings and underliner: The leakage reduced with a decrease in the hydraulic conductivity of the tailings, \( k \) (i.e., as the percent fines in the tailings increased). The \( k \)-underliner had little effect on leakage for tailings with a nominal \( k \sim 1.1 \times 10^{-7} \) m/s over a range of \( 9.5 \times 10^{-8} \leq k \)-underliner \( \leq 1.2 \times 10^{-5} \) m/s.
2. Failure due to piping: With pea gravel underliner \( (d_{50} = 10 \text{ mm}, d_{10} = 6 \text{ mm}) \) and 10-mm-diameter hole in the geomembrane, internal erosion and piping failure occurred. Placing a filter geotextile between the geomembrane and the pea gravel underliner prevented piping and the measured flow was only slightly larger than the one with silty-sand underliner (6.5 lpd vs. 5.2 lpd). For a 1.5-mm-diameter hole in a geomembrane above pea gravel, there was no evidence of piping.

3. Geomembrane type and hole sizes: Geomembrane thickness (1 and 2 mm) and type (LLDPE and HDPE) had no effect on the flow. The leakage through 10 and 20-mm-diameter holes were same and less than 7 lpd for the tested materials. Flow reduced by three orders of magnitude for a 1.5-mm-diameter hole.

4. Effect of applied stress and head: For a 10-mm-diameter hole, there was a non-linear increase in flow with increase in applied head. For 1.5-mm-diameter hole, the flow first increased then decreased with increase in effective stresses. At larger effective stresses the flow was affected by consolidation and migration of fines in and around the hole.

5. Migration of fines: There was evidence of an increase in fines in the tailings and underliner in and around the hole.

6. Geotextile protection layer: When a geotextile protection layer was present above the geomembrane, there was a modest increase in leakage although it appeared the increase was mitigated by an accumulation of tailings clogging the geotextile with a consequent 3-fold decrease in transmissivity in the geotextile.

For the materials and conditions examined in this study, the measured flow would correspond to a leakage not exceeding 40 litres per hectare per day (lphd) with a maximum of 5
holes per hectare. These flows would be insignificant compared to that for a similar facility without geomembrane and with the same foundation layers and subjected to similar heads and stresses. This study had not examined the effect of wrinkles.
5.6 References


TRI Environmental, Inc. (2013). Electrical leak location survey general guide, Austin, Texas.

Table 5.1 Properties of materials used in the test.

<table>
<thead>
<tr>
<th>Material</th>
<th>Grain size (mm)</th>
<th>% fines (dia. &lt;75μm)</th>
<th>Hydraulic conductivity k (m/s)</th>
<th>Applied stresses for k measurement (kPa)</th>
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<tr>
<td></td>
<td>d85  d50 d10 Cu Ct</td>
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<td>T-8</td>
<td>0.27 0.08 0.01 10 2.5</td>
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<td>4.2x10^{-7}</td>
<td>600 100 500</td>
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<td>1.6x10^{-7}</td>
<td>1100 100 1000</td>
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<tr>
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<td>Note: * Average of 9.5x10^{-8}, 1.1x10^{-7}, 1.2x10^{-7} m/s</td>
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<td>Geomembrane</td>
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Note: * A 25 mm gravel particle was placed beneath the geomembrane near the hole; GTX = geotextile; GMB = geomembrane.
Figure 5.1 Cross-section showing: (a) Geomembrane hole in a typical municipal solid waste landfill configuration, and (b) Geomembrane hole in a mine tailings containment configuration.
Figure 5.2 Schematic of apparatus (0.5 m high and 0.59 m diameter) showing 0.14 m of compacted underliner and 0.3 m of tailings slurry.
Figure 5.3 Test result for 10-mm-diameter hole: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time.

Test conducted with: T-8 raw tailings ($k = 2.9 \times 10^{-8}$ m/s) and UL-6 cyclone sand underliner ($k = 6.9 \times 10^{-7}$ m/s)
Figure 5.4 Flow through a 10-mm-diameter geomembrane hole with UL-6 underliner \((k = 6.9 \times 10^{-7} \text{ m/s at } p' = 1500 \text{ kPa})\) but different tailings under the same applied stress of \(p = 3000 \text{ kPa}, u = 1500 \text{ kPa}, p' = 1500 \text{ kPa}\). The error bar represents the range of measured flow for multiple tests.
Figure 5.5 Flow results showing little effect of underliner with same overlying tailings. The error bar represents the range of measured flow for multiple tests.
Figure 5.6 Photograph shows the underliner after termination of Test 5 and removal of the geomembrane. The area just beneath the centrally located hole contains relatively high percentage fines (much greater than 25%) with the percentage fines decreasing with radial distance from the hole.
Figure 5.7 (a) Tailings and underliner allowed to settle in glass bottles filled with water before and after Test 5: (i) T-5 underliner before test, (ii) T-7 tailings before test, (iii) no change in underliner sample taken 10 cm away from centre, (iv) increase in fines in underliner sample from just below the hole, (v) no change in underliner sample taken from 10 cm away from centre; (b) Approximate sampling locations for samples iii, iv, and v.
Figure 5.8 Photograph showing cross-section of geotextile used in Test 12 where the geotextile was used as a filter between gravel underliner and geomembrane with hole to prevent piping failure.
Figure 5.9 Effect of geomembrane hole size. (a) Test conducted with a 1.5-mm-diameter hole in the geomembrane, and (b) Tests conducted with 10 and 20-mm-diameter holes. The error bar represents the range of measured flow for multiple tests. Note: The vertical scales for the plots are not same.
Figure 5.10 Photograph showing cross-section through the virgin and exhumed geotextile from Test 11. Pore spaces in the exhumed geotextile are filled with tailings.
Figure 5.11 Effect of applied effective stresses on flow for (a) 1.5-mm-diameter hole, and (b) 10-mm-diameter hole. The error bars represent the range of measured flow for multiple tests.
Figure 5.12 Photograph taken after termination of Test 13. The geomembrane has been removed to expose the 25 mm gravel particle placed near the hole and the initial gap between the geomembrane and underliner has been filled with tailings. The blue dye shows where the flow predominatly went into the underliner after passing through the hole.
Figure 5.13 Hydraulic conductivity of silty-sand with corresponding percentage fines (particles passing sieve No. 200).
Figure 5.14 Calculated leakage through a 10-mm-diameter hole in a 1-mm-thick geomembrane backfilled with different tailings over a UL-6 underliner under different head above the liner. Tailings were submerged beneath a 0.3 m pressure head in all simulations.
Chapter 6

Physical and hydraulic response of geomembrane wrinkles underlying saturated fine tailings

6.1 Introduction

Geomembranes used in mining applications are most commonly either high-density polyethylene (HDPE) or linear low-density polyethylene (LLDPE) (Rowe et al. 2013). Typically, the geomembranes are 1.0 to 2.5 mm thick and are used, either as a single liner or as a component of a composite liner system, to minimize both advective and, for inorganic contaminants, diffusive transport. With these geomembranes, the leakage (fluid flow under a hydraulic gradient) is effectively limited to flow through holes in the geomembrane that most commonly arise either during construction (including during placement of material over the geomembrane) or subsequently due to stress cracking (Rowe et al. 2004; Rowe 2012). It is often assumed that a geomembrane installed with good construction quality control (CQC) will have 2.5 - 5 holes per hectare (Giroud and Bonaparte 1989, 2001). The number of holes may be substantially higher with poor CQC or if the geomembrane is in contact with an underliner (foundation) containing gravel and/or is overlain by a coarse (gravel) backfill (e.g., drainage layer) without adequate geomembrane protection (Rowe et al. 2013; Brachman et al. 2014). On the other hand, with good CQC, a well-graded smooth foundation and a suitable overlying protection layer, short- and long-term damage to the geomembrane can be kept to a very low level (Saathoff and Sehrbrock 1994; Tognon et al. 2000; Gudina and Brachman 2006; Brachman and Gudina 2008; Dickinson and Brachman 2008; Rowe et al. 2013; Brachman et al. 2014).
Leakage through a geomembrane will depend on: the number and size of holes; the thickness and hydraulic conductivity of the soils in contact with the geomembrane; the hydraulic gradient across the liner; the interface transmissivity between the geomembrane and the adjacent soil; and, wrinkles (waves) in the liner (Giroud 1997; Rowe 1998; Rowe et al. 2004; Rowe 2012).

Wrinkles are either due to irregularities (e.g., due to geometry such as corners or due to poor placement) or in-plane thermal expansion caused due to the rise in geomembrane surface temperature after the geomembrane is welded (Pelte et al. 1994; Take et al. 2012). Wrinkling causes a loss of intimate contact between the geomembrane and underlying soil layer (Rowe 1998; Rowe et al. 2004). If these wrinkles are buried when fill is placed over the geomembrane and then subjected to an overburden pressures, they will experience some reduction in height and width, but a gap remains between the geomembrane and the underlying soil (Stone 1984; Soong and Koerner 1998; Gudina and Brachman 2006; Brachman and Gudina 2008; Take et al. 2012). Previous studies have also shown that two or more wrinkles can intersect forming a network of interconnected wrinkles which increases: (i) the total effective length of a wrinkle; (ii) the probability of a hole coinciding with a wrinkle in the interconnected wrinkle network; and, (iii) leakage through the liner. For example, Chappel et al. (2012a) conducted a field study to quantify the effective length of connected wrinkles at different times of the day and reported that on the flat base portion of a municipal solid waste (MSW) landfill, the maximum connected length was 6600 m/ha at 13:45 on a hot day in June. For a wrinkle network of this magnitude, Rowe’s (1998) equation gives a flow of over 1000 litres per day per hectare (lpdh) when the hole size is sufficient that it does not limit the flow and there is an underlying geosynthetic clay liner (GCL) with hydraulic conductivity, \( k = 2 \times 10^{-10} \text{ m/s} \), thickness, \( t = 0.01 \text{ m} \), interface transmissivity between the geomembrane and GCL, \( \theta = 2 \times 10^{-10} \text{ m}^2/\text{s} \) and applied hydraulic head, \( h = 0.3 \text{ m} \).
Prior to this present study, little was known about the potential leakage through a hole in a geomembrane wrinkle in a tailings storage facility since knowledge from the landfill configuration cannot be transferred to a tailings configuration due to the substantial differences in the nature of the underlying and overlying materials (Figure 6.1) and, consequently, the stresses transferred to the geomembrane wrinkle. Modern landfills commonly have a 0.3 m thick gravel drainage layer above the geomembrane liner (Figure 6.1a). With the leachate head generally regulated at \( \leq 0.3 \) m, the vertical effective stress acting on top of the liner is generally very close to the total stresses due to the overlying waste. At the geomembrane wrinkle, due to the deformation of the relatively flexible wrinkle under an applied stress, arching may be induced in the interlocking gravel particles (Terzaghi et al. 1996) thereby reducing the stresses transferred to the wrinkle (especially horizontally). Whereas, in tailings storage facility, it is reasonable to assume that saturated tailings with a low solids content and initially very low shear stiffness applies isotropic or near isotropic stresses to the wrinkle surface (Figure 6.1b). In addition to that there is a possibility that any gap present within the wrinkle may get filled with a free-flowing tailings if there is a hole coincident with the wrinkle. However, it is presently unknown as to how the physical and hydraulic performance of geomembrane wrinkles at the base of a tailings containment facility would be influenced by the combined effect of: (i) the hydraulic properties of the overlying tailings; (ii) stress distribution on the geomembrane wrinkle; and (iii) presence of a free-flowing tailings adjacent to the geomembrane.

The objective of this study is to provide the first insight regarding the short-term physical response of geomembrane wrinkles under simulated tailings containment facility conditions. The influence on wrinkle deformation of type and thickness of geomembrane, backfill, applied total vertical stress and pore pressure are examined. Additionally, the effect of tailings migration through
a 10-mm-diameter hole into the gap beneath the geomembrane wrinkle on wrinkle deformation and leakage through the hole are also studied.

6.2 Experimental details

6.2.1 Apparatus and boundary conditions

The experiments performed in this study were conducted in a rigid cylindrical steel test cell with an inside diameter of 590 mm, height of 500 mm, 7-mm-thick side walls and a 50-mm-thick top and bottom cap (Figure 6.2). A total vertical pressure up to 1000 kPa could be applied by introducing fluid pressure on top of a rubber bladder secured tightly between the lid and the body of the test cell. Horizontal stresses corresponding to essentially zero lateral strain conditions develop due to the rigidity of the cell limiting outward deflection. Pore pressures were applied by injecting water at a controlled pressure between two geocomposite drains (GCDs) placed on top of the tailings. A GCD was also placed at the bottom of the cell above the steel bottom to conduct water to the drainage outlet and provided a known bottom boundary hydraulic head. The cell wall provided a radial no flow boundary. Friction along the inner wall surface was reduced by using two layers of 0.1-mm-thick polyethylene sheets with a special lubricant between them to allow the outer layer to slip with very little resistance as the soil in the cell consolidates and compresses. Tognon et al. (1999) showed that the sidewall friction angle is reduced to less than 5º with this arrangement. Development of the test apparatus and method is discussed in Chapter 4 and Appendix B.18.

6.2.2 Materials and test procedure

The key index properties of the four geomembranes examined in the study (1 and 2-mm-thick LLDPE and HDPE) are given in Table 6.1 and in Appendix B.15. The stiffness index, κ, defined here as the ratio of yield strength to yield strain for each geomembrane, was calculated (Table 6.1).
The stiffness index was then normalized with respect to the value for the least stiff (i.e., the 1-mm-thick LLDPE) geomembrane to give a value, $\Omega$ (Table 6.1) which is the relative tensile stiffness of that geomembrane compared to the 1-mm-thick LLDPE used in this study. For example, $\Omega = 3.4$ and 3.9 for a 2-mm-thick HDPE in machine and cross-machine direction implies that the 2-mm-thick HDPE is 3.4 times stiffer compared to the 1-mm-thick LLDPE geomembrane in the machine direction and 3.9 times stiffer in cross-machine direction. A geomembrane with higher $\Omega$ value is expected to provide greater resistance to wrinkle deformation if subjected to similar stresses by a given surcharge. In addition to the values for the geomembranes examined in this study, the corresponding values for a 1.5-mm-thick HDPE geomembrane used by the previous researchers in a landfill configuration is also included for comparison (Table 6.1) and is discussed later.

In all experiments, a 0.14-m-thick silty-sand base underliner ($d_{50} = 0.19$ mm, $d_{10} = 0.06$ mm, $C_u = 7.3$, $C_c = 3.4$) was compacted at a dry density of 1650 kg/m$^3$ at 10.6% gravimetric water content. The silty-sand had approximately 12% non-plastic fines ($< 75$ $\mu$m) with less than 1% clay size ($< 2$ $\mu$m) (Appendix B.1) and a hydraulic conductivity, $k$, of $3.6 \times 10^{-6}$ m/s at an effective stress $p' = 500$ kPa (total stress $p = 600$ kPa, pore pressure $u = 100$ kPa) (Appendix B.8). Once placed, this underliner was saturated from the bottom.

A geomembrane with a prescribed wrinkle was placed on the saturated underliner (Figure 6.2 and Figure 6.3; Appendix B.5). As placed, the geomembrane wrinkle was 60 mm high and 200 mm wide (Figure 6.4). These dimensions were selected to be within the range reported based on field observations for 1.5 and 2-mm-thick geomembrane HDPE (Pelte et al. 1994, Rowe et al. 2012, Chappel et al. 2012b). A bentonite based perimeter seal was applied on top and bottom of the geomembrane edges around the circumference to limit any preferential flow (Figure 6.2; Appendix A.3; B.5).
Several prototype tests (Appendix B.9) suggested that a wrinkle in the 1-mm-thick geomembrane without any holes may deform to an extent that the inner sides of the wrinkle would come in contact with each other at 250 kPa applied vertical stress. To provide documentary evidence of any such contact, one of the inner sides of the wrinkle was painted white and a grid in black ink was placed on the other side (Figure 6.5a) such that upon contact, the ink mark would transfer to the white paint (Figure 6.5b, c). Also a double-sided adhesive tape was attached on the side with the paint in order to preserve the shape of the compressed wrinkle during the post-test observation (Figure 6.5a, b). Although deformations of 2-mm-thick geomembrane wrinkles were not expected to be as large as in 1-mm-thick geomembranes, white paint, ink marks and double-sided adhesive tape were applied for consistency.

In all tests, except in Test W3, a 10-mm-diameter hole was introduced (Appendix B.3) to study leakage and/or tailings migration into the gap beneath the wrinkle. While the hole size remained the same in all tests, the tests differed in terms of the time of introduction of the hole. For Tests W1 (with 1-mm-thick LLDPE) and W5 (with 2-mm-thick LLDPE), the hole was introduced in the geomembrane wrinkle prior to the placement of tailings slurry to simulate field conditions where holes were formed and went undetected prior to backfilling. For Tests W2 (with 1-mm-thick LLDPE) and W4 (with 1-mm-thick HDPE), the hole was drilled in the wrinkle after the tailings slurry had been consolidated at 250 kPa for 100 hours (Appendix B.3) to simulate field conditions where a hole was formed after backfilling and consolidation of tailings and that the gap below the wrinkle was not filled with tailings migrating from elsewhere.

A 300 mm thick layer of tailings ($d_{50} = 0.19$ mm, $d_{10} = 0.014$ mm, $C_u = 18.4$ and $C_c = 2.9$) as a slurry with 65% solids content by mass was placed on top of the geomembrane layer at a bulk density of 1780 kg/m$^3$. The tailings had approximately 27% non-plastic fines with less than 3%
clay size fraction (Appendix B.1) and a hydraulic conductivity of $5.4 \times 10^{-7}$ m/s at an effective stress of 50 kPa (total stress $p = 150$ kPa, pore pressure $u = 100$ kPa) and $4.2 \times 10^{-7}$ m/s at effective stress of 500 kPa ($p = 600$ kPa, $u = 100$ kPa) (Appendix B.8). The same tailings were used in all tests.

Above the tailings, two layers of geocomposite drains, 30-mm-thick leveling sand layer and a rubber bladder was placed to complete the test setup (see Figure 6.2). The geocomposite is where the pore pressure was applied along the top surface of the tailings, while the rubber bladder was used to apply the total vertical pressure. Once all the materials were placed in the cell, vertical pressures were applied in 50 kPa increments every 10 minutes to reach 250 kPa, which was then held constant for 100 hours (with the exception of Tests W1 and W5, as discussed later). The excess pore pressure generated in the tailings and underliner, due to increase in total stress, was allowed to dissipate from the drainage port on the side of the test cell and flow collection ports at the bottom of the cell respectively (Figure 6.2). After 100 hours, the extent of wrinkle deformation was quantified (Table 6.2) through a narrow vertical observation trench excavated for this purpose (Figure 6.6). After making the observations, the tailings removed from the trench were re-packed into the trench at 25% moisture content and the tailings was re-consolidated at 250 kPa for another 100 hours prior to starting the permeation phase of the experiment.

Tests W2, W4 and W5, were permeated at a combination of different applied pressures to simulate a tailings storage facility at various stages of development. The first combination approximates a thickness of tailings applying a total stress of $p = 250$ kPa on the lower 0.3 m of tailings where the tailings are submerged under sufficient water to generate a pore pressure in the lower 0.3 m of tailing of $u = 200$ kPa, giving an effective stress $p' = 50$ kPa in the lower 0.3 m of tailings. Considering the stresses in the same lower 0.3 m of tailings, the second stress combination
had tailings applying $p = 1000$ kPa, water ponding on the tailings yielding $u = 500$ kPa and $p' = 500$ kPa in the lower 0.3 m of tailings (Figure 6.7a, b, c).

Permeation tests were terminated after reaching steady-state-flow (e.g., Figure 6.7d; Appendix B.11). In all tests, a narrow vertical observation trench at the centre of the cell was excavated through the tailings to acquire the final deformed shape of the geomembrane wrinkle using a line laser profiler (Figure 6.6).

6.3 Results

The base underliner, the tailings and hole size (if present) were kept the same in all experiments so that the effect of geomembrane type and thickness, applied total stress, applied pore pressure and time of hole placement could be explored. These variables are discussed below.

6.3.1 Physical response of geomembrane wrinkles under applied vertical stresses

6.3.1.1 1-mm-thick geomembranes

A 1-mm-thick LLDPE geomembrane wrinkle with a 10-mm-diameter hole on the side (Figure 6.3; Test W1) was covered with 300 mm thick tailings slurry at 65% solids content (applying approximately 6 kPa of total vertical stress) and left for 24 hours without any externally applied load. A cross-section of the initial and deformed shape of the geomembrane (Figure 6.4) shows that the wrinkle height and width were reduced to 67% (40 mm) and 50% (100 mm) of their original values. The final wrinkle was non-symmetrical and skewed away from the side where the hole was placed (Appendix B.6). The wrinkle possibly skewed as the tailings that entered through the hole first resisted any additional lateral stress (due to the increasing depth of tailings) on the side with the hole and allowed the other side to cave in. It is not known whether the same would happen for tailings with lower solids content however it can be anticipated that the tailings with lower solids
would flow even more easily through the hole into the gap beneath the wrinkle than the tailings slurry tested.

Experiments were conducted using a 1-mm-thick LLDPE (Test W2) and HDPE (Test W3) geomembrane with a wrinkle (but without hole) to investigate the effect of larger applied stress on the geomembrane wrinkle, initially without tailings intrusion into the wrinkle. In Test W2, the hole was added after the tailings slurry had been consolidated at 250 kPa for 100 hours to simulate field conditions where a hole was formed after backfilling and consolidation of tailings (discussed in detail later). Test W3 was terminated after evaluating wrinkle deformation. The final shape of the wrinkle when subjected to a total vertical pressure of 250 kPa for 100 hours for otherwise the same test conditions as in Test W1 are shown in Figure 6.8. Post-test observation revealed that the inner sides of the wrinkle were squeezed together to give a near vertical projection. The geomembrane wrinkle deformation resulted in a very high curvature on the crest and toe of the wrinkle where there were large strains that could, in the long-term, cause stress cracking (e.g., Abdeltaal et al. 2013). However, with no remaining gap below the wrinkle, a hole/crack formed at the toe of the wrinkle may lead to a larger flow compared to a hole/crack formed on the crest of the wrinkle.

Inspection of the underside of both geomembrane wrinkles provided further evidence of contact as the ink marks were found to have transformed onto the side with paint (Figure 6.5b, c). Figure 6.9 shows a photograph of the deformed 1-mm-thick LLDPE wrinkle. The final remaining height and width at the base of the 1-mm-thick LLDPE wrinkle were 45% (27 mm) and 10% (20 mm) of the initial dimensions and that for 1-mm-thick HDPE wrinkle were 43% (26 mm) and 19% (38 mm). The larger remaining width in the 1-mm-thick HDPE geomembrane wrinkle was likely due to its slightly higher stiffness compared to the 1-mm-thick LLDPE geomembrane (Table 6.1).
6.3.1.2 2-mm-thick geomembranes

An experiment was conducted with a 2-mm-thick HDPE geomembrane wrinkle (Test W4), initially without hole, subjected to same conditions as in Test W3 with 1-mm-thick HDPE geomembrane wrinkle (total stress of 250 kPa sustained for 100 hours). After 100 hours, the height and width of the wrinkle were reduced to 67% (40 mm) and 40% (80 mm) of the initial dimensions. The remaining void beneath the 2-mm-thick HDPE wrinkle was 1.5 to 2 times larger than that in 1-mm-thick HDPE geomembrane (Figure 6.10). The larger remaining gap beneath the wrinkle in 2-mm-thick geomembrane is attributed to the thicker geomembrane having greater stiffness and hence greater resistance to bending along the geomembrane crest line compared to the thinner and less-stiff 1-mm-thick geomembranes (Table 6.1). At a higher applied pressure of \( p = 1000 \text{ kPa, } u = 500 \text{ kPa (} p’ = 500 \text{ kPa)\), the wrinkle was reduced to a height and width of 64% (38 mm) and 35% (70 mm) but the gap beneath the wrinkle remained (Figure 6.11).

Test W5 was conducted with a 2-mm-thick LLDPE geomembrane where a 10-mm-diameter hole was placed on the top-side of the wrinkle prior to tailings placement so that the tailings slurry could enter the geomembrane wrinkle even before any external stress was applied. As a result, the deformed wrinkle took a different shape to that observed in the 2-mm-thick HDPE wrinkle where there was no hole in the wrinkle prior to backfilling (Figure 6.11). In addition to the central large wrinkle, there were two other smaller wrinkles on each side of the central wrinkle introducing multiple locations with higher curvature. These smaller wrinkles caused the final width of the wrinkle to be wider than the case where no hole was present in the geomembrane wrinkle prior to backfilling. This unique shape of the wrinkle was likely due to the wrinkle deformation occurring only after the gap beneath the wrinkle was partially filled with tailings slurry. The deformed wrinkle was symmetrical at the crest-line unlike that observed for a less stiff
1-mm-thick LLDPE in Test W1. The final width of the central large wrinkle after being subject up to $p = 1000$ kPa and $p' = 500$ kPa was similar to the 2-mm-thick HDPE wrinkle in Test W4 for same applied stresses however the height of the wrinkle was about 3 mm smaller likely due to the presence of smaller wrinkles formed on each side of the central large wrinkle.

6.3.2 Leakage through 10-mm-diameter holes on geomembrane wrinkle

6.3.2.1 Hole at the base of the wrinkle after tailings consolidation

Following a post-consolidation physical evaluation of the wrinkle in the 1-mm-thick LLDPE (Test W2), a 10-mm-diameter hole was drilled at the base of the wrinkle that had been squeezed together, with no gap remaining beneath the wrinkle, due to the previously applied pressure (Figure 6.8a; Appendix B.3). Tailings that had been removed from the vertical observation trench (at ~21% moisture content) were mixed with water to about 25% moisture content (wet but not free flowing) and were packed back into the trench (to reduce arching) and permeation test was started after another 100 hours of consolidation. The intent of filling the hole with tailings containing low moisture content was to prevent free flow of the slurry into the hole. However, it was uncertain to what extent this reproduced the original stiffness of the excavated material. The steady-state flow through the hole at $p = 250$ kPa and $u = 200$ kPa ($p' = 50$ kPa) was 2.3 lpd. When the applied stress and pore pressure were increased to $p = 1000$ kPa and $u = 500$ kPa ($p' = 500$ kPa), the flow increased 3.3 fold to 7.6 lpd.

6.3.2.2 Hole formed on the top-side of the wrinkle after tailings consolidation

Initially, the 2-mm-thick HDPE geomembrane wrinkle in Test W4 did not have any hole. After 100 hours of sustained vertical pressure of 250 kPa, the stress was removed and an observation trench was excavated to allow inspection of the wrinkle (Figure 6.10). After the inspection, a 10-
mm-hole was drilled at the top of the wrinkle (Figure 6.12). The observation trench was backfilled and the backfill was consolidated as described for Test W2 before starting the permeation phase of the test at \( p = 250 \) kPa and \( u = 200 \) kPa \( (p' = 50 \) kPa; Figure 6.7). A steady-state flow of 8.5 lpd was measured in a permeation test that lasted for 44 days. Although steady-state flow conditions were attained in 20 days the test was allowed to run for twice that time to confirm steady-state had been reached and that there was no time-dependent effect on flow. The test was continued but at a higher applied stress and pore pressure \( (p = 1000 \) kPa, \( u = 500 \) kPa; \( p' = 500 \) kPa). At first the flow increased, but eventually (26 days after the stress was increased) the steady-state flow was at a lower rate of 2.5 lpd (Table 6.3; Figure 6.7). This flow at \( p' = 500 \) kPa is about a third of that when the hole was at the base of the wrinkle.

6.3.2.3 Hole formed on the top-side of the wrinkle prior to backfilling with tailings slurry

The effect on flow of having a hole on the geomembrane wrinkle prior to tailings placement was investigated by placing a 10-mm-diameter hole on a 2-mm-thick LLDPE geomembrane wrinkle prior to backfilling with tailings slurry (Test W5). In this test, a total stress of 250 kPa and a pore pressure of 200 kPa (effective stress of 50 kPa) were applied without a period of tailings pre-consolidation prior to permeation that was permitted in the tests discussed above. The leakage measured at \( u = 200 \) kPa \( (p' = 50 \) kPa; \( p = 250 \) kPa) was 8.4 lpd and steady-state flow conditions were achieved within 10 days of permeation. At \( u = 500 \) kPa \( (p' = 500 \) kPa; \( p = 1000 \) kPa), flow decreased to 2.6 lpd reaching steady-state flow conditions within 11 days of permeation (Table 6.3).

6.3.3 Migration of tailings into the wrinkle gap
Migration of tailings into the void beneath the wrinkle was observed to occur in two ways: (i) free-flow into the gap beneath the wrinkle through a hole and (ii) flow under a hydraulic gradient (piping).

When the wrinkle (with hole) in a 1-mm-thick LLDPE was backfilled with 300-mm-thick layer of free-flowing tailings at 65% solids content and left for 24 hours, the gap beneath the wrinkle was partially filled with tailings (Test W1). The tailings migrated in and spread out about 6.5 cm laterally into the wrinkle above the foundation sand (Figure 6.4). The percentage of fines in the tailings inside the wrinkle was same as in the overlying tailings (27%).

When there was no hole in the 1-mm-thick LLDPE wrinkle prior to tailings placement, there was no migration of tailings into the gap beneath the wrinkle (Test W2). The void beneath the wrinkle was in fact partially filled with the silty-sand subgrade due to foundation deformation under applied stresses (Figure 6.8a).

Test W4 examined the effect of applied hydraulic gradient on tailings migration into the gap beneath the wrinkle in a 2-mm-thick HDPE geomembrane. Although the tailings backfill placed after placing a hole on the wrinkle was 75% solids (i.e., not free flowing), post-termination observation of Test W4 revealed that the void beneath the wrinkle was entirely filled with tailings (Figure 6.13a). This implies that, in this case, the tailings mostly migrated under the hydraulic gradient. The tailings migrated laterally up to 15 cm on each side from the centrally located hole. Due to the limited dimension of the test apparatus and length of tested wrinkle, the extent of potential lateral spreading of tailings into the wrinkle could not be determined.

Similar observations were made in Test W5 where the tailings backfill was placed at 65% solids (free-flowing) and there was a hole present in the wrinkle in the 2-mm-thick LLDPE
geomembrane prior to backfilling. The entire gap beneath the wrinkle was filled with tailings (Figure 6.13b). It could not be verified if the entire gap was filled with tailings slurry before any pore pressure was applied or the gap was partly filled with tailings that migrated under the hydraulic gradient. However, from the final deformed shape of the wrinkle, it appeared that the wrinkle deformation happened in at least two stages and that at the time the second deformation occurred, the bottom half of the wrinkle may have been already filled with tailings.

The percentage of fines in the tailings was evaluated at different locations on a vertical plane perpendicular to the geomembrane wrinkle at the centre of the test cell (Figure 6.14a) for a test with a 2-mm-thick HDPE wrinkle (Test W4) and one with 2-mm-thick LLDPE wrinkle (Test W5; Figure 6.14b). The percentage of fines inside the wrinkle, close to the hole, was generally higher than at other locations within the wrinkle or above the wrinkle. A slight increase in the fines content of the foundation immediate beneath the wrinkle void was observed.

6.4 Discussion

If there are no holes in the geomembrane, there will be no significant leakage through the liner. Geomembrane wrinkles are of concern because if there is a hole at the wrinkle there is potential for considerable leakage of fluid through the hole and along the wrinkle network. In a landfill application and others with a highly permeable material above the wrinkle, fluid can have unobstructed access into the gap beneath the wrinkle through a hole. If the hydraulic head, thicknesses and hydraulic conductivity of the underlying soils, interface transmissivity between the geomembrane and underlying soil, length and width of the wrinkle, and size of the hole in the wrinkle are known, then the leakage can be calculated (Rowe 1998). However, based on this study,
it appears that the situation is very different with lower permeability and higher compressibility tailings placed over a geomembrane wrinkle.

6.4.1 Wrinkle deformations

Without a hole, the 1-mm-thick geomembrane wrinkles subjected to 250 kPa total stress, deformed to an extent that both inner sides of the wrinkle were in contact with each other with the final remaining height and width at the base of 45% and 10% for 1-mm-thick LLDPE and 43% and 19% for 1-mm-thick HDPE. Since 1-mm-thick geomembranes are not used in the bottom of modern landfills it is not known with certainty whether the same would occur in the presence of a coarse gravel drainage layer – however it is considered unlikely based on observations for 1.5-mm-thick geomembranes in a landfill-based configuration (i.e., with gravel backfill; Figure 6.1b). For example, for a 1.5-mm-thick HDPE geomembrane wrinkle with same test conditions (initial wrinkle size, \( W = 200 \text{ mm} \) and \( H = 60 \text{ mm} \); applied vertical stress = 250 kPa; test duration = 100 hours) but in a landfill-based configuration, Brachman et al. (2011) reported a final remaining wrinkle with height and width of 66% and 45%. In this study, the remaining final height and width of a stiffer 2-mm-thick HDPE geomembranes were \( H = 67\% \) and \( W = 40\% \), which is smaller than those reported by Brachman et al. for a 1.5-mm-thick HDPE geomembrane.

Although the comparison is not straightforward for wrinkles with two different geomembrane thicknesses and buried beneath different backfills, it is considered likely that a larger lateral stress is applied on the wrinkle surface in a tailings configuration than in a landfill with a gravel drainage layer. This would give rise to larger wrinkle deformations in contact with tailings in a slurry for a geomembrane with same thickness and without a hole. The larger wrinkle
deformations and smaller remaining wrinkle would be expected to reduce leakage through a given hole in the wrinkle.

### 6.4.2 Leakage through hole in the wrinkle

When a hole was positioned at the base of a wrinkle in a 1-mm-thick LLDPE, the leakage was 7.6 litres per day per hole at \( p = 1000 \) kPa, \( u = 500 \) kPa at 0.3 m above the liner \( (p' = 500 \) kPa; Test W2). With 5 such holes per hectare, the leakage could be 40 litres per hectare per day \( (\text{lphd}) \) under these conditions. However, this is a relatively small leakage and considers a worst case where there is no head loss in the tailings until the 0.3 m above the liner. The highest measured flow in this study \( (8.5 \) lpd) was for a 2-mm-thick geomembrane with a hole on the top of the wrinkle at \( p = 250 \) kPa and \( u = 200 \) kPa \( (p' = 50 \) kPa). Assuming 5 such holes per hectare the flow would be a still relatively small 42.5 lpd. This is substantially smaller than that calculated by Rowe (2012) for a pond lined only with a 0.6 m thick compacted clay liner (CCL) or 0.01 m thick geosynthetic clay liner (GCL) under an applied head of 5 m. This comparison supports the use of a geomembrane as a liner in a tailings storage facility for situations where leakage is to be reduced.

In the field, the leakage under stresses similar to those applied in this study may be lower than reported in Table 6.3. The leakage could be impeded by the combined effect of: (i) consolidation of tailings overlying the geomembrane; (ii) further deformation of wrinkle; (iii) consolidation of tailings inside the wrinkle gap due to wrinkle deformation and (iv) higher resistance to flow due to the increased tailings thickness compared to a limited thickness of tailings placed in this study.

### 6.4.3 Long term performance of the geomembrane

174
With such large wrinkle deformations and all remaining gaps beneath the wrinkle filled with tailings, the effect of having a wrinkle with a hole on leakage may in fact be of a lesser concern than having a same wrinkle with hole in a landfill type application. There may however be a concern regarding long-term stress cracking at the locations where high curvatures were introduced on the wrinkle. Any strain induced cracking along these locations will increase leakage. More research is needed into this aspect.

6.5 Conclusions

Results from experiments involving wrinkles in four different geomembranes (1 and 2-mm-thick LLDPE and HDPE) below a saturated tailings backfill were reported for a range of stress conditions. For the specific conditions and materials examined, it is concluded that:

1. Wrinkle deformations depended on the stiffness of the geomembrane and applied stresses. The 1-mm-thick LLDPE and HDPE geomembrane wrinkles deformed to an extent that the gap beneath the wrinkle was eliminated with both inner sides of the wrinkle physically coming in contact at 250 kPa. For 2-mm-thick HDPE and LLDPE geomembrane wrinkles, the initial gap beneath the wrinkle was reduced in both height and width but remained up to the maximum applied total stress of 1000 kPa.

2. The shape of the deformed geomembrane wrinkle was controlled by geomembrane stiffness and the presence of a hole in the wrinkle prior to placement of a tailings slurry. Winkles in the 1-mm-thick geomembrane without any hole deformed to a much narrower wrinkle giving a near vertical projection with high curvatures at the wrinkle crest and base. A 2-mm-thick geomembrane wrinkle without any hole reduced in both height and width forming a single smaller wrinkle. For wrinkles with hole present
prior to tailings placement, the final wrinkle shape was dependent of the extent that the gap beneath the wrinkle was filled with tailings. The 1-mm-thick geomembrane wrinkle experienced non-symmetrical deformation with the wrinkle crest shifted towards the side without hole. The stiffer 2-mm-thick LLDPE geomembrane wrinkle was partially filled with tailings and the wrinkle surface contained multiple locations with high curvature.

3. The 2-mm-thick HDPE geomembrane wrinkle below saturated tailings experienced a larger lateral deformation than that reported for a less stiff 1.5-mm-thick HDPE geomembrane wrinkle below a gravel backfill under same applied total stress.

4. Flow through a hole placed at the bottom of the wrinkle increased from 2.3 litres per day (lpd) to 7.6 lpd with an increase in total stress and pore pressure from total stress \( p = 250 \text{ kPa} \), pore pressure \( u = 200 \text{ kPa} \) to \( p = 1000 \text{ kPa} \), \( u = 500 \text{ kPa} \). Leakage through a hole placed on top of the wrinkle—irrespective of time of hole formation—decreased from 8.5 lpd to 2.5 lpd with an increase in total stress and pore pressure from \( p = 250 \text{ kPa} \), \( u = 200 \text{ kPa} \) to \( p = 1000 \text{ kPa} \), \( u = 500 \text{ kPa} \).

The leakage inferred from these cases would appear to be quite small for a reasonable number of holes with a wrinkle, although more research is needed to quantify additional cases.
6.6 References


Table 6.1 Index stress-strain properties (measured in machine (MD) and cross-machine (X-MD) direction) of the HDPE and LLDPE geomembranes studied (Tested according to ASTM 2015).

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<th>GMB type</th>
<th>Thickness (mm)</th>
<th>Yield strength (kN/m)</th>
<th>Yield strain (%)</th>
<th>Break strength (kN/m)</th>
<th>Break strain (%)</th>
<th>Yield strength ÷ yield strain (kN/m) (κ)</th>
<th>KGMB ÷ κ1 mm LLDPE (Ω)</th>
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* Amr Ewais (Pers. Comm); β Ramy Awad (Pers. Comm); # Abdelaal et al. (2012)
Table 6.2 Initial and final wrinkle dimensions of geomembrane wrinkles subjected to different stresses.

<table>
<thead>
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<th>Test conditions (kPa)</th>
<th>Final wrinkle dimensions (mm)</th>
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</tbody>
</table>

* At the top of the tailings; the pore pressure below the hole is about 1-1.5 kPa and the effective stress in the tailings above the hole will be substantially higher than at the top due to seepage forces.

** The reported dimensions are for the central big wrinkle only (see Figure 6.11). Height measured from the top of the foundation.
Table 6.3 Summary of permeation tests conducted at 22°C. Materials used in all tests are (a) Silty-sand underliner with ~ 12% fines (passing US sieve #200), (b) Tailings with ~ 27% fines. Initial dimensions of geomembrane wrinkle: 200 mm wide and 60 mm high (see Figure 6.4). Hole diameter 10 mm.

<table>
<thead>
<tr>
<th>Test #</th>
<th>Geomembrane thickness and type</th>
<th>Test conditions (kPa)</th>
<th>Time of hole placement</th>
<th>Measured flow (lpd&lt;sup&gt;b&lt;/sup&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Total stress</td>
<td>Pore pressure&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Effective stress&lt;sup&gt;a&lt;/sup&gt;</td>
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<tr>
<td>W1</td>
<td>1 mm LLDPE</td>
<td>~ 6</td>
<td>-</td>
<td>~ 6</td>
</tr>
<tr>
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<td>1 mm LLDPE</td>
<td>250</td>
<td>200</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>W3</td>
<td>1 mm HDPE</td>
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<td>W4</td>
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<td>50</td>
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<tr>
<td></td>
<td></td>
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<td>500</td>
<td>500</td>
</tr>
<tr>
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<td>2 mm LLDPE</td>
<td>250</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>500</td>
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</tbody>
</table>

<sup>a</sup> At the top of the tailings; the pore pressure below the hole is about 1-1.5 kPa and the effective stress in the tailings above the hole will be substantially higher than at the top due to seepage forces.

<sup>b</sup> lpd = litres per day
Figure 6.1 (a) Stress distribution on the surface of a geomembrane wrinkle covered by gravel drainage layer in a municipal solid waste landfill configuration. Magnitude of horizontal component of the stresses is smaller than the vertical component due to interlocking of gravel particles and positive arching. (b) Stress distribution on the surface of a geomembrane wrinkle in a mine tailings containment configuration. Vertical and horizontal components of the applied stresses are equal due to isotropic or near isotropic conditions.
Figure 6.2 Cross-section of the test apparatus and test configurations.
Figure 6.3 An artificially formed geomembrane wrinkle (200 mm wide and 60 mm high) with a 10-mm-diameter hole on the side (1-mm-thick LLDPE; Test W1). Steel weights were used to form the shape of the wrinkle and were removed during backfilling.
Figure 6.4 Cross-section showing the initial and final shape of the wrinkle with tailings inside the gap beneath the wrinkle (Test W1). The wrinkle was covered with 300 mm tailings slurry (with 65% solids) and left for 24 hours.
Figure 6.5 (a) Underside of the 1-mm-thick LLDPE geomembrane before Test W2 with white paint on one side of wrinkle crest line and ink marks on the opposite side. A double-sided tape is attached on one side to prevent the geomembrane from relaxing after the applied stress is removed. (b) Post-test photograph showing underside of the geomembrane after the termination of Test W2. (c) Enlarged view of inset in Figure 6.5b showing ink marks transferred from one side of the wrinkle to the white paint on the opposite side confirming contact between the inner sides of the wrinkle.
Figure 6.6 Photograph showing deformed geomembrane wrinkle being profiled using a line laser through a vertical observation trench. The 1-mm-thick HDPE geomembrane wrinkle was allowed to deform under 250 kPa overburden stress for 100 hours (Test W3).
Figure 6.7 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time for Test W4.
Figure 6.8 Cross-section measured with surface scanning laser through deformed 1-mm-thick geomembranes (initially 200 mm wide and 60 mm high) after being subjected to 250 kPa for 100 hours (a) LLDPE wrinkle (Test W2), (b) HDPE wrinkle (Test W3).
Figure 6.9 Deformed wrinkle from Test W2 after it had been subjected to 250 kPa overburden stress for 100 hours. Note that due to the presence of double-sided tape on the inner wall of geomembrane wrinkle, the sides are still touching even after removal of stress.
Figure 6.10 Cross-section through deformed 2-mm-thick HDPE geomembrane wrinkle (initially 200 mm wide and 60 mm high) after subjected to 250 kPa for 100 hours. There is some missing data at the location of the hole because the laser signal did not get reflected along the width of the hole.
Figure 6.11 Cross-section through deformed 2-mm-thick geomembrane wrinkles subjected to a total stress of 1000 kPa. In Test W4, the hole was placed after consolidation of tailings under 250 kPa for 100 hours. In Test W5, the hole was placed prior to backfilling with tailings. The different shape of deformed wrinkle in Test W5 is due to the gap beneath the wrinkle being partially filled with tailings prior to wrinkle deformation under externally applied stresses.
Figure 6.12 Hole being placed on the top-side of the exposed wrinkle (Test W4). The wrinkle was painted white to have a reflecting surface for laser scanning.
Figure 6.13 Photographs taken after removing the deformed geomembrane wrinkle followed by permeation test termination. (a) After Test W4 with 2 mm HDPE geomembrane where the hole was placed after tailings consolidation (see Figure 6.12). (b) In Test W5 with 2-mm-thick LLDPE geomembrane where the hole was placed before placement of tailing.
Figure 6.14 Post-test evaluated percentage fines (passing US sieve #200) from different locations on a vertical plane perpendicular to the geomembrane wrinkle at the centre of the test cell in, (a) Test W4 with 2-mm-thick HDPE wrinkle, (b) Test W5 with 2-mm-thick LLDPE wrinkle.
Chapter 7

Conclusions and Recommendations

7.1 General

In the absence of holes, flow through a geomembrane liner is negligible. However, it is extremely difficult to have a defect free installation in practical situations (Giroud and Bonaparte 1989, 2001; Rowe 2012). The flow through geomembrane holes depends on: (i) the number and size of holes; (ii) hydraulic conductivity of the overlying and underlying materials; (iii) thickness of the overlying and underlying materials; (iv) interface transmissivity between the geomembrane and the overlying and underlying materials; (v) hydraulic gradient across the geomembrane and (vi) any geometrical imperfections such as geosynthetic clay liner (GCL) seams and geomembrane wrinkles that may exist in the liner (Giroud 1997; Rowe 1998; Rowe et al. 2004; Rowe 2012). Depending on the type of containment facility, a geomembrane may be used as a single liner or in conjunction with GCLs or compacted clay liners (CCLs) as a composite. Thus factors affecting flow through the holes may vary from one facility to another.

Results from experiments conducted to quantify leakage through holes in a geomembrane in two different containment facilities municipal solid waste (MSW) landfills and mine tailings storage were reported in this thesis. This chapter provides a summary of the results and conclusions drawn from the work presented. General conclusion of the thesis, practical implications of the work and recommendations for future research work to better understand the issues are also discussed.
7.2 Summary and main conclusions

7.2.1 Hydraulic performance of overlapped Geosynthetic Clay Liner seams requiring field-applied supplemental bentonite

This study evaluated the performance of overlapped seams (overlaps) of three GCLs requiring field-applied supplemental bentonite under non-uniform stresses from an overlying geomembrane wrinkle in experiments coupling physical and hydraulic conditions at the liner level in a MSW landfill. Tests were conducted with the geomembrane wrinkle oriented parallel and perpendicular to the overlapped GCL seam. It was observed that when the wrinkle was aligned directly above and parallel to the seam, flow was a function of the width of the seam relative to the deformed width of the wrinkle. When the width of the seam was wider than the deformed wrinkle (i.e., both edges of the seam confined by the deformed wrinkle), the measured flow was lower than it would be when directly over a single panel of GCL (due to having two layers of GCL with a layer of supplemental bentonite in between) and up to five orders of magnitude smaller than when the seam was narrower and both edges of the seam were not under any confinement. This shows the importance of obtaining the manufacturers’ minimum specified GCL seam width if wrinkles could be present when the liner is covered.

Orienting the wrinkle perpendicular to the seam introduced an unstressed width of the seam equal to the width of the deformed wrinkle and the flow along the seam depended on: the presence and distribution of supplemental bentonite; type of geotextile and applied vertical stress. 400 g per linear metre of supplemental bentonite placed in a pile between the overlapped panels at the seam decreased the flow (per seam-wrinkle intersection) by over two orders of magnitude compared to having no supplemental bentonite. The flow with piled bentonite was slightly smaller than when the same 400 g/m of bentonite was evenly distributed along the entire width of the seam (producing
a thinner layer of supplemental bentonite in the seam). Flow reduced with increase in the applied vertical stress. The reduction in flow was attributed to: narrower width of the deformed wrinkle, higher confining stresses on the GCL and decrease in GCL-geomembrane interface transmissivity away from the wrinkle. Evidence of preferential flow along the nonwoven geotextile component (as carrier or cover) of the GCL at the seam was found.

7.2.2 Hydraulic performance of GCL seams without field-applied supplemental bentonite below a geomembrane wrinkle

Results from experiments on overlapped seams of four GCLs not requiring field-applied supplemental bentonite under non-uniform stresses from an overlying geomembrane wrinkle were reported. Two different seam sealing techniques: one with a narrow, linear factory melted groove in the cover nonwoven geotextile, the other with factory applied powdered bentonite were tested under a hydraulic head of 0.3 m and applied vertical pressure of 250 kPa with a geomembrane wrinkle oriented perpendicular to the GCL seam.

The performance of the seams with a melted groove depended on the quality of the melt. Incomplete melt (i.e., where there were still nonwoven geotextile fibres retaining panel bentonite along the entire width of unstressed seam) hindered intrusion of panel bentonite into the overlapped seam and the recorded flow (per seam-wrinkle intersection) was two orders of magnitude higher than when the groove allowed panel bentonite to freely swell into the seam. Although heat-tacking improved the performance of seams containing incomplete melt in some experiments, it was concluded that the method, width of the heat-tack zone and its positioning at the seam all can significantly affect the performance of the heat-tacked seam.
For GCLs with the nonwoven carrier geotextile impregnated with powered bentonite, the seam performance depended on the amount of bentonite present relative to voids that developed in the GCL due to free swelling beneath the geomembrane wrinkle. It was observed that of the two GCLs tested, one was able to limit the variation on free swell thickness to less than 1 mm whereas in the second GCL, voids as large as 4 mm were formed. The formation of larger voids in the second GCL was attributed to the presence of linear, alternate bands (1-2 mm wide) of high and low concentration of needle-punching coupled with very effective restraint of the needle-punched fibres from thermal treatment. Measured flow per seam-wrinkle intersection of the GCL containing larger voids was up to 700 times higher than that in GCL with smaller voids. It was shown that with 400 g/m² bentonite added to the seam, all voids at the overlap were filled and the flow decreased by 2 to 3 orders of magnitude.

7.2.3 A new laboratory apparatus for measuring leakage through geomembrane holes beneath mine tailings

The design and performance of a new apparatus and method of measuring leakage through geomembrane holes in large tailings storage facilities was reported. The apparatus was designed to simultaneously apply vertical stresses representing the weight of the overburden material above the deeply buried geomembrane and pore pressure generated due to submerged conditions. The physical and hydraulic boundary conditions applied in the test cell were first numerically compared to those for a field scale that is up to 500 times larger than the test cell dimensions. It was shown that the boundary conditions applied in the test cell were able to simulate field conditions very well. The apparatus and the method were then applied to examine how the permeability of the soil overlying the geomembrane affects the flow through geomembrane hole for effective stresses simulating a very deep tailings storage facility. It was shown that the flow through a 10-mm-
diameter hole reduced by 3-4 times due to having a low hydraulic conductivity, $k$, material ($k = 4.6 \times 10^{-9} \text{ m/s}$) on top of the geomembrane than having a high $k$ material ($k \approx 0.08 \text{ m/s}$) for same low $k$ material ($k = 1.8 \times 10^{-9} \text{ m/s}$) underlying the geomembrane.

### 7.2.4 Leakage through holes in geomembranes below saturated fine tailings

Potential leakage through geomembrane holes of 1.5, 10 and 20-mm-diameter placed on a silty-sand or pea gravel underliner and covered with saturated fine tailings were quantified based on a series of laboratory-scaled tests aimed at investigating the effect of: (i) tailings permeability, (ii) underliner permeability, (iii) effective stress, (iv) presence of geotextile filter/protection layer adjacent to the geomembrane and (v) geomembrane type and thickness. It was concluded that the overlying tailings with lower $k$ had a larger effect on flow through the holes than the underliners examined (provided the underliner meets the filter compatibility requirements). The measured flows were 4-5 times lower than that calculated using finite-element seepage model where a uniform $k$ for the tailings and the underliner was assumed. Evidence of fines migration into the pore space of geotextile or silty-sand in contact with the tailings was found where the migrating fines potentially reduced the $k$ locally in and around the geomembrane hole and could be attributed to lower measured flow in the experiments. A non-linear decrease in flow with increase in effective stress was observed and was attributed to a larger reduction in permeability of the tailings at higher applied stresses. For the tested materials and conditions, the leakage through a 10-mm and 20-mm-diameter hole were essentially the same whereas the leakage through a 1.5-mm-diameter hole was three orders of magnitude lower. The flow was essentially the same for both the 1-mm-LLDPE and 2-mm-HDPE geomembranes examined for a GMB in direct contact with the underliner (foundation).
7.2.5 Physical and hydraulic response of geomembrane wrinkles underlying saturated fine tailings

This study reported results from physical and hydraulic experiments conducted on wrinkles in four different geomembranes (1 and 2-mm-thick LLDPE and HDPE) below a saturated tailings backfill.

The geomembrane wrinkle (without hole) below saturated tailings experienced a larger lateral deformation than that reported for wrinkles below a gravel backfill under same applied vertical stress. The extent of wrinkle deformation depended on the geomembrane stiffness. For the less stiff (1-mm-thick LLDPE and HDPE) geomembranes, the deformations were very large to an extent that both inner sides of the wrinkles were physically touching at an applied vertical stress of 250 kPa (inducing a very high strain at the bend). For stiffer, 2-mm-thick HDPE and LLDPE geomembrane wrinkles, the initial gap beneath the wrinkle was reduced in both height and width but remained up to an applied total stress of 1000 kPa.

For wrinkles with a hole present prior to tailings placement, tailings migrated into the gap beneath the wrinkle and the final wrinkle shape depended on the extent the gap beneath the wrinkle was filled with tailings at the time of stress application. The 1-mm-thick geomembrane wrinkle experienced non-symmetrical deformation with the wrinkle crest shifted towards the side without a hole. The stiffer 2-mm-thick geomembrane wrinkle experienced symmetrical deformation and contained multiple locations with high curvature.

Measured flow through a 10-mm-diameter hole placed on the wrinkle (before or after wrinkle deformation under stress) was same. Suggesting there was no effect on flow of how tailings migrated into the wrinkle (i.e., as a free flowing slurry or flow under applied hydraulic gradient). With increase in applied vertical stress, flow decreased. The decrease in flow at larger applied stress was attributed to reduction in permeability of tailings both inside and above the wrinkle.
7.3 General conclusions and practical implications

This study showed the need to follow manufacturers’ recommendation of adequately overlapping the GCL seam and covering of the GCL-geomembrane composite liner while minimum wrinkles are present. However, recognizing that some holes and wrinkles are likely in most practical field cases and that these wrinkles often align with or cross GCL seams, it is important to have adequate bentonite between the overlapped panels, and that the overlap at the time the composite liner is covered be, at a minimum, around 150 mm (i.e., after any shrinkage). This work indicated that, when below a geomembrane that could have wrinkles, GCL overlaps require field-applied supplemental bentonite. It was demonstrated that better performance can be expected with piled bentonite in a 300 mm overlap than a 150 mm overlap.

Leakage through holes in geomembrane liners in a tailings storage facility configurations can be significantly less than that when geomembrane is not present for a similar tailings and similar foundation layers. However, limiting the frequency and size of the geomembrane holes is still necessary to minimize leakage into the environment. The short-term effect of having a hole in a wrinkle on flow in tailings configuration appears to be largely reduced due to the potential for tailings to migrate and fill the voids. However, physical response of the wrinkles subjected to isotropic stress due to the tailings slurry backfill showed that the geomembranes can be excessively strained and that there could be serious long-term performance issues, especially for 1-mm-thick geomembranes, if those geomembranes are backfilled while wrinkles are still present.

7.4 Recommendations for future work

With the thesis providing new insights into the hydraulic performance of geosynthetic liners with defect, it has raised some questions that should be address with future research, as suggested below:
- The good performance observed for virgin GCL seams in Chapter 2 and 3 raises interest in examining the hydraulic performance of GCL seams that have been exposed to field conditions for prolonged period of time. It is recommended that further study on the seams be performed with real or simulated landfill leachate under elevated temperatures typical to that recorded at the liner level.

- Additional testing would be required to generalize the observation that the coating on the GCL does not have negative effect on flow through the GCL seam (since different coatings and laminations may perform differently and, potentially, not as well as that tested in Chapter 2).

- The hydraulic conductivity of the tailings used in Chapter 5 represented a narrow band of possible grain size distributions for mine tailings (coarser than fine grained tailings that may have much larger amount of fines and lower hydraulic conductivities at the same applied vertical effective stress). Further study with a fine grained tailings is recommended.

- The tailings tested in this thesis was non-reactive and only contained a small amount of total suspended and dissolved solids. The pore fluid had pH close to neutral. It is recommended that the effect of these factors on the overall hydraulic conductivity of the tailings and flow through geomembrane hole with time be studied.

- The USEPA (United States Environmental Protection Agency) has recently promulgated national regulations to provide a comprehensive set of requirements for the safe disposal of coal combustion residuals (CCRs). With this, it is expected that the geomembrane use in CCR impoundments will increase. Some future study may need to focus on understanding the effect of having geomembrane holes in a facility containing CCR.
• In some tests in Chapter 5 and 6, biological activity was observed close to the geomembrane holes however the effect it has on flow through the hole was not investigated. Some future research is recommended.

• In one test in Chapter 5, an issue with filter compatibility was encountered where failure due to piping occurred. Though the issue was resolved with the use of a geotextile filter, the cost associated with placing such filter over the footprint of a tailings storage facility may be substantial. Further study to better understand the piping phenomenon and attempt to define some performance limit is recommended.

• A larger diameter cell be deployed to study the effect on flow of having: a larger diameter hole in tailings configuration, longer wrinkles, and the dimension of the test apparatus specifically in the wrinkle study where the dimension of the apparatus used (0.6 m internal diameter) limited the extent of lateral migration of tailings into the wrinkle in Chapter 6.
7.5 References


Appendix A
Supplementary materials for Chapter 2 and 3 (Chapter 2: Hydraulic performance of overlapped Geosynthetic Clay Liner seams requiring field-applied supplemental bentonite), (Chapter 3: Hydraulic performance of GCL seams without field-applied supplemental bentonite below a geomembrane wrinkle)
Appendix A.1 Grain size distribution of supplemental bentonite, foundation sand and drainage gravel used in Chapter 2 and 3.
Figure A.1 Grain size distribution of supplemental bentonite, foundation sand and drainage gravel used in Chapter 2 and 3. All tests done according to ASTM (2009).

Reference:

Appendix A.2 Steps taken while setting up and terminating permeation tests on GCL seams.
Following steps were taken for setting up and terminating each permeation tests.

1. Place a geocomposite drain (GCD) of diameter equal to cell diameter at the bottom of a clean GLLS cell.

2. Apply friction treatment only 10 cm from the top of the GCD.

3. Compact foundation sand in three lifts to achieve a dry density of 1.91 g/cc and height of 14 cm.

4. Cut a circumferential wedge, 3 cm wide and 2 cm deep, along the top interface of the foundation and GLLS.

5. Fill the wedge with dry bentonite and place wet bentonite to cover the dry bentonite.

6. Hydrate the foundation from below with nominal head (<5 cm) and close the bottom valve after hydration.

7. Place the GCL lower panel, apply supplemental bentonite if required and place upper panel overlapping on top.

8. Fill the edges with hydrated bentonite. Place extra bentonite at the location beneath the wrinkle and cover the bentonite layer with a polyethylene sheet and tuck tape to avoid free hydration and migration of bentonite towards the centre of the cell.

9. Place geomembrane wrinkle on top. After desired shape is obtained, secure the wrinkle with weights and place small amount of cement grout on top of the geomembrane-GLLS interface to anchor and let dry.

10. Pour dry bentonite along the periphery and cover with wet bentonite.
11. Cover the entire layer of bentonite with a layer of polyethylene sheet.

12. Place friction treatment. Extend the lower part of the friction treatment to cover the perimeter seal (Figure A.3).

13. Check wrinkle dimension.

14. Place geotextile protection layer.

15. Place protection rings.

16. Place 30 cm gravel drainage layer starting from flatter portion of geomembrane coming towards the wrinkle.

17. Place a geotextile separation layer.

18. Place filler sand.

19. Place bladder and tighten the lid.

20. Using side ports, for GCL hydration, introduce water to create ~2 cm deep pond on top of the GCL layer. Keep for 100 hours. Top up when needed.

21. Open bottom valve and set the head at the bottom of the cell at the GCL level (15 cm).

22. Apply pressure @ 50 kPa/10 min to reach desired stress level. Keep for 100 hours.

23. Apply hydraulic head and start flow collection.

24. After steady-state is reached terminate the test.

25. All the steps go backwards from here, take measurements, samples and photographs.
Figure A.2 Photographs showing setting up and terminating a typical physical test.
Figure A.2 (cont...) Photographs showing setting up and terminating a typical physical test.
Appendix A.3 Friction treatment and bentonite based side seal details.
Friction treatment (Tognon et al. 1999) was used to decrease the possible side wall frictional losses and a protection layer was used to protect the friction treatment layer and the cell from being damaged. The friction treatment comprised of a high-temperature bearing grease (Dow Corning 44®) sandwiched between two layers of 0.1-mm-thick polyethylene sheets. Two separate friction treatments, below and above the GCL layer, were used to prevent any preferential sidewall leakage along the friction treatment.

A bentonite perimeter seal was developed to obtain a zero flow boundary around the outer perimeter of the geomembrane where it met with the inner wall of the test apparatus. The bentonite seal was placed in dry and wet layers. The wet layer would provide an initial seal during the consolidation phase and the dry layer which would hydrate under confined conditions would: (i) provide a very low $k$ core and (ii) make up for any vertical displacement of the seal. As a check the seal performed well and to provide visual evidence of any preferential flow through the seal, blue dye solution was sprayed on top. The perimeter seal was covered with a 0.1 mm thick polyethylene sheet to isolate the seal and prevent tailings contamination, bentonite migration and dilution of the blue dye.
Figure A.3 (a) Section through the test cell showing details of protection layer, friction treatment and bentonite based perimeter seal, and (b) Photograph showing seal and friction treatment.

Reference:

Appendix A.4 Physical test results not reported in Chapter 2 and 3.
Table A.1 List of physical tests not reported in Chapter 2 and 3.

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<tr>
<th>Test #</th>
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<th>Final wrinkle dimensions (mm)</th>
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<td></td>
<td></td>
<td></td>
<td>Height</td>
<td>Width</td>
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<td>Parallel</td>
<td>150</td>
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<td>60</td>
<td>200</td>
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<td>GCL2</td>
<td>Single panel (no seam)</td>
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</table>
Figure A.4 Initial and deformed shape of wrinkle in Test 1. Test with 150 mm dry GCL2 seam parallel below a 1.5 mm thick HDPE GMB wrinkle under an applied pressure of 250 kPa for 100 hrs.

Observations:

- H/Ho = 66%
- W/Wo = 43%
- No slippage at the seam beneath the wrinkle
- Small upward movement of GCL (~4 mm) beneath the wrinkle.
Figure A.5 Initial and deformed shape of wrinkle in Test 2. Test with 150 mm hydrated GCL2 seam parallel below a 1.5 mm thick HDPE GMB wrinkle under an applied pressure of 250 kPa for 100 hrs.

Observations:

- \( \frac{H}{H_0} = 71\% \)
- \( \frac{W}{W_0} = 50\% \)
- GCL initial water content = 125\%
- GCL final water content = 74\%
- No slippage at the seam beneath the wrinkle
- No upward movement of GCL beneath the wrinkle.
Figure A.6 Initial and deformed shape of wrinkle in Test 3. Test with 150 mm dry GCL2 seam perpendicular below a 1.5 mm thick HDPE GMB wrinkle under an applied pressure of 250 kPa for 100 hrs.

Observations:

- $H/H_0 = 62\%$
- $W/W_0 = 45\%$
- No slippage at the seam beneath the wrinkle
- Small upward movement of GCL (~ 5 mm) beneath the wrinkle.
Figure A.7 Initial and deformed shape of wrinkle in Test 4. Test with 150 mm hydrated GCL2 seam offset 155 mm centre-to-centre a 1.5 mm thick HDPE GMB wrinkle under an applied pressure of 250 kPa for 100 hrs.

Observations:

- $H/H_0 = 52\%$
- No slippage at the seam beneath the wrinkle
- No upward movement of the seam.
- Small upward movement of GCL beneath the wrinkle.
Figure A.8 Initial and deformed shape of wrinkle in Test 5a. Test with 50 mm hydrated GCL2 seam below a 1.5 mm thick HDPE GMB wrinkle under an applied pressure of 250 kPa for 100 hrs.

**Observations:**

- \( \frac{H}{H_0} = 73\% \)
- \( \frac{W}{W_0} = 56\% \)
- No slippage at the seam beneath the wrinkle
- Vertical upward movement of GCL (~ 6 mm) beneath the wrinkle.
Figure A.9 Initial and deformed shape of wrinkle in Test 5b. Test with 50 mm hydrated GCL2 seam below a 1.5 mm thick HDPE GMB wrinkle under an applied pressure of 250 kPa for 100 hrs.

Observations:

- $H/H_0 = 70\%$
- $W/W_0 = 48\%$
- No slippage at the seam beneath the wrinkle.
- Seam opening 90\%.
- Vertical upward movement of GCL (~ 8 mm) beneath the wrinkle.
Figure A.10 Initial and deformed shape of wrinkle in Test 6. Test with 50 mm hydrated GCL3 seam below a 1.5 mm thick HDPE GMB wrinkle under an applied pressure of 250 kPa for 100 hrs.

Observations:

- $H/H_0 = 62\%$
- $W/W_0 = 44\%$
- No slippage at the seam beneath the wrinkle.
- Vertical upward movement of GCL (~ 6 mm) beneath the wrinkle.
- Seam opening 100%.
- Initial GCL water content = 144% 
- Final GCL water content = 65%.
Figure A.11 Initial and deformed shape of wrinkle in Test 7. Test with 50 mm hydrated GCL2 seam below a 1.5 mm thick HDPE GMB wrinkle under an applied pressure of 100 kPa for 100 hrs.

Observations:

- $\frac{H}{H_0} = 69\%$
- $\frac{W}{W_0} = 63\%$
- No slippage at the seam beneath the wrinkle
- No upward movement of GCL beneath the wrinkle.
- Initial GCL water content = 127\%
- Final GCL water content = 75\%.
Figure A.12 Initial and deformed shape of wrinkle in Test 8. Test with 50 mm hydrated GCL2 seam below a 1.5 mm thick HDPE GMB wrinkle under an applied pressure of 250 kPa for 100 hrs.

Observations:

- $H/H_0 = 55\%$
- $W/W_0 = 44\%$
- No slippage at the seam beneath the wrinkle
- Slight upward movement of GCL beneath the wrinkle.
- Initial GCL water content = 120%
- Final GCL water content:
  - Below wrinkle = 105%.
  - Away from wrinkle = 93%
Figure A.13 Initial and deformed shape of wrinkle in Test 13. Test with 150 mm hydrated GCL2 seam below a 1.5 mm thick HDPE GMB wrinkle (W=300 mm, H=90 mm) under an applied pressure of 250 kPa for 100 hrs.

Observations:

- H/Ho = 55%
- W/Wo = 29%
- No slippage at the seam beneath the wrinkle
- Slight upward movement of GCL (~4 mm) beneath the wrinkle.
- Initial GCL water content = 122%
- Final GCL water content:
  - Below wrinkle = 85%.
  - Away from wrinkle = 61%
Figure A.14 Deformed wrinkle in Test 27. Test with a single panel of dry GCL2 placed below a 1.5 mm thick HDPE GMB wrinkle under an applied pressure of 250 kPa for 100 hrs. Tested in a 1 mm-diameter test cell to evaluate physical boundary conditions.

Observations:

- $H/H_0 = 75\%$
- $W/W_0 = 50\%$
- Slight upward movement of GCL (~4 mm) beneath the wrinkle.
Appendix A.5 Submerged hydration of GCL3, 4, 5 and 6 under 2 kPa applied stress.
Figure A.15 Moisture content vs. time for four GCLs hydrating under 2 kPa confining stress under submerged conditions.
Appendix A.6 Determination of metals in tap water used in Chapter 2 and Chapter 3 by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) method.
Table A.2 Metal concentration in tap water used in Chapter 2 and Chapter 3.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Blank</th>
<th>Control</th>
<th>Control Target</th>
<th>Tap Water</th>
<th>DI water</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1.2</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Al</td>
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<td>3.0</td>
<td>3.1</td>
<td>&lt;1.0</td>
<td>&lt;1.0</td>
</tr>
<tr>
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<td>4.0</td>
<td>&lt;0.03</td>
<td>&lt;0.03</td>
</tr>
<tr>
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<td>2.0</td>
<td>&lt;1.0</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td>Ba</td>
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<td>6.0</td>
<td>6.0</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
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<tr>
<td>Be</td>
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<td>3.0</td>
<td>2.8</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Ca</td>
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<td>6.0</td>
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<tr>
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<td>&lt;0.025</td>
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<tr>
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<td>&lt;0.02</td>
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<tr>
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<tr>
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<tr>
<td>Fe</td>
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<td>&lt;0.05</td>
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<tr>
<td>Mg</td>
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<td>6.1</td>
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<td>&lt;0.05</td>
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<tr>
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<td>3.0</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
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<tr>
<td>Na</td>
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<td>1.6</td>
</tr>
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<td>&lt;0.3</td>
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<tr>
<td>P</td>
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<td>&lt;1.0</td>
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<td>Pb</td>
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<td>&lt;0.03</td>
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<tr>
<td>S</td>
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<td>12.3</td>
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<td>Sb</td>
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<td>&lt;0.1</td>
<td>&lt;0.1</td>
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<tr>
<td>Se</td>
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<td>3.0</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
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<td>2.9</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Sr</td>
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<td>3.0</td>
<td>0.2</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Ti</td>
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<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
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<td>3.0</td>
<td>&lt;0.025</td>
<td>&lt;0.025</td>
</tr>
<tr>
<td>U</td>
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<td>2.0</td>
<td>2.0</td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>V</td>
<td>&lt;0.02</td>
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<td>3.0</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>Zn</td>
<td>&lt;0.01</td>
<td>15.0</td>
<td>14.8</td>
<td>0.44</td>
<td>0.01</td>
</tr>
</tbody>
</table>

All results are in µg/ml
Appendix A.7 Swell index test on bentonite hydrated with dye (Brilliant Blue G-250, Fisher BioReagents) water for 30 days.
The procedure is briefly described below:

- 200 ml of tap water was taken in a 500 ml beaker and 0.08 g (@ 0.4 g/l) of Brilliant Blue G-250 dye was added and mixed.

- 20 g of supplemental bentonite was taken. 10 g of which was added to the dye solution and mixed thoroughly the other 10 g was stored in an air tight container.

- After keeping the solution for 30 days at room temperature, the bentonite was removed from the beaker and placed in a ventilator for air drying.

- 2 g of the air dried sample was taken for moisture content determination and the rest was grinded for swell index testing as per ASTM (2006).

- Two swell index tests were done on the dyed bentonite. In addition to that two tests were done on the virgin bentonite previously stored in an air tight container (Figure A.16).

**Observation:**

It was observed that the swelling properties of the supplemental bentonite did not alter even after hydrating with dyed tap water for up to 30 days.
Figure A.16 Picture showing no difference in swelling behaviour of virgin and supplemental bentonite hydrated in dyed water for 30 days.

Reference:

Appendix A.8 Leakage calculation for field wrinkles based on the GLLS permeation tests.
### Table A.3 Single panel of GCL beneath a wrinkle (Test T36)

<table>
<thead>
<tr>
<th>Measured flow through 0.59 m long single panel in Test T36 (m³/s)</th>
<th>Length of wrinkle L (m)</th>
<th>Total flow (lpd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.6x10⁻¹¹</td>
<td>1</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.1</td>
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<tr>
<td></td>
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<td>0.6</td>
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<td></td>
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<td>1.1</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>11.1</td>
</tr>
</tbody>
</table>

### Table A.4 Flow through GCL seam parallel to an overlying wrinkle (Test T19)

<table>
<thead>
<tr>
<th>Flow measured in Test T19 (m³/s)</th>
<th>Equivalent flow through 1 m long overlap beneath the wrinkle (m³/s)</th>
<th>Length of wrinkle (m)</th>
<th>Total flow (m³/s)</th>
<th>Total flow (lpd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6 x 10⁻¹¹</td>
<td>2.7 x 10⁻¹¹</td>
<td>1</td>
<td>2.7 x 10⁻¹¹</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>2.7 x 10⁻¹⁰</td>
<td>0.023</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>1.3 x 10⁻⁹</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>2.7 x 10⁻⁹</td>
<td>0.23</td>
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<td>1000</td>
<td>2.7 x 10⁻⁸</td>
<td>2.34</td>
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</table>
Table A.5 Flow through GCL seam perpendicular to an overlying wrinkle (Test T34)

<table>
<thead>
<tr>
<th>Length of wrinkle (m)</th>
<th>Number of seam-wrinkle intersections (GCL roll width = 4.5 m)</th>
<th>Flow through single wrinkle-overlap intersection (lpd) in Test T34</th>
<th>Flow through all intersections (lpd)</th>
<th>Flow through 0.59 m long single panel (lpd) in Test T36</th>
<th>Flow through single panel only (lpd)</th>
<th>Total flow (lpd)</th>
<th>Total flow (lpd)</th>
<th>Flow through overlap (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2</td>
<td>0.040</td>
<td>0.0066</td>
<td>0.097</td>
<td>0.14</td>
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<td>50</td>
<td>11</td>
<td>0.202</td>
<td>0.0066</td>
<td>0.484</td>
<td>0.69</td>
<td>0.7</td>
<td>29%</td>
<td></td>
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<tr>
<td>100</td>
<td>22</td>
<td>0.403</td>
<td>0.0066</td>
<td>0.967</td>
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<td>1.4</td>
<td>29%</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>222</td>
<td>4.03</td>
<td></td>
<td>9.670</td>
<td>13.7</td>
<td>13.7</td>
<td>29%</td>
<td></td>
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</table>

Table A.6 Flow through GCL seam perpendicular to an overlying wrinkle (Test T26)

<table>
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<tr>
<th>Length of wrinkle (m)</th>
<th>Number of seam-wrinkle intersections (GCL roll width = 4.5 m)</th>
<th>Flow through single wrinkle-overlap intersection (lpd) in Test T26</th>
<th>Flow through all intersections (lpd)</th>
<th>Flow through 0.59 m long single panel (lpd) in Test T36</th>
<th>Flow through single panel only (lpd)</th>
<th>Total flow (lpd)</th>
<th>Total flow (lpd)</th>
<th>Flow through overlap (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2</td>
<td>0.01</td>
<td>0.0066</td>
<td>0.097</td>
<td>0.11</td>
<td>0.11</td>
<td>11%</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>11</td>
<td>0.06</td>
<td>0.0066</td>
<td>0.484</td>
<td>0.54</td>
<td>0.5</td>
<td>11%</td>
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<tr>
<td>100</td>
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<td>0.12</td>
<td>0.0066</td>
<td>0.967</td>
<td>1.08</td>
<td>1.1</td>
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<tr>
<td>1000</td>
<td>222</td>
<td>1.17</td>
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<td>9.670</td>
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<td>10.8</td>
<td>11%</td>
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Table A.7 Flow through GCL seam perpendicular to an overlying wrinkle (Test T28a)

<table>
<thead>
<tr>
<th>Length of wrinkle (m)</th>
<th>Number of seam-wrinkle intersections (GCL roll width = 4.35 m)</th>
<th>Flow through single wrinkle-overlap intersection (lpd) in Test T28a</th>
<th>Flow from all intersections (lpd)</th>
<th>Flow through 0.59 m long single panel (lpd) in Test T36</th>
<th>Flow through single panel only (lpd)</th>
<th>Total flow (lpd)</th>
<th>Total flow (lpd)</th>
<th>Flow through overlap (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2</td>
<td>0.019</td>
<td>0.04</td>
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<td>0.13</td>
<td>34%</td>
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<tr>
<td>50</td>
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<td>0.22</td>
<td>0.22</td>
<td>0.429</td>
<td>0.65</td>
<td>0.6</td>
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<tr>
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<td>0.44</td>
<td>0.44</td>
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<td>1.3</td>
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<td></td>
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<tr>
<td>1000</td>
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<td>4.37</td>
<td>8.571</td>
<td>12.9</td>
<td>12.9</td>
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Table A.8 Flow through GCL seam perpendicular to an overlying wrinkle (Test T33)

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<tr>
<th>Length of wrinkle (m)</th>
<th>Number of seam-wrinkle intersections (GCL roll width = 4.35 m)</th>
<th>Flow through single wrinkle-overlap intersection (lpd) in Test T33</th>
<th>Flow from all intersections (lpd)</th>
<th>Flow through 1 m long single panel (calculated; lpd)</th>
<th>Flow through single panel only (lpd)</th>
<th>Total flow (lpd)</th>
<th>Total flow (lpd)</th>
<th>Flow through overlap (%)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.03</td>
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<td>0.04</td>
<td>0.04</td>
<td>75%</td>
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<tr>
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<td>0.2</td>
<td>75%</td>
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<tr>
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<td>0.34</td>
<td>0.11</td>
<td>0.45</td>
<td>0.4</td>
<td>75%</td>
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<td>230</td>
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<td>4.5</td>
<td>4.5</td>
<td>75%</td>
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Table A.9 Calculated flow through GCL seam in Test T22

<table>
<thead>
<tr>
<th>Measured flow</th>
<th>Calculated flow through GCL below wrinkle (m³/s)</th>
<th>Total flow through GCL only (m³/s) (Q1+Q2*2)</th>
<th>Flow through the seam</th>
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</thead>
<tbody>
<tr>
<td>m³/s</td>
<td>Parameters</td>
<td>At the seam (Q1)</td>
<td>Away from the seam (Q2)</td>
</tr>
<tr>
<td></td>
<td>GCL thickness (cm)</td>
<td>1*2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Hydraulic gradient (i)</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Area (m²)</td>
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<td>0.0152</td>
</tr>
<tr>
<td></td>
<td>k (m/s)</td>
<td>5 x 10⁻¹¹</td>
<td>5 x 10⁻¹¹</td>
</tr>
<tr>
<td>2.20 x 10⁻¹⁰</td>
<td>Q (m³/s)</td>
<td>9 x 10⁻¹²</td>
<td>2.3 x 10⁻¹¹</td>
</tr>
</tbody>
</table>
Appendix A.9 Inferring the interface-transmissivity along the GCL seam using measured flow.
Inferring the interface transmissivity at the seam for Test T10

According to the ASTM (2014),

\[
\text{Hydraulic transmissivity } \left( \frac{m^2}{s} \right) = \frac{\text{Measured average quantity of fluid discharged per unit time } \left( Q, \frac{m^3}{s} \right) \times \text{Length of specimen (L, m)}}{\text{Width of specimen (W, m) } \times \text{Difference in total head across the specimen (H, m)}}
\]

In Test T10,

Flow along the seam (Q) = \(2.79 \times 10^{-8}\) m\(^3\)/s

Width of overlapped seam (L) = 0.15 m

Width of deformed wrinkle W = 0.08 m

Applied head (H) = 0.3 m

\[
\theta \left( m^2 / s \right) = \frac{2.79 \times 10^{-8} m^3 / s \times 0.15 m}{0.08 m \times 0.3 m} = 2 \times 10^{-7} m^2 / s
\]

Reference:

ASTM (2014), Standard Test Method for Determining the (In-plane) Flow Rate per Unit Width and Hydraulic Transmissivity of a Geosynthetic Using a Constant Head, ASTM D4716 / D4716M-14, West Conshohocken, PA.
Appendix A.10 Evidence of leakage through GCL seam and panel in Test T11.
Test T11 was conducted with a 150 mm wide GCL2 seam with supplemental bentonite evenly distributed along the seam at the manufacturer’s recommended rate of 400 grams per linear metre. A steady-state flow rate of $5 \times 10^{-10}$ m$^3$/s was measured. This flow is two times larger than that measured in Test T12 (Chapter 2) with exact same test conditions.

Upon test termination, in addition to flow along the seam, flow directly through GCL panel was observed. The measured hydraulic conductivity of the GCL at the leaky location was $1.1 \times 10^{-7}$ m/s compared to $1.5 \times 10^{-10}$ m/s of the sample taken adjacent to the leak location. Higher Calcium and Iron concentration and lower Sodium concentration was observed in the bentonite at the leak location (Table A.10). Photographs showing GCL panel before and after Test T11 are shown in Figure A.17-20.
Figure A.17 Photograph showing the GCL2 overlapped panels before Test T11.
Figure A.18 Photograph showing flow path at the interface between the supplemental bentonite and the lower GTX of the upper GCL in Test T11.
Figure A.19 Photograph taken after the GCL panels were removed to expose the foundation sand. Evidence of flow along the seam and an isolated location in the intact panel was found.
Figure A.20 Photograph taken to show the underside of GCL (that in contact with the foundation sand). The dye stains on the upper panel is due to the flow along the seam. The dye stains in the lower panel is due to the flow through the intact GCL panel.
Table A.10 Concentration of 30 elements in the bentonite sample extracted from leaky and non-leaky samples extracted from Test T11.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Non-leaky panel sample T11</th>
<th>Leaky panel sample T11</th>
<th>Blank</th>
</tr>
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<tbody>
<tr>
<td>Ag</td>
<td>&lt;2.0</td>
<td>&lt;2.0</td>
<td>&lt;2.0</td>
</tr>
<tr>
<td>Al</td>
<td>24600</td>
<td>23900</td>
<td>&lt;50</td>
</tr>
<tr>
<td>As</td>
<td>4.0</td>
<td>3.0</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td>B</td>
<td>&lt;20</td>
<td>&lt;20</td>
<td>&lt;20</td>
</tr>
<tr>
<td>Ba</td>
<td>401</td>
<td>336</td>
<td>&lt;5.0</td>
</tr>
<tr>
<td>Be</td>
<td>&lt;4.0</td>
<td>&lt;4.0</td>
<td>&lt;4.0</td>
</tr>
<tr>
<td>Ca</td>
<td>9680</td>
<td>11700</td>
<td>&lt;100</td>
</tr>
<tr>
<td>Cd</td>
<td>&lt;1.0</td>
<td>&lt;1.0</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td>Co</td>
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<td>&lt;5.0</td>
</tr>
<tr>
<td>Cr</td>
<td>&lt;20</td>
<td>&lt;20</td>
<td>&lt;20</td>
</tr>
<tr>
<td>Cu</td>
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<td>&lt;5.0</td>
<td>&lt;5.0</td>
</tr>
<tr>
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<td>9820</td>
<td>10200</td>
<td>&lt;50</td>
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<td>K</td>
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<td>121</td>
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</tr>
<tr>
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<td>&lt;2.0</td>
<td>&lt;2.0</td>
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<td>3330</td>
<td>&lt;75</td>
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<tr>
<td>Ni</td>
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<td>&lt;5.0</td>
<td>&lt;5.0</td>
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<td>246</td>
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<tr>
<td>Pb</td>
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<td>30.0</td>
<td>&lt;10</td>
</tr>
<tr>
<td>S</td>
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<tr>
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<tr>
<td>Se</td>
<td>&lt;10</td>
<td>&lt;10</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Sn</td>
<td>&lt;2.0</td>
<td>&lt;2.0</td>
<td>&lt;2.0</td>
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<tr>
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<td>306</td>
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<tr>
<td>Ti</td>
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<td>&lt;10</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Tl</td>
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<td>&lt;1.0</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td>U</td>
<td>&lt;10</td>
<td>&lt;10</td>
<td>&lt;10</td>
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</tr>
<tr>
<td>Zn</td>
<td>103</td>
<td>54.5</td>
<td>&lt;15</td>
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</table>

Solid samples results in µg/g
Appendix A.11 Finite element modelling using SEEP/W.
Figure A.21 SEEP/W input data for a 2D model of applied head boundary conditions and assumed $k$ for GCL in Test T19. Width of the model = 0.53 m (cell dia. minus two times bentonite seal width), height of sand foundation = 0.15 m, thickness of GCL = 0.01 m, width of wrinkle = 0.08 m.

Figure A.22 Model output showing calculated flow in the simulated boundary conditions of Test T19. The calculated flow from the 2D model was multiplied by 0.53 m to compare with the measured flow in Test T19.
Figure A.23 SEEP/W input data for a 2D model of applied head boundary conditions and assumed $k$ for GCL in Test T36. Width of the model = 0.53 m (cell dia. minus two times bentonite seal width), height of sand foundation = 0.15 m, thickness of GCL = 0.01 m, width of wrinkle = 0.08 m.

Figure A.24 Model output showing calculated flow in the simulated boundary conditions of Test T36. The calculated flow from the 2D model was multiplied by 0.53 m to compare with the measured flow in Test T36.
Figure A.25 SEEP/W input data for a 2D model of applied head boundary conditions and assumed $k$ for GCL4 in Test T37. Width of the model = 0.53 m (cell dia. minus two times bentonite seal width), height of sand foundation = 0.15 m, thickness of GCL = 0.01 m, width of wrinkle = 0.08 m.

Figure A.26 Model output showing calculated flow in the simulated boundary conditions of Test T37. The calculated flow from the 2D model was multiplied by 0.53 m to compare with the measured flow in Test T37.
Appendix A.12 Groove inspection of GCL3 and GCL4.
GCL3 and GCL4 grooves were inspected prior to sample selection for testing. The entire 15 m length of GCL4 groove inspected was categorized as having a complete melt. Of the 10 m of GCL3b groove inspected (5 m along each edge of the roll), significant differences on the extent of groove melt were observed (Table A.11). Along the right hand side of the roll, 78% of the groove was completely melted but there were four continuous zones with incomplete melting, the longest of which was 0.5 m long. Along the left hand side of the roll, only 32% of the groove was completely melted and there were 1.4 m, 1 m, and 0.7 m long continuous zones where there was incomplete melting. Out of the inspected 3.6 m long melted groove of GCL3, about 3.4 m had an incomplete melt. GCL3b test samples were taken from location with incomplete melt.
Table A.11 Categorization of groove on each side of GCL3b roll.

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Degree of melt on the left side of the roll</th>
<th>Degree of melt on the right side of the roll</th>
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</thead>
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<tr>
<td></td>
<td>Complete</td>
<td>Incomplete</td>
</tr>
<tr>
<td>0.1</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>0.2</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>0.3</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>0.4</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>0.5</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>0.6</td>
<td>G</td>
<td></td>
</tr>
<tr>
<td>0.7</td>
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<td></td>
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<tr>
<td>0.8</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>0.9</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>1</td>
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<tr>
<td>1.1</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>1.3</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>B</td>
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<tr>
<td>1.6</td>
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<tr>
<td>2.1</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>2.2</td>
<td>G</td>
<td></td>
</tr>
<tr>
<td>2.3</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>2.4</td>
<td>B</td>
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</tr>
<tr>
<td>2.5</td>
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<tr>
<td>2.6</td>
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<td>2.7</td>
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<td>2.8</td>
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<tr>
<td>2.9</td>
<td>B</td>
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<td>3</td>
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<td>3.1</td>
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<tr>
<td>3.2</td>
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</tr>
<tr>
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<tr>
<td>Test T14 sample post-test inspection</td>
<td>Upper panel</td>
<td></td>
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<tr>
<td>-------------------------------------</td>
<td>-------------</td>
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<tr>
<td></td>
<td>Complete</td>
<td>Incomplete</td>
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<td>0.25</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>0.3</td>
<td>B</td>
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<td>0.35</td>
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<tr>
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<tr>
<td>0.6</td>
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</tr>
<tr>
<td>Percentage %</td>
<td>8%</td>
<td>92%</td>
</tr>
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</table>

Table A.12 Categorization of groove on GCL3b samples from Test T14.
Table A.13 Categorization of groove on GCL3 samples from Test T29.

<table>
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<th>Test T29 sample post-test inspection</th>
<th>Upper panel</th>
<th>Lower panel</th>
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<tbody>
<tr>
<td></td>
<td>Complete</td>
<td>Incomplete</td>
</tr>
<tr>
<td>0.05</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>B</td>
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</tr>
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<td>0.15</td>
<td>B</td>
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<tr>
<td>0.2</td>
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<tr>
<td>0.25</td>
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<tr>
<td>0.3</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>0.35</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>0.4</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>0.45</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>0.55</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td>B</td>
<td></td>
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</table>

Percentage | % | 17% | 83% | 0%  | 100% |
Table A.14 Categorization of groove on GCL 3 samples from Test T39.

<table>
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<th>Lower panel</th>
<th></th>
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<tbody>
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<td>Incomplete</td>
<td>Complete</td>
<td>Incomplete</td>
</tr>
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<td>B</td>
<td>B</td>
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<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
</tr>
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<td>0.15</td>
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<td>B</td>
<td>B</td>
<td>B</td>
</tr>
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<td>0.2</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
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<td>0.25</td>
<td>B</td>
<td></td>
<td>G</td>
<td>B</td>
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<tr>
<td>0.3</td>
<td>B</td>
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<td>B</td>
</tr>
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<td>B</td>
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<td>B</td>
<td>B</td>
<td>B</td>
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<td>0.45</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
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<tr>
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<td>B</td>
</tr>
<tr>
<td>Percentage</td>
<td>%</td>
<td>0%</td>
<td>100%</td>
<td>8%</td>
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Appendix A.13 Groove hydration of GCL3 and GC4.
Figure A.27 Dry GCLs. GCL4 with a through cut and well exposed groove and GCL3 with an incomplete melt.

Figure A.28 GCL3 and 4 hydration (2 hours after submersion).
Figure A.29 GCL3 and 4 hydration (day 2).

Figure A.30 GCL3 and 4 hydration (day 3).
Figure A.31 GCL3 and 4 hydration (day 4).

Figure A.32 GCL3 and 4 hydration (day 5).
Appendix A.14 Differential settlement of sand subgrade due to pressure distribution that developed around wrinkle.
Figure A.33 Differential settlement of sand due to pressure distribution around wrinkle in Test 24.
Appendix A.15 Submerged hydration of GCL4 sample with 0.5 and 1 in. edge bentonite removed.
Figure A.34 Submerged hydration of GCL4 with edge bentonite removed. The width of the bentonite free zone is indicated in the photographs. There was no sign of bentonite along the edge where 1 in. wide bentonite free zone was present.
Appendix A.16 Free swelling of GCL5 and GCL6 under submerged conditions.
Figure A.35 Laser scan of top surface of free swelling GCL5 and GCL6 in day 0 (dry), 1, 2, 5, and 7.
Appendix A.17 Peel strength tests on GCL5 and GCL6.
Table A.15 Summary of peel strength tests. Tests conducted according to ASTM (2009).

<table>
<thead>
<tr>
<th>GCL Type</th>
<th>Average Peel Strength (N/m)</th>
<th>Average Peak Peel Strength (N)</th>
<th>Maximum Recorded Peel Strength (n=5)</th>
<th>Minimum Recorded Peel Strength (n=5)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Roll Std. dev. (n=5)</td>
<td>X-Roll Std. dev. (n=5)</td>
<td>Roll Std. dev. (n=5)</td>
<td>X-Roll Std. dev. (n=5)</td>
</tr>
<tr>
<td>GCL5</td>
<td>1128.8 194.6 1000.1 143.2 222.3 39.8 160.8 22.0 2697.1</td>
<td>2020.4 355.9 460.0</td>
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<td></td>
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<tr>
<td>GCL6</td>
<td>767.9 69.5 685.2 86.7 131.0 15.0 102.2 14.1 1471.9</td>
<td>1205.0 385.8 357.8</td>
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### Table A.16 Mass per unit area of peel test samples (GCL5)

<table>
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<tr>
<th>Sample #</th>
<th>Mass of peel test sample (g)</th>
<th>Average Mass (g)</th>
<th>Area of Sample (cm²)</th>
<th>Mass Per Unit Area (g/m²)</th>
<th>Standard Deviation (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Roll</td>
<td>X-roll</td>
<td>Roll</td>
<td>X-roll</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>100.80</td>
<td>98.50</td>
<td>99.45</td>
<td>95.30</td>
<td>5040</td>
</tr>
<tr>
<td>2</td>
<td>99.00</td>
<td>96.30</td>
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<td>4950</td>
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<td>3</td>
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<td>94.50</td>
<td>99.45</td>
<td>95.30</td>
<td>5130</td>
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<td>4</td>
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<td>92.70</td>
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<td>4883</td>
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</table>

### Table A.17 Mass per unit area of peel test samples (GCL6)

<table>
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<th>Mass of peel test sample (g)</th>
<th>Average Mass (g)</th>
<th>Area of Sample (cm²)</th>
<th>Mass Per Unit Area (g/m²)</th>
<th>Standard Deviation (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Roll</td>
<td>X-roll</td>
<td>Roll</td>
<td>X-roll</td>
<td></td>
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<tr>
<td>1</td>
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<td>102.71</td>
<td>97.78</td>
<td>5488</td>
</tr>
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<td>98.51</td>
<td>94.43</td>
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<td></td>
<td>4926</td>
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<td>111.11</td>
<td>102.71</td>
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<td>5</td>
<td>106.68</td>
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Figure A.36 Peel test results on GCL5 samples.
Figure A.37 B4000 roll direction samples (20 cm x 10 cm) x-rayed before peel test.
Figure A.38 GCL5 X-roll direction samples (20 cm x 10 cm) x-rayed before peel test.
Figure A.39 Peel test results on NSP4900 samples.
Figure A.40 GCL6 roll direction samples (20 cm x 10 cm) x-rayed before peel test.
Figure A.41 GCL6 X-roll direction samples (20 cm x 10 cm) x-rayed before peel test.
Reference:

Appendix A.18 Mass per unit area (MPUA) of GCL5 and GCL6 at and away from the seam area.
Table A.18 Mass per unit area of GCL5 virgin samples (samples shown in Figure A.43)

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Mass of Oven Dried Sample (g)</th>
<th>Average Mass (g)</th>
<th>Area of Specimen (cm²)</th>
<th>Mass Per Unit Area (g/m²)</th>
<th>Standard Deviation (g)</th>
<th>Average MPUA (g/m²)</th>
<th>Average Mass of Supplemental Bentonite/100 cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Panel (P)</td>
<td>Overlap (O)</td>
<td>P</td>
<td>O</td>
<td>P</td>
<td>O</td>
<td>P</td>
</tr>
<tr>
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<td>47.68</td>
<td>60.32</td>
<td>47.66</td>
<td>58.82</td>
<td>100</td>
<td></td>
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<td>58.64</td>
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<td>56.71</td>
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<td>4</td>
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<td>59.20</td>
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<td>59.24</td>
<td></td>
<td></td>
<td></td>
<td>4849</td>
<td>5924</td>
</tr>
</tbody>
</table>

1 If an overlap width of 300 mm and a length of 1000 mm is considered (area = 300000 mm² = 3000 cm²), the amount of supplemental bentonite at the overlap will be = 3000*11/100 = 330 g i.e 330 g per linear meter. Specification for non-self-sealing overlap is generally 400 g per linear meter.
Table A.19 Mass per unit area of GCL6 virgin samples (samples shown in Figure A.45)

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Mass of Oven Dried Sample (g)</th>
<th>Average Mass (g)</th>
<th>Area of Specimen (cm²)</th>
<th>Mass Per Unit Area (g/m²)</th>
<th>Standard Deviation (g)</th>
<th>Average MPUA (g/m²)</th>
<th>Average Mass of Supplemental Bentonite/100 cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Panel and Overlap</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>44.97</td>
<td>53.33</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>45.32</td>
<td>55.30</td>
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<td></td>
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<td></td>
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</tr>
<tr>
<td>3</td>
<td>51.51</td>
<td>59.47</td>
<td>47.56</td>
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<tr>
<td>4</td>
<td>49.64</td>
<td>55.62</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>5</td>
<td>46.36</td>
<td>54.03</td>
<td></td>
<td></td>
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</table>

* Based on the calculation shown in footnote 1 (pg. 283), the total supplemental bentonite per linear meter = 240 g.
<table>
<thead>
<tr>
<th>Sample #</th>
<th>Mass of oven dried sample (g)</th>
<th>Average Mass (g)</th>
<th>Area of Sample (cm$^2$)</th>
<th>Mass Per Unit Area (g/m$^2$)</th>
<th>Standard Deviation (g)</th>
<th>Average Mass Per Unit Area (g/m$^2$)</th>
<th>Mass of Bentonite/100 cm$^2$</th>
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<tr>
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<td>104.95</td>
<td></td>
<td>174</td>
<td>6905</td>
<td></td>
<td>4766</td>
<td>21$^3$</td>
</tr>
</tbody>
</table>

$^3$ Does not necessarily mean there is higher amount of impregnated bentonite at the overlap. In this case it is more due to the higher mass per unit area of the extracted sample.
Table A.21 Mass per unit area of GCL5 samples extracted after Test T40.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Mass of oven dried sample (g)</th>
<th>Average Mass (g)</th>
<th>Area of Sample (cm²)</th>
<th>Mass Per Unit Area (g/m²)</th>
<th>Standard Deviation (g)</th>
<th>Average Mass Per Unit Area (g/m²)</th>
<th>Mass of Bentonite/100 cm²</th>
</tr>
</thead>
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<tr>
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<td></td>
<td>99</td>
<td></td>
<td></td>
<td>6053</td>
<td>13</td>
</tr>
</tbody>
</table>
Table A.22 Mass per unit area of GCL6 samples extracted after Test T38.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Mass of oven dried sample (g)</th>
<th>Average Mass (g)</th>
<th>Area of Sample (cm²)</th>
<th>Mass Per Unit Area g/m²</th>
<th>Standard Deviation (g)</th>
<th>Average Mass Per Unit Area (g/m²)</th>
<th>Mass of Bentonite/100 cm²</th>
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</thead>
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<tr>
<td>1</td>
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<td>5476</td>
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<td>98.58</td>
<td>5442</td>
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<td></td>
<td>8</td>
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</tbody>
</table>


Figure A.42 Sample cut from underside of the roll to prevent any overlap bentonite loss.

Figure A.43 Specimens (10 x 10 cm) taken for MPUA measurement. The edges were wetted to minimize the loss of bentonite while cutting and oven drying.
Figure A.44 GCL5 specimens x-rayed after oven drying. The needle punches are concentrated as bands of 1 cm wide with spacing of 1-2 cm in between the bands in the cross-roll direction.
Figure A.45 GCL6 specimens x-rayed after oven drying. No distinct band of needle-punch visible.
Physical response of geomembrane wrinkles near GCL overlaps

R. W. I. Brachman, P. Joshi, R. K. Rowe, F. ASCE, and S. Gudina

ABSTRACT

Results from physical experiments are reported to quantify the deformations of geomembrane wrinkles near overlaps in an underlying geosynthetic clay liner (GCL) when subjected to vertical overburden pressure. The height and width of the wrinkle decreased, but a void remained between the geomembrane and GCL when subjected to a vertical pressure of 250 kPa. It was found that the deformation of the geomembrane wrinkle was not significantly altered by the presence of the overlap and that for the conditions tested there was no discernable opening of the GCL overlap when subjected to stress. It is anticipated that the proximity and orientation of the geomembrane wrinkle relative to the GCL overlap and the stress conditions arising from the deforming wrinkle can influence the hydraulic performance of the GCL overlap.

INTRODUCTION

A composite geosynthetic liner consisting of a geomembrane (GM) on top of a geosynthetic clay liner (GCL) – see Figure 1 – can be very effective to limit leakage (i.e. flow under a hydraulic gradient) though landfill barrier systems. The geomembrane limits leakage to flow through holes (e.g., damage caused by puncture during construction or from the weight of overlying materials),
while the presence of a low permeability GCL limits the amount of leakage through any holes. The rate of leakage will depend on (Rowe et al. 2004): the number and size of holes in the geomembrane; the thickness and hydraulic conductivity of the GCL; the thickness and hydraulic conductivity of any other soil materials beneath the GCL (e.g., a foundation/attenuation layer); the hydraulic gradient across the system; the interface transmissivity between the geomembrane and GCL; and any geometrical imperfections that may exist in the composite liner.

Two sorts of imperfections are illustrated in Figure 1: geomembrane wrinkles (Fig. 1a) and GCL overlaps (Fig. 1b). Wrinkles are out-of-plane buckles that develop from thermal expansion when heated (e.g., while being exposed to the sun during construction) that, if not eliminated prior to burial, create features that permit essentially unobstructed lateral flow over an area equal to the length and width of the wrinkle. If a hole develops in the geomembrane at or near a wrinkle, the potential leakage rate can be substantially larger than if there was no wrinkle. Overlaps are the locations connecting adjacent panels of GCLs and consist of a physical overlap between 0.15 to 0.3 m, or more, depending on the manufacturer, product, engineering application and exposure conditions. Supplemental loose bentonite may be placed in between the overlap to improve its hydraulic performance. The GCL overlap creates a small linear feature between GM and GCL and also introduces potential preferential lateral flow paths depending on the hydraulic performance of the overlap.
The hydraulic performance of GCL overlaps has been studied under conditions of uniform vertical stress (e.g., Benson et al. 2004). However, Dickinson and Brachman (2006) have shown that wrinkles create potentially complex stress conditions for an underlying GCL when subject to vertical overburden pressure. Prior to conducting more elaborate tests that measure hydraulic performance of the overlap under actual physical conditions, the purpose of this paper is to report the results from a series of preliminary tests conducted to examine whether GCL overlaps impact geomembrane wrinkle deformations and also whether the deforming wrinkle causes movement at the GCL overlap that could impact its hydraulic performance.

**METHOD**

**Test setup**

A rigid cylindrical test cell of internal diameter 590 mm and height 500 mm was used for all the experiments. A cross-section of the test cell showing test setup and materials tested is shown in Figure 2. Vertical overburden pressure is applied using air pressure to a rubber bladder placed on
top of leveled sand along the top surface of simulated drainage layer. Rigidity of the test cell limited the outward deflection and produced horizontal stresses corresponding to zero lateral strain conditions. The inner wall of the test cell was lined with a friction treatment comprised of two 0.1 mm thick polyethylene sheets lubricated with high temperature grease. Direct contact of tested materials with friction treatment, in upper granular drainage layer, might cause physical damage to the friction treatment. The possible damage is prevented by the use of a protection layer. The protection layer consisted of six bands of 1.5-mm-thick geomembrane rings attached to a nonwoven geotextile (540 g/m²) using double sided tape. Each geomembrane ring is 45 mm wide and each ring is spaced 10 mm with the adjacent ring to permit vertical movement. This treatment has been shown to reduce the sidewall friction to less than 5° (Tognon et al. 1999). For the size of the test cell and the friction treatment employed, the pressure loss due to boundary friction at the location of the geomembrane is calculated to be less than 5% (Brachman and Gudina 2002). Since the effect of boundary friction is minimized, but not eliminated, the reported values of applied pressure should be reduced by 5% when considering an equivalent burial depth in a landfill.

![Cross-section through test cell for test 1 and 2. Dimensions in mm.](image)

Figure 2 Cross-section through test cell for test 1 and 2. Dimensions in mm.
Materials

The case of a firm foundation layer beneath the GCL was examined in these tests by using a 150-mm-thick layer of poorly-graded dry sand (SP) as the subgrade. The sand used had dry density of 1.75 g/cm³ with a water content of less than 0.2%. The grain size distribution curve is shown in Figure 3.

The GCL tested had sodium bentonite (4500 g/m²) sandwiched between a scrim-reinforced nonwoven carrier geotextile (200 g/m²) and nonwoven cover geotextile (200 g/m²) held together with needle-punching. The needle-punching fibers were thermally fused to the bottom of the carrier geotextile. The GCL was tested at two different initial water contents. For test 1, a dry GCL with an initial gravimetric water content of 4% and thickness of approximately 5.5 mm was used. For tests 2, 3 and 4, the GCL was hydrated with tap water for seven days under a confining stress of 20 kPa. The resulting initial water content of these samples was between 119 and 125% and had average initial thicknesses of 7.5 mm. In all tests, an overlap of 150 mm was examined, the centre of the GCL overlap was aligned with the centre of the test cell and no supplemental bentonite was added to the overlap.

In all tests, a 1.5-mm-thick smooth high-density polyethylene geomembrane with an artificially formed wrinkle was placed above the GCL. The wrinkles had an initial height of approximately 60 mm and width of 200 mm. Figure 4 details the three different scenarios of the wrinkle location relative to the GCL overlap were tested. In tests 1 and 2, the crest line of the wrinkle coincided with the centre-line of GCL seam (Fig. 4a). In test 3, the wrinkle was positioned at 90° to the GCL seam (Fig. 4b), while in test 4, the wrinkle crest line was offset 155 mm from the centre of GCL seam (Fig. 4c).

A nonwoven needle-punched geotextile (GT) was placed between the geomembrane and the overlying coarse gravel drainage layer. This geotextile had mass per unit area of 540 g/m².
Overlying the geomembrane wrinkle and geotextile protection layer was a 300 mm-thick layer of nominal 50-mm poorly-graded gravel (GP50) to simulate a granular leachate collection system and meet the requirement of Ontario, Canada landfill regulations (MOE, 1998). The gravel layer was placed, without any compaction, at a dry density of 1.52 g/cm$^3$.

![Figure 3 Grain size distributions of foundation (SP) and drainage layer (GP50).](image)

Figure 3 Grain size distributions of foundation (SP) and drainage layer (GP50).
Figure 4 Plan and cross-section views showing location of GM wrinkle relative to the GCL overlap. Dimensions in mm.

Procedure

Materials were carefully placed in the test cell and the initial geometry of foundation layer, GCL and the geomembrane was measured to an accuracy of ±0.1 mm using a profiler. The rubber bladder was placed on top of leveled sand along the top surface of gravel layer and was clamped between the flange and lid of the test cell (Figure 3). The pressure was applied at the rate of 50 kPa increment in every 10 minutes and then held constant at a maximum applied pressure of 250 kPa for 100 hours. Temperature was maintained at 22 ± 1°C throughout the test.
After 100 hours, but while the pressure was still applied, a low shrinkage grout of plaster of Paris was injected into the remaining void space beneath the geomembrane to record the deformed shape of wrinkle. After the grout was allowed to set for approximately 30 minutes, the pressure was released and all the materials overlying the wrinkle were carefully removed. The final height and width of the geomembrane wrinkle, GCL and sand were then measured using the profiler.

**PRELIMINARY RESULTS**

The initial and deformed shapes from test 1 are plotted in Figure 5, while initial and final photographs of the GCL overlap are shown in Figure 6. Here and in all other tests, the datum of the elevation shown in Figure 5 is taken as the initial elevation of the top surface of the GCL. Points directly on the centre of the wrinkle deformed vertically downwards, while points mid-way along the side of the wrinkle deformed vertically downwards and horizontally towards the centre of the wrinkle. Consequently, the wrinkle experienced a decrease in height of 28 mm and a decrease in width of 100 mm from the application of load, but a void with a height of 44 mm and width of 98 mm remained beneath the wrinkle. A photograph of the grout filled zone beneath the wrinkle is shown in Figure 6b. These observations are similar to the results reported by Brachman and Gudina (2008) for otherwise the same conditions but without a GCL overlap and with the pressure held constant for only 10 hours instead of 100 hours. The remaining height and width (H and W) when normalized by the initial height and width (Ho and Wo) were $H/Ho = 66\%$ and $W/Wo=45\%$ in test 1 compared to respective values of 69% and 52% reported by Brachman and Gudina (2008). The slightly smaller final wrinkle in test 1 is attributed to pressure being sustained for a longer period of time.
As expected with a firm foundation layer beneath the GCL, there was only small movement of the GCL induced by the movement of the underlying sand.

Figure 5 shows that in test 1 there was only small (less than 4 mm) downward vertical movement of sand beside the wrinkle and little (less than 6 mm) upward vertical movement (i.e. heave) of sand directly beneath the wrinkle. The heave results from small upward movements into the stress free zone beneath the wrinkle. Again, this is similar to what Brachman and Gudina (2008) observed for similar conditions but without a GCL overlap.

There was no discernable displacement or opening of the GCL overlap following application of the pressure in test 1. The small heave of foundation soil beneath the wrinkle, the inward displacement of points on the side of the wrinkle and compressive vertical stress on either side of the overlap where the deformed wrinkle was in direct contact with the GCL overlap produced physical
conditions such that, for the specific conditions tested, there appeared to be no movement of the overlap that would be detrimental to its hydraulic performance.

The results from test 2 are plotted in Figure 7. Here, the GCL had a higher initial water content, but otherwise had the same configuration as test 1. This resulted in a higher and wider deformed wrinkle in the geomembrane, but again, no opening of the GCL overlap was observed. The major difference between tests 1 and 2 was that local reductions in thickness of the GCL from lateral bentonite extrusion were more prominent at the higher water content – see Dickinson and Brachman (2006, 2010) for a more detailed discussion of the nature and significance of these sorts of indentations.

![Figure 7 Initial and deformed shapes from test 2.](image)

The deformed shape from test 3, where the geomembrane wrinkle was oriented perpendicular to the GCL overlap, is presented in Figure 8. The deformed shape of the wrinkle is not significantly different to that from test 2. Figure 9 shows initial and final photographs of the GCL overlap. No movement of the GCL overlap was detected.

Figure 10 shows the deformed shape of the wrinkle from test 4, where the centre of the wrinkle was laterally offset from the GCL overlap. Given the limited dimensions of the test apparatus, it is likely that the wrinkle deformations in this test were impacted by the close proximity to the test cell boundary. It was observed that the reduction in wrinkle height was larger in test 4 than the other three tests. Despite the larger displacements, there was no measurable slippage at the GCL overlap.
DISCUSSION

It is interesting at this point to take the preliminary results from tests 1-4 and examine how the physical conditions at a geomembrane wrinkle and a GCL overlap could possibly impact how significant the hydraulic performance of the GCL overlap may be to the leakage rate if there is a hole in the geomembrane wrinkle.

When the centre of the wrinkle was aligned with the centre of the GCL overlap, the nature of deformed shape in tests 1 and 2 was such that fluid in the wrinkle would not have access for direct
entry into the GCL overlap, but would either have to flow downward through the upper GCL or laterally along the interface between the deformed geomembrane and upper GCL to then reach the interface. It is likely that the hydraulic performance of the GCL overlap would benefit from vertical stress acting on the interface on either side of the remaining wrinkle (e.g., between 50 to 80 mm and -50 to -80 mm from the centre of the wrinkle in Fig. 5). It may be of interest to conduct permeation tests for this case where the GCL overlap is subjected to both confined and stress-free regions.

The conditions examined in test 4 were such that any fluid in the wrinkle would also not have access for direct entry into the GCL overlap, but would have to first flow laterally along the interface between the geomembrane and upper GCL of the overlap for the length of the overlap. This situation would also benefit from having vertical stress acting on the entire overlap from above (e.g., between 60 to 220 mm from the centre of the wrinkle in Fig. 10). A situation related to the test 4, but with the position of the upper and lower GCLs exchanged for each other in the overlap region (i.e. if the wrinkle formed on the other side of the overlap) would not be as favorable since any fluid in the wrinkle could flow preferentially along the GCL overlap.

Of the conditions tested, the orientation of geomembrane wrinkle at a right angle to the GCL overlap in test 3 would be expected to produce conditions where the resulting leakage rate would be most sensitive to poor hydraulic performance of the overlap. This is because any fluid beneath the geomembrane wrinkle would have direct access to the overlap. Further, a portion of the GCL overlap equal to the width of the deformed wrinkle would not be subject to any vertical stress. Thus there appears to be merit to conduct permeation testing of GCL overlaps under such physical conditions.
SUMMARY

A series of preliminary physical tests were conducted to study the deformations of geomembrane wrinkles near GCL overlaps. It was found that the deformation of the geomembrane wrinkle was not significantly altered by the presence of the overlap and that for the conditions tested there was no discernable opening of the GCL overlap when subjected to 250 kPa of vertical stress. It is anticipated that the proximity and orientation of the geomembrane wrinkle relative to the GCL overlap and the stress conditions arising from the deforming wrinkle can influence the hydraulic performance of the GCL overlap. Additional testing is currently underway to confirm the preliminary results reported in this paper and assess the impact of geomembrane wrinkles near GCL overlaps on the overall hydraulic performance of these composite liners.

ACKNOWLEDGEMENTS

This work was funded by the Natural Sciences and Engineering Research Council of Canada through a Strategic Project Grant in partnership with the Ontario Ministry of the Environment, Solmax International Inc., Terrafix Geosynthetics Inc., AECOM, AMEC Earth and Environmental, Golder Associates and CTT Group.

REFERENCES


Heat-tacked overlap strength of four GCLs

Prabeen Joshi, Richard W.I. Brachman & R. Kerry Rowe GeoEngineering Centre at Queen’s–RMC, Queen’s University, Kingston, Ontario, Canada

ABSTRACT
Panel separation of Geosynthetic Clay Liners (GCLs) when installed beneath a geomembrane and left exposed to ambient conditions with no cover has been attributed to an accumulation of permanent shrinkage strain from cyclic wetting and drying. Heat tacking of GCL panel overlaps is being considered as one possible approach to mitigate panel separation. This approach will require the resistance of the heat-tacked seam to exceed the force developed in the GCL panel upon shrinkage. This paper presents the results of tensile strength tests on virgin and heat-tacked specimens of four commercially available GCLs. Heat-tacked specimens were found to have reduced strength compared to the virgin specimens in both the roll and cross-roll directions. The heat-tacked samples were observed to fail in three different ways. The same GCL type failed differently when loaded in roll and cross-roll directions. Pre-engineered grooves in GCLs provided preferential locations for rupture.

RÉSUMÉ
Séparation du panneau des des géosynthétique bentonitique (GSB) lorsqu'il est installé sous une géomembrane et exposés à des conditions ambiantes sans couverture de gauche a été attribuée à une accumulation de souche rétrécissement permanent de cyclique de mouillage et de séchage. Chaleur joignant des chevauchements de panneau GSB est envisagée comme l'une des approches possibles pour atténuer la séparation du panneau. Cette approche exigera la résistance de la couture accrochées à la chaleur à dépasser la force développée dans le panneau GSB dès le retrait. Cet article présente les résultats des tests de résistance à la traction sur des spécimens vierges et accrochées à la chaleur de quatre spécimens disponibles commercialement GSB. chaleur-plaquées ont montré des force réduite par rapport aux spécimens vierges dans le rouleau et les directions de la Croix-roll. Les échantillons de chaleurplaquées ont été observés à l’échec de trois façons différentes. Le même type GSB n'a pas différemment lors du chargement en rouleau et les orientations de la Croix-roll. Rainures préfabriqués en GSB emplacements préférentiels prévus en cas de rupture.
1 INTRODUCTION

1.1 Geosynthetic Clay Liners

Geosynthetic clay liners (GCLs) can be integral parts of modern composite liners. GCLs are often comprised of a layer of bentonite sandwiched between upper and lower geotextiles, which are commonly held together by needle punching. For some products, the needle-punched fibers drawn from the upper geotextile are thermally fused to the lower geotextile (referred to as thermal treatment). All together the total thickness of GCL is normally between 5-10 mm.

The very low hydraulic conductivity of GCL, typically with \( k_w < 5 \times 10^{-11} \text{ m/s} \) when permeated with water, can make it very effective in limiting leakage through any holes in an overlying geomembrane (GM) (e.g., see Rowe et al. 2004; Rowe 2011).

GCL panels have a fixed dimension and need to be overlapped (e.g., see Fig. 1) effectively to prevent preferential leakage at the overlaps. Typically supplemental powder bentonite is placed, at a rate specified by the manufacturer, between the two overlapped panels. However for some products, a preengineered groove in the lower geotextile of the GCL is used to expose the bentonite in order to self-seam the overlaps without the addition of supplemental bentonite.

![Figure 1. Illustration of a GCL overlap beneath a geomembrane (GM).](image)

![Figure 2. Illustration of loss of overlap between GCL panels beneath an exposed GM.](image)

1.2 GCL Panel Shrinkage

GCLs may be susceptible to shrinkage under cyclic wetting and drying cycles (Thiel et al. 2006; Rowe et al. 2010). Various cases have been reported where GCLs covered by a geomembrane (GM) and left exposed for 2 to 36 months resulted a panel separation from 200 mm to 1200 mm (Fig. 2) that had an initial overlaps of 150 mm (Thiel and Richardson 2005; Koerner and Koerner 2005a, 2005b).

Gassner (2009) reported 50-80 mm of shrinkage during 18 months of exposure when a 5 mm thick offwhite geotextile protection layer covered the geomembrane. The use of a light colored geotextile was believed to reduce the extent of shrinkage; however, it clearly did not prevent shrinkage.

Two possible means of reducing the risk of panel separation are to increase the overlap to
300 mm and place cover soil on the GM as quickly as possible (Thiel and Rowe 2010); however in some cases it may not be possible to achieve these solutions.

1.3 GCL Overlaps and Heat Tacking

GCL panels are typically overlapped by 150 to 300 mm depending on the manufacturer, product, engineering application and exposure conditions. When immediate covering of composite liner is not possible, it appears that the technique of heat-tacking the overlaps has potential for reducing the risk of shrinkage induced separation (Thiel and Thiel 2009; Rowe et al. 2009). Heat tacking involves melting some of the fibres from the upper geotextile from one GCL panel and pressing these molten fibres into contact with the lower geotextile of the adjacent GCL panel with which they bond. Thiel and Thiel (2009) documented the use of heat tacking of GCL overlaps to prevent panel separation in a 60 ha heap leach pad at a site in Arizona. The 150 mm GCL panel overlaps were heat-tacked using a flame torch and pressed together by the weight of a sand bag that was dragged over the seam following the torch. The geomembrane was placed over the GCL on the same day but the composite liner it was left uncovered for 60 days or more before cover soil was placed over the composite liner. Rowe et al. (2010) reported that the bonded seams from the site generally performed well.

1.4 Objective

The objective of this paper is to quantify the tensile strength of four different GCLs in the roll and cross-roll directions and to quantify the tensile strength of heat-tacked GCL overlaps also in the roll and cross-roll directions.

2 METHOD

2.1 GCLs Tested

To quantify the tensile strength of seamed and unseamed GCL in roll (machine) and cross-roll (crossmachine) direction, four different GCLs from two different manufactures were tested. Descriptions of the GCLs tested are given in Table 1. All GCLs contained natural granular Wyoming bentonite.

All four GCLs were needle-punched to improve the mechanical bond between the layers. The needle punched fibres from the upper geotextile of GCLs 1 and 2 were thermally fused to the lower geotextile, GCLs 3 and 4 were not thermally treated. GCL3 and 4 each had a preengineered groove intended to eliminate the need for placing powdered bentonite.

2.2 Sample Preparation

Edge samples measuring approximately 400 mm wide and 2000 mm long were taken from each GCL in both the roll and cross-roll
directions. Samples were overlapped by 150 mm and were bonded using a propane flame torch and then pressed together by the operator dragging his foot over the heated seam (Figure 3). Heating melted the fibres of the lower geotextile of upper GCL and upper geotextile of lower GCL, which fused together creating a heat-tacked seam. The heat-tacked portion of the seam ranged from 30 mm to less than 110 mm. Each sample was then cut into 5 pieces, 400 mm square, sealed in a plastic bag and transported back to lab for the preparation of the test specimens.

Test specimens, 100 mm wide x 200 mm long, were prepared prior to testing. The portion of seam other than heat-tacked were carefully cut and removed. All the specimens were at the off-the-roll moisture content.

2.3 Testing

Testing (ASTM D 6768) involved taking a 100 mm wide x 200 mm long specimen, clamping it in a tensile testing machine (Fig. 4) with a 100 mm gauge length, and subjecting it to a constant rate of elongation of 300 mm/min until complete rupture of the specimen occurred.

Five replicate tests were performed for each set of virgin and heat-tacked specimens.

Figure 3. Heat-tacking GCL panels to form a seam.

Table 1. Description of the GCLs tested.

<table>
<thead>
<tr>
<th>GCL</th>
<th>Top GTX*</th>
<th>Bottom GTX*</th>
<th>Bonding mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>GCL 1</td>
<td>Nonwoven staple-fibre needle-punched</td>
<td>Woven Slit film</td>
<td>Needle-punched, Thermally treated</td>
</tr>
<tr>
<td>GCL 2</td>
<td>Nonwoven staple-fibre needle-punched</td>
<td>Woven slit-film needle-punched to a needle-punched nonwoven staple-fibre</td>
<td>Needle-punched, Thermally treated</td>
</tr>
<tr>
<td>GCL 3</td>
<td>Woven slit-film</td>
<td>Needle-punched nonwoven staple-fibre</td>
<td>Needle-punched</td>
</tr>
<tr>
<td>GCL 4</td>
<td>Nonwoven staple-fibre needle-punched</td>
<td>Needle-punched nonwoven staple-fibre</td>
<td>Needle-punched</td>
</tr>
</tbody>
</table>

GTX = geotextile.

* Top and bottom refer to whether the GTX is on the top or bottom of the GCL as it comes off the roll.
3 RESULTS

Figure 5 shows the load-displacement curves for the four different virgin GCLs in the roll direction. The tensile force, in each case, built up as the displacement increased and reached a peak. Sudden decreases in post-peak force were experienced for each GCL. GCLs 1, 2 and 3 all showed a gradual increase in load carrying capacity beyond the peak force. GCL4, which has both upper and lower nonwoven needle-punched geotextiles showed only a decrease in load post peak.

The maximum average tensile force was measured for GCL4 and least for GCL3. GCL4 showed the greatest variability, with a standard deviation of 1.9 kN/m and coefficient of variation of 15%, for otherwise identical test conditions. The results are presented in Table 2.
Comparing Figure 5a, b and c, GCL1 has a higher rupture strain than GCL2 and 3. GCL1 and 2 both have the same upper nonwoven geotextile. GCL1 has a woven lower (carrier) geotextile while GCL2 has a nonwoven staple fibre geotextile needle-punched to a woven geotextile as a carrier geotextile.

Table 2. Summary of maximum tensile strength (kN/m) of four different virgin GCLs in roll direction.

<table>
<thead>
<tr>
<th>GCL type</th>
<th>Mean (kN/m)</th>
<th>Std dev. (kN/m)</th>
<th>Coef. of variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.5</td>
<td>0.6</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>9.8</td>
<td>0.6</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>6.9</td>
<td>0.6</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>12.9</td>
<td>1.9</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 3. Summary of maximum tensile strength (kN/m) of four different virgin GCLs in cross-roll direction.

<table>
<thead>
<tr>
<th>GCL</th>
<th>Mean (kN/m)</th>
<th>Std dev. (kN/m)</th>
<th>Coef. of variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.9</td>
<td>0.6</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>22.8</td>
<td>1.8</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>6.5</td>
<td>0.3</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>14.7</td>
<td>2.0</td>
<td>13</td>
</tr>
</tbody>
</table>

Figure 6 shows the force-displacement curve for the virgin GCLs in cross-roll direction and Table 3 summarizes the tensile strengths. In this orientation, GCL2 had the maximum peak strength while GCL3 had the minimum peak strength.

GCL1 showed a similar pattern of load-displacement response as in the roll direction. However, GCL2 was much stronger in the cross-roll direction than in the roll direction. This is because an anisotropic woven silt-film geotextile was used for GCL2, with stronger slit films in the cross-roll direction. Figure 7 shows photographs of the different failure mechanisms for GCL2 in the roll and cross-roll directions.

GCL3 and 4 both failed at the pre-engineered grooves. The upper woven geotextile in GCL3 continued to resist displacement even after the failure of the preengineered grooves (see Fig. 8a) but in case of GCL4 the lower nonwoven geotextile failed simultaneously with the pre-engineered groove (see Fig. 8b) and hence there is no post-peak load. Rowe et al. (2010) also reported failure of GCL4 from the pre-engineered grooves. The average strength of pre-engineered groove of GCL4, reported by Rowe et al. (2010) was 12.7 kN/m with a standard deviation of 2.8 and the average strength measured during this test was 14.7 kN/m with a standard deviation of 2.

Figures 9 and 10 show the load-displacement curves for the heat-tacked specimens in the roll and cross-roll directions. Tables 4 and 5 summarize the maximum tensile strengths of the heat-tacked specimens. The heat-tacked specimens showed different modes of failure when loaded in different directions. Compared to the virgin specimens, heat-tacked specimens had decrease in strength and exhibited a greater variability.
GCL2 recorded the maximum heat-tacked tensile force in both the roll and cross-roll directions. The minimum heat-tacked tensile force, on average, was found for GCL1 in the roll direction and GCL3 in the cross-roll direction. The ratios of average heat-tack strength to virgin strength are summarized in Table 6.

Figure 6. Load-displacement curves for four GCLs in cross-roll direction.

Figure 7. Failure of virgin GCL2 in a) Roll direction b) Cross-roll direction.

Figure 8. Failure at pre-engineered groove in: (a) GCL3, and (b) GCL4

Table 4. Summary of maximum tensile strengths (kN/m) of four different heat-tacked GCLs in roll direction.

<table>
<thead>
<tr>
<th>GCL type</th>
<th>Mean (kN/m)</th>
<th>Std dev. (kN/m)</th>
<th>Coef. of variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.5</td>
<td>1.1</td>
<td>23</td>
</tr>
<tr>
<td>2</td>
<td>10.3</td>
<td>1.2</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>5.3</td>
<td>0.7</td>
<td>13</td>
</tr>
</tbody>
</table>
Table 5. Summary of maximum tensile strength (kN/m) of four different heat-tacked GCLs in cross-roll direction.

<table>
<thead>
<tr>
<th>GCL type</th>
<th>Mean (kN/m)</th>
<th>Std dev. (kN/m)</th>
<th>Coef. of variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.8</td>
<td>0.9</td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>13.5</td>
<td>2.6</td>
<td>19</td>
</tr>
<tr>
<td>3</td>
<td>4.4</td>
<td>0.9</td>
<td>21</td>
</tr>
<tr>
<td>4</td>
<td>9.2</td>
<td>1.2</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 6. Ratio of average maximum heat-tacked strength to virgin strength in the roll and cross-roll directions.

<table>
<thead>
<tr>
<th>GCL</th>
<th>Roll</th>
<th>Cross-roll</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0.6</td>
</tr>
<tr>
<td>3</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>4</td>
<td>0.6</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Figure 9. Load-displacement curves for four heat-tacked GCLs in roll direction

Although the lower geotextiles of both GCLs 1 and 2 had already been thermally treated and had a noticeably smoother surface compared to GCLs 3 and 4, this did not appear to affect the heat-tacking of overlaps, probably because only the bottom side of GCLs 1 and 2 were thermally treated and the non-thermally treated upper side of these GCLs were able to
develop an effective bond with the lower geotextile upon heat tacking. The heat-tacked specimens of GCL1 and 2 did not fail at the seam except for GCL2 in the cross-roll direction, which is most likely because GCL2 has a very high strength in cross-roll direction (Table 3). For GCL1, the lower woven geotextile failed when the specimen was loaded in the roll direction and the upper nonwoven geotextile failed when loaded in the cross-roll direction. GCL3 failed at the seam when loaded in cross-roll direction whereas partial failure of heat-tacked seam and the upper geotextile was observed when loaded in roll direction. GCL4 consistently failed at the pre-engineered groove when loaded in cross-roll direction and at the heat-tacked seam in roll direction (where there was no pre-engineered groove).

**CONCLUSIONS**

Results of tests carried out to quantify the tensile strength of heat-tacked GCL overlaps for four different GCLs from two different manufacturers were presented. These results were compared with the virgin (i.e., intact) GCL strength. In all but one case, the strength of heat-tacked seam was less than the intact specimen. The virgin specimens also generally exhibited less variability in strength (both in roll and cross-roll direction) than the heat-tacked specimens.

In the cross-roll direction, which represents the critical direction for the majority of overlaps/seams, the greatest heat-tacked strength was obtained for GCL2 and the least for GCL3.

Three different modes of failure were observed for the heat-tacked samples. Tearing
of one or both geotextiles adjacent to the seam was observed when the GCL did not fail at the seam. GCLs with pre-engineered grooves failed at the grooves.

Heat-tacking of GCLs that were already once thermally treated were found to develop effective heat-tacked seams and so it appears that heat-tacking is an option for minimizing the risk of seam separation due to shrinkage for all the GCLS tested, but particularly for GCL2 (with the scrim-reinforced carrier and thermal treatment) which exhibited the highest heat-tacked strength.

ACKNOWLEDGEMENTS

The research presented in this paper was funded by the Natural Science and Engineering Research Council of Canada (NSERC) and used equipment provided by funding from the Canada Foundation for Innovation (CFI) and Ontario Ministry of Research and Innovation. The authors are grateful to their industrial partners, Solmax International, Terrafix Geosynthetics Inc, Ontario Ministry of Environment, the Canadian Nuclear Safety Commission, AECOM, AMEC Earth and Environmental, Golder Associates Ltd., Knight-Piesold, and CTT Group for their participation in, and contributions to, the overarching project; however the opinions expressed in the paper are solely those of the authors.

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Thiel, R., Thiel, C., February/March 2009. GCL shrinkage – a possible solution. Geosynthetics, 10–21
Appendix B
Supplementary materials for Chapter 4, 5 and 6 (Chapter 4: A new laboratory apparatus for measuring leakage through geomembrane holes beneath mine tailings), (Chapter 5: Leakage through holes in geomembranes below saturated fine tailings), (Chapter 6: Physical and hydraulic response of geomembrane wrinkles underlying saturated fine tailings)
Appendix B.1 Grain size distribution of materials used in Chapter 4, 5 and 6.
Figure B.1 Grain size distribution of materials used in Chapter 4, 5 and 6. All tests were done according to ASTM (1998) and ASTM (2009).

Reference:


Appendix B.2 Steps taken for setting up and terminating permeation tests.
1. Place a geocomposite drain (GCD) of diameter equal to cell diameter at the bottom of a clean GLLS cell.

2. Apply friction treatment 10 cm tall from the top of the GCD.

3. Fill the bottom 14 cm with underliner at specified dry density and moisture content.

4. Saturate the underliner with tap water from below (via the port in the bottom of the cell) using a reservoir with water head at the top level of the underliner (minimum gradient).

5. Record the volume of water required to saturate the underliner and compare with the calculated volume of water required (volume of voids) to achieve complete saturation of the underliner.

6. Place a GMB of desired thickness and defect diameter and make sure there is no air entrapped between the underliner and the GMB.

7. Seal the edges with bentonite paste and cover the seal with a thin plastic sheet in order to prevent any contamination of tailings with bentonite.

8. Sprinkle or spray powered or liquid dye on top of the seal to check the performance of the seal.

9. Apply friction treatment to the upper 30 cm from the GMB layer. Cover the bentonite seal with the lower portion of friction treatment for separation of the tailings and the seal.

10. Place overliner slurry prepared at specified moisture content.

11. Leave upper 5 cm for placement of upper drainage layer and filler sand layer.

12. Place two layers of rubber bladder and tighten the bolts.

13. Purge the space between the upper drainage layer and bladder.

14. Apply desired total stress and hydraulic head at preselected sequences.
15. If the pump runs very fast (1 beat per < 10 sec) for a prolonged period of time (> 5 min) then there might be a leak in the system.

16. Collect consolidated water from the side port and bottom of the cell if the total stress is stepped.

17. After final stress levels are reached start recording the flow.

18. After steady-state is reached terminate the test.

19. All the steps go backwards from here, take measurements, samples and photographs.
Appendix B.3 Placing a hole in the geomembrane.
Two methods were used to place holes in the geomembrane: (i) using a hollow hole punch, (ii) using a drill.

For tests where a hole was formed in the geomembrane prior to tailings placement, the hole was placed outside the test cell using the hole punch shown in Figure B.2. For tests with 1.5 mm dia. hole and where a hole was formed after tailings consolidation a drill bit was used. The drill bit was attached to a flexible bendable extended extension magnetic shaft. Photographs of the 1.5 and 10 mm dia. drill bit are shown in Figure B.3.

Figure B.2 Photograph showing 10 mm dia. hollow hole punch and hole placed in the geomembrane.
Figure B.3 (a) Photograph showing a 1.46 mm (~1.5 mm) diameter drill bit used to make holes in the geomembrane used in Tests 9 and 10 (Chapter 5), (b) A 10 mm dia. drill bit attached to an extension rod to drill a hole on a deformed wrinkle in Tests W2 and W4 in Chapter 6.
Appendix B.4 Gravel used in Test 13 (Chapter 5).
Figure B.4 Photographs of the gravel placed below the geomembrane hole in Test 13 (Chapter 5).
Appendix B.5 Artificially formed wrinkle and perimeter seal.
Figure B.5 Steel weights were used to form the wrinkle in place before applying the top perimeter seal.

Figure B.6 Pile of bentonite placed below the ends of the wrinkle to prevent any preferential flow. The plastic sheet was folded over on to the bentonite pile to partially cover the pile and prevent migration of bentonite towards the centre of the cell.
Appendix B.6 Photograph showing tailings inside the gap beneath the 1-mm-thick geomembrane wrinkle backfilled with 30 cm tailings slurry at 65% solids (Test W1, Chapter 6).
Figure B.7 Photograph showing geomembrane wrinkle skewed away from the side containing hole.

Figure B.8 Photograph taken after removing the geomembrane to expose the tailings present inside the gap beneath the wrinkle.
Appendix B.7 Granular filter design for $k$ test in GLLS$^4$

$^4$ Refer Part 633 National Engineering Handbook - Chapter 26 (NRCS 1994) 334
Two layers of filter were designed to act as a graded underliner. First layer of finer sand filter was designed to be adjacent to the base material (Tailings). A second layer of coarser filter was designed as a filter for the first layer of finer sand filter.

Procedure as directed by Part 633 National Engineering Handbook - Chapter 26 (NRCS 1994) was followed while designing both filters. An example of the filter envelop is shown for T-7 base tailings.

The steps are summarized below,

1. Plot the gradations of base soils for which a filter is being designed.

2. Determine the finest base soil that will control filter requirements. Also determine the soil with the coarsest limits that will control permeability requirements for the filter.

3. If the finest base soil has particles larger than the No. 4 sieve, regrade the soil on the No. 4 sieve.

4. Determine within which base soil category the regraded sample falls.

5. Determine the maximum $d_{15}$ size based on filter criterion in criteria tables for that base soil category using the finest soil of the category plotted.

6. Determine the minimum $d_{15}$ size based on permeability criterion in criteria tables, considering the coarsest sample plotted.

7. Calculate the ratio of the maximum $d_{15}$ to the minimum $d_{15}$ sizes from steps 5 and 6. If the ratio is less than or equal to 5, label the points control points 1 and 2, respectively and continue to step 8. If the ratio is greater than 5, determine whether filtering or drainage is the most important function of the filter being designed. If filtering is most important, go to step 7A. If permeability is the most important consideration, go to step 7B.
7A. Filtering controls—Label the minimum \( d_{15} \) size as control point 2. Multiply minimum \( d_{15} \) by 5. This is the maximum \( d_{15} \) size; plot on Form 130 and label as control point 1. Go to Step 8.

7B. Permeability controls design—Label the maximum \( d_{15} \) size as Control point 1. Divide the maximum \( d_{15} \) size by 5. This is the minimum \( d_{15} \) size; plot on Form 130 and label as Control point 2. Go to Step 8.

8. Calculate a value for the maximum \( d_{10} \) size by dividing the maximum \( d_{15} \) size (Control point 1) determined in step 7 by 1.2. (This factor of 1.2 is based on the assumption that the slope of the line connecting \( d_{15} \) and \( d_{10} \) should be on a coefficient of uniformity of about 6.) Calculate a value for maximum \( d_{60} \) by multiplying the maximum \( d_{10} \) size by 6. Label this as Control point 3. Determine the minimum allowable \( d_{60} \) size for the fine side of the band by dividing the determined maximum \( d_{60} \) size by 5. Label this Control point 4.

9. Plot the minimum \( d_{5} \) (for all filters) as equal to 0.075 mm (the No. 200 sieve). Label as Control point 5 on Form 130. Plot the maximum \( d_{100} \) (for all filters) as equal to 3 inches. Label as Control point 6 on Form 130.

10. Calculate a value for the minimum \( d_{10} \) size by dividing the minimum \( d_{15} \) size (Control point 2) determined in step 7 by 1.2. (This factor of 1.2 is based on the assumption that the slope of the line connecting \( d_{15} \) and \( d_{10} \) should be on a coefficient of uniformity of about 6.) Based on the determined value of minimum \( d_{10} \) size, obtain from table 26–6 the maximum allowable \( d_{90} \) size for the filter. Plot this value on Form 130 and label it as Control point 7.

11. Connect Control points 6, 7, 3, and 1 to form the coarse side of the initial filter design band. Connect Control points 4, 2, and 5 to form the fine side of the initial filter design band. Extrapolate the previously drawn lines to complete the preliminary fine and coarse
limits of the preliminary filter band to 0 and 100 percent passing values. Adjust these limits to intercept relatively even values of percent passing at standard sieve sizes to simplify specifications (generally rounded at the nearest 5 on the percent passing scale) staying within the preliminary band. In most cases avoid sharp breaks in the design envelopes that might allow too broadly graded filter materials to be used in this final design step. If necessary to meet available gradations, adjust Control points 3 and 4 to the left, maintaining the ratio of diameters at 5, then draw other preliminary fine and coarse limits.

12. Design filters surrounding perforated pipe with an additional control point, determined as the minimum $d_{85}$ size of the filter according to criteria tables. Label this value as Control point 8, and re-examine the design obtained in step 11.

Designed parameters for T-7 tailings are summarized in Table B.1 and plotted in Figure B.9.
Table B.1 Calculated filter bands for T-7 base tailings according to part 633 National Engineering Handbook - Chapter 26

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Base soil (Tailings)</th>
<th>Fine filter</th>
<th>Coarse filter</th>
<th>Approximate k</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{5 \text{ min}}$</td>
<td>0.075 mm</td>
<td>0.08 mm</td>
<td>3 mm / 8 mm</td>
<td>Fine filter = 4x10^{-3} m/s</td>
</tr>
<tr>
<td>$d_{10 \text{ min}} / d_{10 \text{ max}}$</td>
<td>0.075 mm / 0.67 mm</td>
<td>1.5 mm / 6 mm</td>
<td>20 mm</td>
<td>Coarse filter = 1 m/s</td>
</tr>
<tr>
<td>$d_{15 \text{ min}} / d_{15 \text{ max}}$</td>
<td>0.075 mm / 0.8 mm</td>
<td>3 mm / 8 mm</td>
<td>35 mm</td>
<td></td>
</tr>
<tr>
<td>$d_{60 \text{ max}}$</td>
<td>0.4 mm</td>
<td>4 mm</td>
<td>50 mm</td>
<td></td>
</tr>
<tr>
<td>$d_{85 \text{ max}}$</td>
<td>25 mm</td>
<td>3 mm / 8 mm</td>
<td>30 mm</td>
<td></td>
</tr>
<tr>
<td>$d_{90 \text{ max}}$</td>
<td>75 mm</td>
<td>70 mm</td>
<td>30 mm</td>
<td></td>
</tr>
<tr>
<td>$d_{100 \text{ max}}$</td>
<td>75 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure B.9 Grain size distribution of coarse and fine filter envelope for T-7 Tailings used in Chapter (5 and 6).

Reference:

Appendix B.8 Hydraulic conductivity tests on Silt, Tailings and Cyclone sands used in Chapter 4, 5 and 6.
Hydraulic conductivity of silt, tailings and underliners were measured in the same test cell at the same effective stresses applied during permeation tests to obtain \( k \) of the materials under the permeation test conditions.

- For the tailings, a 0.14 m thick graded granular filter (designed according to steps listed in Appendix B.7) was first placed at the bottom of the test cell. A 0.3 m thick layer of tailings slurry was then placed directly on top of the filter. The tailings layer was consolidated to the test effective stresses prior to application of a hydraulic head.

- Hydraulic conductivity tests on the foundation were conducted after termination of the permeation tests. First, the tailings and geomembrane from the permeation tests were replaced by a 0.3 m thick layer of washed pea gravel then the underliner was subjected to the maximum effective stress applied during the permeation phase of the experiment before applying a hydraulic head.

The measured \( k \) values of silt, tailings and underliners given in Figure B.10-12.
Figure B.10 Hydraulic conductivity of silt and tailings tested at 1500 kPa effective stress.
Figure B.11 Hydraulic conductivity of underliners tested at 1500 and 3000 kPa effective stress.
Hydraulic conductivity of T-7 tailings at different effective stresses

*Previous test at same effective stress - $1.2 \times 10^{-7}$ m/s

Figure B.12 Hydraulic conductivity of T-7 tailings at different effective stresses.
Appendix B.9 Prototype tests to observe wrinkle deformation and test perimeter seal.
Figure B.13 Prototype test (#1) conducted with saturated masonry sand on top of geomembrane wrinkle and tested under 250 kPa applied vertical pressure to observe wrinkle deformation. Note that the geomembrane wrinkle have regained part of its shape because there was no double sided tape placed below the geomembrane (tests with double sided tape below the wrinkle are described in Chapter 6).
Figure B.14 Prototype test (#2) conducted with saturated masonry sand on top of geomembrane wrinkle and tested under 250 kPa applied vertical pressure to observe wrinkle deformation. Note that the geomembrane wrinkle have regained part of its shape because there was no double sided tape placed below the geomembrane (tests with double sided tape below the wrinkle are described in Chapter 6).
Figure B.15 Prototype test (#3) conducted with saturated masonry sand on top of geomembrane wrinkle and tested under 250 kPa applied vertical pressure to observe wrinkle deformation. Note that the geomembrane wrinkle have regained part of its shape because there was no double sided tape placed below the geomembrane (tests with double sided tape below the wrinkle are described in Chapter 6).
Appendix B.10 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time for tests in Chapter 5.
Figure B.16 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time for Test 1A.
Figure B.17 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time for Test 1B.
Figure B.18 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time for Test 1C.
Figure B.19 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time for Test 1D.
Figure B.20 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time for Test 2.
Figure B.21 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time for Test 3.
Figure B.22 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time for Test 4.
Figure B.23 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time for Test 5.
Figure B.24 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time for Test 7.
Figure B.25 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time for Test 8.
Figure B.26 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time for Test 9.
Figure B.27 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time for Test 10.
Figure B.28 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time for Test 11.
Figure B.29 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time for Test 12.
Figure B.30 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time for Test 13.
Appendix B.11 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time for tests in Chapter 6.
Figure B.31 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time for Test W2.
Figure B.32 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time for Test W4.
Figure B.33 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, and (d) Measured flow versus time for Test W5.
Appendix B.12 Modelling of leakage through single hole in a geomembrane using SEEP/W.
The numerical model used in Chapters 4 and 5 was an axi-symmetric flow model generated using a finite element based software SEEP/W (GeoStudio 2012 version 8.0.10.6504). Axi-symmetric models were developed to simulate three-dimensional problems with symmetry along a vertical axis of rotation. This vertical axis passes through the centre of the geomembrane hole where present. SEEP/W was used because it is a well-recognized software for flow analysis through porous media.

The governing equation used in SEEP/W is,

\[
\frac{\partial}{\partial x} \left( k_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial h}{\partial y} \right) = \frac{\partial \theta}{\partial x}
\]

where \( h \) is the hydraulic head [L]; \( k_x, k_y \) the hydraulic conductivity in the x and y direction [LT\(^{-1}\)]; \( \theta \) the volumetric water content [-]. At fully saturated conditions and where \( k \) is isotropic (conditions assumed in this thesis), the equation can be rewritten as,

\[
\left( \frac{\partial^2 h}{\partial x^2} \right) + \left( \frac{\partial^2 h}{\partial y^2} \right) = 0
\]

A sensitivity analysis was performed to define the acceptable mesh refinement in a field-scale model (150 m thick, 150 m wide tailings layer on top of a 0.15 m thick foundation). It was found that the leakage measured was mainly affected by the element size. The examined mesh size ranged from a uniform global size of 4 m with 3733 three-noded elements to having a graded mesh with finer elements close to the geomembrane hole and getting coarser with distance away from the hole with a total of 87,675 three-noded elements. The minimum size of the elements in and around the circular hole was 0.5 mm to have at least two elements through the thickness of the 1 mm thick geomembrane. The maximum size of the elements was 15 m at the top and radial model boundaries. For the lab-model, the mesh distribution in the field-model within a vertical distance of 0.3 m and radial distance of 0.295 m from the centre of the geomembrane hole were kept same.
There are in total of 3639 three-noded elements in the lab model. Screen shot of the field scale model is shown in Figure B.34 and an area in and around the hole is shown in Figure B.35. Screen shot of the lab-model is shown in Figure B.36.

A sensitivity analysis of the effect of tailings on flow through geomembrane hole was performed for the base case examined in Chapter 5 (Table B.2). While keeping the $k$-underliner constant at $6.9 \times 10^{-7} \text{ m/s}$, the $k$-tailings were assigned values equal to the mean minus one standard deviation and mean minus two standard deviations. This would cover 95.45% of the band around the mean $k$-tailings. With the lowest $k$-tailings assigned globally, calculated flow through a 10-mm-diameter geomembrane hole was three times higher than the average and 2.6 times higher than the maximum measured flow in the laboratory. This indicates that the difference between predicted and calculated flow is due to more than uncertainty regarding the typical $k$-tailings due to larger applied vertical effective stresses. Additional discussion is included in Chapter 5.
Figure B.34 Finite element model showing refined mesh used for the field-scale analysis in Chapter 4 and 5.

Region isolated in Figure B.35.
Figure B.35 Region from Figure B.34 showing mesh distribution in and around a 10-mm-diameter hole in the geomembrane.
Figure B.36 SEEP/W model scaled to match the dimensions of the test cell used to conduct all laboratory tests.
Table B.2 Sensitivity analysis of the SEEP/W model for base case examined in Chapter 5.

<table>
<thead>
<tr>
<th>Independent measured $k$ of T-7 tailings (m/s)</th>
<th>Average (m/s)</th>
<th>Standard deviation (m/s)</th>
<th>Mean - 2 SD (m/s)</th>
<th>Mean - 1 SD (m/s)</th>
<th>Calculated flow using $k$ mean of the T-7 tailings and the average $k$ of UL-6 underliner (6.9x10$^{-7}$ m/s) (lpd)</th>
<th>Calculated flow using mean - 2xSD</th>
<th>Calculated flow using mean – 1x SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.5x10$^{-8}$</td>
<td>1.1x10$^{-7}$</td>
<td>1.3x10$^{-8}$</td>
<td>8.3x10$^{-8}$</td>
<td>9.6x10$^{-8}$</td>
<td>20.4</td>
<td>15.8</td>
<td>18</td>
</tr>
<tr>
<td>1.1x10$^{-7}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2x10$^{-7}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table B.3 Comparison of measured flow and calculated flow using SEEP/W for different tailings with same underliner UL-6 ($k = 6.9 \times 10^{-7} \text{ m/s}$) in Chapter 5.

<table>
<thead>
<tr>
<th>Tailings ($k$)</th>
<th>Test flow (lpd)</th>
<th>SEEP/W model flow (lpd)</th>
<th>Model flow/Test flow</th>
<th>Test flow normalized with the base case test flow</th>
<th>Model flow normalized with the base case model flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-8 ($2.9 \times 10^{-8} \text{ m/s}$)</td>
<td>0.5</td>
<td>2.1</td>
<td>4.1</td>
<td>0.10</td>
<td>0.09</td>
</tr>
<tr>
<td>T-7* ($\sim 1.1 \times 10^{-7} \text{ m/s}$)</td>
<td>5.2</td>
<td>20.4</td>
<td>3.9</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>T-6 ($1.6 \times 10^{-6} \text{ m/s}$)</td>
<td>7</td>
<td>124.0</td>
<td>17.7</td>
<td>1.35</td>
<td>6</td>
</tr>
</tbody>
</table>

* Base case.
Appendix B.13 Filter compatibility check for the nonwoven geotextile for use as a filter beneath T-7 tailings.
Geotextile properties:

Apparent opening size ($O_{95}$) = 0.15 mm (taken from manufacturer’s spec sheet)

Soil (tailings) properties:

$d_{85}$ = 0.43 mm

Linear coefficient of uniformity:

$$C'_{u} = \left( \frac{d'_{100}}{d'_{0}} \right)^{0.5}$$

$$= \left( \frac{0.7}{0.05} \right)^{0.5}$$

$$= 3.74$$

Giroud’s retention criteria for geotextile filters Giroud (1988):

For loose soil with $C'u \geq 3$ (worst case) $O_{95}$ must be less than:

$$O_{95} < \left( \frac{9 \times d_{85}}{C'_{u}^{1.7}} \right)$$

$$O_{95} < \left( \frac{9 \times 0.43}{3.74^{1.7}} \right)$$

0.15 < 0.41 True.

The Geotextile meets the filter requirement for the T-7 tailings.

Reference:

Appendix B.14 Report on the in-plane transmissivity flow measurement on virgin geotextile and geotextile exhumed from Test 11 in Chapter 5.
# ANALYSIS REPORT

**SCC Accreditation No.: 40‡**

<table>
<thead>
<tr>
<th>IDENTIFICATION:</th>
<th>Geotextile E-7G6L1 GTX 225/9/2014: Virgin, From the test cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Received:</td>
<td>December 19, 2014</td>
</tr>
</tbody>
</table>

| STANDARD:       | Determining the (In-plane) Hydraulic Transmissivity of a     |
|-----------------| Geosynthetic by Radial Flow                                  |
|                | ASTM D6574 - 13e1                                            |

<table>
<thead>
<tr>
<th>TEST CONDITIONS:</th>
<th>Temperature of the water (°C): 22</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D1: Inside diameter (mm): 50</td>
</tr>
<tr>
<td></td>
<td>D2: Outside diameter (mm): 300</td>
</tr>
<tr>
<td></td>
<td>Seating period: 15 minutes</td>
</tr>
<tr>
<td></td>
<td>Tested January 19 and 20, 2015</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RESULTS:</th>
<th>Individual Data</th>
<th>Avg.</th>
<th>S.D.</th>
<th>% CV</th>
</tr>
</thead>
</table>

### Virgin

<table>
<thead>
<tr>
<th>Gradient:</th>
<th>0.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal pressure:</td>
<td>200 kPa</td>
</tr>
<tr>
<td>Transmissivity (E-9 m:mm):</td>
<td>1.20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gradient:</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal pressure:</td>
<td>200 kPa</td>
</tr>
<tr>
<td>Transmissivity (E-9 m:mm):</td>
<td>1.24</td>
</tr>
</tbody>
</table>

### From the test cell

<table>
<thead>
<tr>
<th>Gradient:</th>
<th>0.1</th>
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</thead>
<tbody>
<tr>
<td>Normal pressure:</td>
<td>200 kPa</td>
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<tr>
<td>Transmissivity (E-9 m:mm):</td>
<td>0.47</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gradient:</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal pressure:</td>
<td>200 kPa</td>
</tr>
<tr>
<td>Transmissivity (E-9 m:mm):</td>
<td>0.43</td>
</tr>
</tbody>
</table>

---

Prepared by: [Signature]
Approved by: [Signature]

---

**For any information concerning this report, please contact Eric Bland**

The reports are identified by an alphanumeric code; the last character refers to the number of revisions; this is entered in ascending order. The samples in relation to this test are received for a period of 30 days following the expiration day of the written report, unless other instructions are received. The fees for all services after the tests are $125.00 per test and for appraisal is $195.00 per hour. The above reported results refer exclusively to the samples submitted for evaluation. This analysis report cannot be purveyed or reproduced, unless in whole, without CTT Group’s written consent. CTT Group is accredited by the SCC for specific tests as listed on www.scss.ca. For customer’s complete address, please refer to the front page.

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saqeco@cttq.com  www.cttq.com  1 877 288 8378  1 450 778 1870  Fax: 1 450 778 3901

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380
ANALYSIS REPORT
SCC Accreditation No.: 407

Mr Praboen Joshi
Queen's University

Date: January 21, 2015
Report: S492-015-78544A

<table>
<thead>
<tr>
<th>IDENTIFICATION:</th>
<th>Geotextile E-7G6L1 GTX 229/2014: Virgin, From the test cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Received:</td>
<td>December 19, 2014</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>STANDARD:</th>
<th>Determining the (In-plane) Hydraulic Transmissivity of a Geosynthetic by Radial Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEST:</td>
<td>ASTM D6674 - 13e1</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>REMARKS:</th>
<th>Mass per unit area of the &quot;Virgin&quot; sample, measured after the test: 588 g/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mass per unit area of the &quot;From the test cell&quot; sample, measured after the test: 1305 g/m²</td>
</tr>
<tr>
<td></td>
<td>See pictures in appendix.</td>
</tr>
</tbody>
</table>

Prepared by: Jonathan Trudel, Tech.

Approved by: Eric Blood, Eng., M.Sc.A.

Date: January 21, 2015

**For any information concerning this report, please contact Eric Blood**

The reports are identified by an alphanumeric code, the last character refers to the number of revisions; this is entered in ascending order. The samples in relation to this test are retained for a period of 30 days following the expedition day of the written report, unless other instructions are received. The fees for all services after the tests are $25.00 5 per hour and for appraisal in Court, $55.00 per hour. The above reported results refer exclusively to the sample submitted for evaluation. This analysis report cannot be copied, used or reproduced, written in whole, without CTT Group prior written consent. CTT Group is accredited by the SCC for specific tests as listed on www.scc.ca. For customer's complete address, please refer to the front page.

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sa.qc@cttca.com www.cttca.com 1 877 288-8378 1 450 778-1870 Fax: 1 450 778-3901

381
Appendix

Picture of the ‘virgin’ sample after the test

Picture of the ‘From the test file’ sample after the test
Appendix B.15 Tensile properties of the 1-mm-thick LLDPE geomembrane tested.
The tensile test was conducted in accordance to ASTM (2015). The geomembrane sample is type IV dog bone shaped sample of an overall length of 11.5 cm and width of the narrow section of 0.6 cm. A tensile testing machine of a constant rate-of cross-head-movement was used with a constant rate of elongation of 50 mm/min. Table B.4 and B.5 lists the stress-strain properties in machine and cross machine directions.

Table B.4 Tensile properties of 1-mm-thick LLDPE geomembrane in machine direction.

<table>
<thead>
<tr>
<th></th>
<th>σ_Y</th>
<th>ε_Y</th>
<th>σ_B</th>
<th>ε_B</th>
<th>h</th>
<th>b</th>
<th>A_0</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD1</td>
<td>12.2</td>
<td>7.1</td>
<td>33.2</td>
<td>570.4</td>
<td>1</td>
<td>6.25</td>
<td>6.25</td>
</tr>
<tr>
<td>MD2</td>
<td>12.5</td>
<td>8.4</td>
<td>39.1</td>
<td>668.5</td>
<td>1</td>
<td>6.25</td>
<td>6.25</td>
</tr>
<tr>
<td>MD3</td>
<td>12.3</td>
<td>7.5</td>
<td>33.0</td>
<td>626.1</td>
<td>1</td>
<td>6.25</td>
<td>6.25</td>
</tr>
<tr>
<td>MD4</td>
<td>12.0</td>
<td>7.0</td>
<td>37.9</td>
<td>651.0</td>
<td>1</td>
<td>6.25</td>
<td>6.25</td>
</tr>
<tr>
<td>MD5</td>
<td>12.1</td>
<td>7.5</td>
<td>33.7</td>
<td>549.9</td>
<td>1</td>
<td>6.25</td>
<td>6.25</td>
</tr>
<tr>
<td>x</td>
<td>12.2</td>
<td>7.4</td>
<td>35.7</td>
<td>619.3</td>
<td>1</td>
<td>6.25</td>
<td>6.25</td>
</tr>
<tr>
<td>s</td>
<td>0.2</td>
<td>0.6</td>
<td>2.7</td>
<td>48.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>v</td>
<td>1.6</td>
<td>7.5</td>
<td>7.5</td>
<td>7.8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table B.5 Tensile properties of 1-mm-thick LLDPE geomembrane in cross-machine direction.

<table>
<thead>
<tr>
<th></th>
<th>σ_Y</th>
<th>ε_Y</th>
<th>σ_B</th>
<th>ε_B</th>
<th>h</th>
<th>b</th>
<th>A_0</th>
</tr>
</thead>
<tbody>
<tr>
<td>XMD1</td>
<td>11.3</td>
<td>7.7</td>
<td>32.3</td>
<td>513.3</td>
<td>1</td>
<td>6.25</td>
<td>6.25</td>
</tr>
<tr>
<td>XMD2</td>
<td>12.0</td>
<td>7.5</td>
<td>39.2</td>
<td>664.6</td>
<td>1</td>
<td>6.25</td>
<td>6.25</td>
</tr>
<tr>
<td>XMD3</td>
<td>11.6</td>
<td>6.8</td>
<td>35.3</td>
<td>635.1</td>
<td>1</td>
<td>6.25</td>
<td>6.25</td>
</tr>
<tr>
<td>XMD4</td>
<td>12.2</td>
<td>6.9</td>
<td>32.9</td>
<td>540.6</td>
<td>1</td>
<td>6.25</td>
<td>6.25</td>
</tr>
<tr>
<td>XMD5</td>
<td>11.7</td>
<td>7.1</td>
<td>33.2</td>
<td>551.0</td>
<td>1</td>
<td>6.25</td>
<td>6.25</td>
</tr>
<tr>
<td>x</td>
<td>11.8</td>
<td>7.2</td>
<td>34.6</td>
<td>580.9</td>
<td>1</td>
<td>6.25</td>
<td>6.25</td>
</tr>
<tr>
<td>s</td>
<td>0.3</td>
<td>0.4</td>
<td>2.8</td>
<td>65.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>v</td>
<td>2.8</td>
<td>5.2</td>
<td>8.1</td>
<td>11.2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
References:

Appendix B.16 Specific gravity determination of T-6, T-7, T-8 and silt used in Chapter 4.
Table B.6 Specific gravity of T-7 tailings

<table>
<thead>
<tr>
<th></th>
<th>Flask 1</th>
<th>Flask 1</th>
<th>Flask 2</th>
<th>Flask 3</th>
<th>Flask 4</th>
<th>Flask 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of Dry Flask, g</td>
<td>189.18</td>
<td>189.18</td>
<td>186.26</td>
<td>182.92</td>
<td>181.30</td>
<td>189.10</td>
</tr>
<tr>
<td>Volume of Flask at Temp T, ml</td>
<td>497.59</td>
<td>497.59</td>
<td>497.58</td>
<td>497.50</td>
<td>497.57</td>
<td>497.47</td>
</tr>
<tr>
<td>Density of Water at Temp T g/ml</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>From Table 2, ASTM D854-14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass of Flask and Water at Test Temperature, T</td>
<td>687.29</td>
<td>687.29</td>
<td>684.36</td>
<td>680.93</td>
<td>679.38</td>
<td>687.09</td>
</tr>
<tr>
<td>Mass of Oven Dried Solids, Ms</td>
<td>97.29</td>
<td>102.85</td>
<td>101.20</td>
<td>100.52</td>
<td>100.10</td>
<td>100.04</td>
</tr>
<tr>
<td>Mass of Flask, Water and Soil Solids at Test Temperature</td>
<td>747.76</td>
<td>749.25</td>
<td>747.52</td>
<td>742.27</td>
<td>740.50</td>
<td>749.78</td>
</tr>
<tr>
<td>Specific Gravity of Soil Solids at the Test Temperature, T</td>
<td>= Gt =</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table B.7 Specific gravity of T-8 tailings

<table>
<thead>
<tr>
<th></th>
<th>Flask 1</th>
<th>Flask 2</th>
<th>Flask 3</th>
<th>Flask 4</th>
<th>Flask 5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature = 22.6 deg C</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass of Dry Flask, g</td>
<td>189.18</td>
<td>186.26</td>
<td>182.92</td>
<td>181.30</td>
<td>189.10</td>
</tr>
<tr>
<td>Volume of Flask at Temperature T, ml</td>
<td>497.59</td>
<td>497.58</td>
<td>497.50</td>
<td>497.57</td>
<td>497.47</td>
</tr>
<tr>
<td>Density of Water at Temperature, T g/ml</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>From Table 2, ASTM D854-14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass of Flask and Water at Test Temperature, T</td>
<td>687.29</td>
<td>684.36</td>
<td>680.93</td>
<td>679.38</td>
<td>687.09</td>
</tr>
<tr>
<td>Mass of Oven Dried Solids, Ms</td>
<td>101.68</td>
<td>102.63</td>
<td>102.73</td>
<td>100.02</td>
<td>100.01</td>
</tr>
<tr>
<td>Mass of Flask, Water and Soil Solids at Test Temperature</td>
<td>750.90</td>
<td>748.66</td>
<td>745.51</td>
<td>742.12</td>
<td>749.45</td>
</tr>
<tr>
<td>Specific Gravity of Soil Solids at the Test Temperature, T = Gt =</td>
<td>2.671</td>
<td>2.678</td>
<td>2.693</td>
<td>2.683</td>
<td>2.656</td>
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</tbody>
</table>

Table B.8 Specific gravity of T-6 tailings

<table>
<thead>
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<th>Flask 1</th>
<th>Flask 2</th>
<th>Flask 3</th>
<th>Flask 4</th>
<th>Flask 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of Dry Flask, g</td>
<td>189.18</td>
<td>186.26</td>
<td>182.92</td>
<td>181.30</td>
<td>189.10</td>
</tr>
<tr>
<td>Volume of Flask at Temp T, ml</td>
<td>497.59</td>
<td>497.58</td>
<td>497.50</td>
<td>497.57</td>
<td>497.47</td>
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<td>Density of Water at Temp, T g/ml</td>
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<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
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</tr>
<tr>
<td>Mass of Flask and Water at Test Temp, T</td>
<td>687.29</td>
<td>684.36</td>
<td>680.93</td>
<td>679.38</td>
<td>687.09</td>
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<tr>
<td>Mass of Oven Dried Solids, Ms</td>
<td>102.20</td>
<td>101.32</td>
<td>100.25</td>
<td>101.75</td>
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<td>Mass of Flask, Water and Soil Solids at Test Temp</td>
<td>750.89</td>
<td>748.46</td>
<td>743.63</td>
<td>743.36</td>
<td>751.54</td>
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<td>Specific Gravity of Soil Solids at the Test Temp, T = Gt = Average Std dev</td>
<td>2.648</td>
<td>2.722</td>
<td>2.670</td>
<td>2.694</td>
<td>2.686</td>
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### Table B.9 Specific gravity of silt used in Chapter 4.

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<td>Mass of Dry Flask, g</td>
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<td>Volume of Flask at T, ml</td>
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<td>Specific Gravity of Soil Solids at T</td>
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**Reference:**

Appendix B.17 Final density of tailings and underliner for tests in Chapter 5 and 6.
Table B.10 Average final density of tailings and underliner after permeation. Initial bulk density of tailings was ~ 1900 kg/m$^3$; initial dry density of underliner was ~ 1650 kg/m$^3$.

<table>
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<th>Test #</th>
<th>Test conditions</th>
<th>Permeation duration (days)</th>
<th>Average final bulk density (kg/m$^3$)</th>
<th>GMB</th>
<th>Protection</th>
<th>Hole dia. (mm)</th>
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<tr>
<td></td>
<td>T</td>
<td>UL</td>
<td>Applied Stress (kPa)</td>
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<td>UL</td>
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<tr>
<td>1A</td>
<td>T-7</td>
<td>UL-6</td>
<td>3000</td>
<td>1500</td>
<td>500</td>
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<td>1B</td>
<td>T-7</td>
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<td>1500</td>
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<td>1C</td>
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<td>UL-6</td>
<td>250</td>
<td>1000</td>
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<td>1D</td>
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<td>UL-6</td>
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<td>53</td>
</tr>
<tr>
<td>2</td>
<td>T-8</td>
<td>UL-6</td>
<td>250</td>
<td>50</td>
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<tr>
<td>3</td>
<td>T-6</td>
<td>UL-6</td>
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<td>4</td>
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<td>UL-7</td>
<td>2000</td>
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<td>6</td>
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<td>Pea gravel</td>
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<td>7</td>
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392
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<td>23</td>
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<td></td>
<td>1-mm-LLDPE On top of GMB</td>
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<td>12</td>
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<td>Pea gravel</td>
<td>250</td>
<td>200</td>
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<tr>
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<td>1500</td>
<td>1500</td>
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</tr>
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Appendix B.18 Conference paper Joshi et al. 2014.
A new laboratory apparatus for testing geomembrane leakage with mine tailings under large earth and fluid pressures

Prabeen Joshi, Richard W.I. Brachman & R. Kerry Rowe
GeoEngineering Centre at Queen’s–RMC, Queen’s University
Kingston, Ontario, Canada

ABSTRACT
The design and development of a new high-pressure apparatus that is capable of simulating large effective stresses on a geomembrane liner is presented. The system is intended to be used for studying leakage from defects in geomembrane liners in large mine tailings application or dams. Results from a prototype test conducted on silty sand with a geomembrane with circular hole and finite element seepage analysis of the test is presented. Preliminary observations show that the apparatus is able to simulate the field conditions extremely well.

RÉSUMÉ
La conception et le développement d’un nouveau système d’application de haute pression pour simuler les grandes contraintes effectives subies par une géomembrane est présenté. Le système est destiné à être utilisé pour étudier les fuites liées à l’existence de défauts dans les géomembranes utilisées comme étanchéité dans les applications de stockage de résidus miniers de grande hauteur ou les barrages. Le résultat d’un essai de prototypage réalisé sur du sable limoneux avec une géomembrane présentant un défaut circulaire et une analyse par éléments finis de l’écoulement dans le test sont également présentés. Des observations préliminaires indiquent que le système est capable d’extrêmement bien simuler les conditions de terrain.

1. INTRODUCTION
Geomembranes can be very effective at controlling leakage for environmental containment where the escape of fluid under a hydraulic gradient is limited to flow through holes in the geomembrane. In municipal solid waste (MSW) landfills, there is typically a very highly permeable material above the geomembrane as a drainage layer (which limits the head acting on the liner) and a very low permeability, $k$, material below the geomembrane (e.g., a geosynthetic clay liner or a compacted clay liner) to limit leakage.
through any holes in the geomembrane, Figure 1.

![Diagram of Geomembrane Hole](image)

Figure 1 Geomembrane hole in a typical municipal solid waste landfill configuration.

Geomembranes have the potential to be used to greatly limit leakage of fluids from tailings storage facilities. Relative to MSW landfills, in many tailings containment applications (Figure 2): the vertical stress acting on the liner can be much higher (possibly affecting both $k$ and interface transmissivity, $\theta$), the pore pressures acting on the liner can be much, much higher (with an increased hydraulic gradient and possible migration of fines with the high local seepage stresses), the hydraulic conductivity of the material above the geomembrane (i.e. tailings) is much lower (providing greater resistance to flow above the hole), and the hydraulic conductivity of the material below the geomembrane (i.e. engineered foundation layer) is not as low (providing less resistance to flow below the hole). However, the net effect of these differences on the resulting leakage for tailing applications is unknown. Measurements of leakage are required from experiments conducted under potentially high total stresses and high pore pressures.

The objective of this paper is to report on the development of a new laboratory apparatus for testing geomembrane leakage for mine tailing applications under large earth and fluid pressures. The boundary conditions of the apparatus and experimental procedures are described. Results from prototype test with silty sand above and below a 1-mm-thick linear low density geomembrane (LLDPE) geomembrane with a 10-mm-diameter hole are presented to illustrate its use at a total applied vertical stress of 3000 kPa and applied pore pressure of 1500 kPa.

2. Laboratory apparatus

2.1 Boundary conditions

The laboratory apparatus adapted for measurement of leakage through geomembrane holes under high pressures is a cylindrical test cell with an inner diameter of 590 mm and height of 500 mm. It was originally developed by Brachman and Gudina.
(2002) to study the physical response of geosynthetic liners and was later used by Gudina and Brachman (2006) to simulate the physical response of geomembrane wrinkles under high pressures. It was also used to quantify local geomembrane strains for municipal solid waste (MSW) landfill applications by Brachman and Gudina (2008) and Dickinson and Brachman (2008) and mining heap leach pads by Rowe et al. (2013) and Brachman et al. (2014). A cross section of the test cell with the new pressure application system designed for this study is shown in Figure 3. Total vertical stress is applied using hydraulic pressure on a rubber bladder. The maximum vertical stress that can be applied is 3000 kPa. For a soil of unit weight 20 kN/m³, 3000 kPa corresponds to a total vertical stress at a burial depth of 150 m. Horizontal stresses corresponding to zero lateral strain conditions (i.e., $K_o$) are developed by having negligible outward deflection of the cell wall. Friction treatment is placed along the inner wall of the cell to reduce sidewall friction (Figure 4). The friction treatment consists of two layers of 0.1 mm thick polyethylene sheets that are lubricated with a layer of high temperature grease. Tognon et al. (1999) showed that friction treatment reduces the side wall friction to less than 5°. For the dimensions of the test cell used in this study and with interface friction of 5°, Brachman and Gudina (2002) calculated more than 95% of the total stress applied on top acting at the elevation of the geomembrane.
Figure 3 Schematic of the test system
Pore pressures are applied by pressurizing the fluid in a thin (0.05 m thick) saturated layer of sand between the bladder and a 0.3-m-thick layer of tailings. Since the head loss is expected to be localized around the small hole in the geomembrane, having distances of 0.3 m above the hole and nearly 0.3 m radially to the lateral boundaries should provide a reasonable physical simulation of flow. Results from preliminary finite-element seepage analysis shown in Figure 5 support that head loss is local and concentrated around the hole. Since radially symmetric, results are shown along a vertical plane for one-half of the cell (where \( r = 0 \) is along the centre and \( z = 0 \) is along the base of the cell). These results were obtained for the dimensions of the apparatus with a prescribed total head of 150.3 m along the top surface (i.e. along \( z = 0.45 \) m), a prescribed total head of 0 along \( z = 0 \) and \( r = 0.05 \) m to simulate the bottom drainage port in the cell, and all other perimeter boundaries modelled as zero flow boundaries. From the bottom-up, the model included: a 0.06 m thick geonet (\( k = 0.5 \) m/s), a 0.04 m thick geotextile (\( k = 5.7 \times 10^{-3} \) m/s), a 0.14 m thick underliner layer (\( k = 2.2 \times 10^{-9} \) m/s), a 1mm thick LLDPE with a 10 mm diameter hole, and a 0.3 m thick overliner (\( k = 2.2 \times 10^{-9} \) m/s). For this particular case, 97% of the head loss occurs within a radial zone 10-times the hole radius (i.e., within 50mm; Figure 5). Post-test finite-element seepage analysis will be conducted following leakage experiments with actual tailings to further quantify the effect of the distance to the upper prescribed total head and lateral zero flow boundaries.

2.2 Procedure

For a typical test setup, a saturated geonet-geotextile drainage composite is first placed at the bottom of the apparatus to get a uniform known head as a bottom boundary condition. An underliner (0.14 m) is then placed and compacted at to a target initial dry density (with the intent to simulate a firm engineered foundation layer beneath the geomembrane). The underliner is saturated from below. A layer of geomembrane with a circular defect of diameter 1.5, 10 or 20 mm at its centre is placed on top of the underliner. Two different types of geomembrane commonly used as liners in containment facilities, high-density and linear-low-density polyethylene (HDPE

399
and LLDPE) will initially be tested. Further, to study an effect of thickness of geomembrane, 1 and 2 mm thick geomembrane of both types will be tested.

To prevent any sidewall leakage between the edge of the geomembrane and the cell, a hydraulic seal made out of layers of dry and wet sodium bentonite is applied. The seal is separated from the tailings on top by a layer of 0.1 mm thick polyethylene sheet (Figure 4 b). After placing and sealing the geomembrane, the 0.3 m thick layer of tailings is then placed. In these simulations, it was decided to place the tailings as a slurry and then consolidate them to a desired effective stress prior to permeation. Another geonet-geotextile drainage composite is placed on top of the tailings, to serve as an upper drainage boundary during consolidation and to assist with apply a uniform distribution of head on top of the tailings, followed by a sand layer. Access to the sand layer, for either injecting or removing fluid, is through existing ports near the middle of the apparatus. These ports permit removal of entrapped air from the system to ensure complete saturation (Figure 3). Air is purged after set-up and before starting each test. After purging, the soil layers are consolidated by applying desired total stress. During consolidation, the tailings are allowed to drain to the sand above, while the underliner is allowed to drain through the bottom of the apparatus. Following the consolidation stage, both total stress and pore pressure are then increased to achieve the desired effective stress. The permeation phase would then start and leakage is measured.

A data acquisition system to monitor and record the pressures in real time is included in the setup. The pump pressure, total stress, and pore pressure is monitored using pressure transducers and dial gauges that are fully calibrated to the range of stresses to be applied. An online monitoring system is also developed to remotely monitor the tests.
3. Prototype test

A prototype test was conducted to verify the ability of the new pressure application system and experimental procedures to permit a physical simulation of leakage through holes in a geomembrane with low permeability soil both above and below the geomembrane. It was conducted not with tailings, but with a silty sand on top and bottom of an LLDPE geomembrane. This soil consisted of 3% medium sand, 62% fine sand and 35% non-plastic silt by mass. The geomembrane was 1 mm thick and had a 10 mm hole located at the centre.

An underliner (0.14 m thick) was prepared by compacting the silty sand in three lifts to achieve an initial dry density of 1.83 kg/m³ at a moisture content of 11% (both corresponding to its Standard Proctor maximum dry density). The underliner was then provided with water from below (via the
port in the bottom of the cell) using a reservoir with water head at the top level of the subgrade to increase its initial degree of saturation. The volume of water required to saturate the underliner was recorded and found to be comparable with the volume of water required to achieve saturation of the underliner. The silty sand selected for the prototype test had lower hydraulic conductivity than the underliner and the typical tailings materials that will be subsequently used in this study. After preparation of the perimeter seal and placement of friction treatment, the overliner (0.3 m thick) was mixed as slurry at 25% gravimetric water content was placed on top of the geomembrane liner. During the consolidation stage, total stress was applied at an incremental rate of 200 kPa per day for first 7 days with a final increment of 100 kPa to reach a total stress of 1500 kPa (Figure 6a). Consolidated water was collected separately from the permeant collection system at the bottom of the cell and from the drainage port at the top of the overliner for a period of 24 ± 4 hours for each increment of total stress which are plotted in Figure 6d. Once consolidated to total vertical stress of 1500 kPa, total stress was increased to 3000 kPa and simultaneously a hydraulic head of 150 m (1500 kPa) was applied on top of the overliner keeping the effective stress constant at 1500 kPa.
Figure 6 Plots of: (a) Applied vertical stress, (b) Applied pore pressure, (c) Effective stress, (d) Cumulative Consolidated water, and (e) Measured flow versus Time
The new pressure application system reached a steady total stress and pore pressure within 1 hr after application of target pressures. The applied bladder and pore pressures were maintained to be within ± 30 kPa of the target pressures for the last 5 days of the prototype test (i.e., within 1% and 0.5% of the target total vertical and pore pressures). Subsequent revisions to the pressure application system (including upgrades to the pump and a manifold system that permits up to three simultaneous tests) increased the precision to less than ± 20 kPa. The permeation stage was run for 17 days. The measured average flow rate for the last 5 days of permeation was 0.26 L/day.

After termination of the test, careful observations were made. The settlement of the consolidated overliner was uniform at 4 cm across the top surface. This shows that the side wall friction treatment was effective at reducing boundary friction, even at the high pressures tested. There was no evidence of preferential flow from side wall. The bentonite used at the perimeter seal was well consolidated. The powdered dye that was sprinkled between the bentonite and thin plastic cover was neither dissolved nor washed out suggesting there was no direct contact of moisture with the perimeter seal.

SUMMARY
The development of a new laboratory apparatus for testing geomembrane leakage for mine tailing applications under large earth and fluid pressures was reported. The boundary conditions of the 0.59-m-diameter and 0.5-m-high apparatus were described and experimental procedures were detailed. Results from prototype test with silty sand above and below a 1-mm-thick LLDPE geomembrane with a 10-mm-diameter hole were presented to illustrate its use at a total applied vertical stress of 3000 kPa and applied pore pressure of 1500 kPa. Additional experiments are underway to quantify the leakage rates with tailings.

Acknowledgements
This work was funded by the Natural Sciences and Engineering Research Council of Canada through a Collaborative Research and Development Grants in partnership with Klohn Crippen Berger Ltd. The apparatus was developed with funding from the Canada Foundation for Innovation.

REFERENCES


Appendix B.19 Whole rock analysis and water chemistry of tailings used in Chapter 5 and 6.
Table B.11 Whole rock analysis results.

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*Loss on ignition.
Table B.12 Fresh and aged tailings supernatant analyses – coarse fraction.

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<td>Conductivity</td>
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<td>38</td>
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<tr>
<td>Hg</td>
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<td></td>
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<tr>
<td>Ag</td>
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<td>&lt; 0.00003</td>
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<td>0.0027</td>
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<td>0.101</td>
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<td></td>
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<td>0.035</td>
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<td>0.00009</td>
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<td>36.3</td>
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<td>0.000044</td>
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<tr>
<td>Co</td>
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<td>0.004</td>
<td>0.000469</td>
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<tr>
<td>Cr</td>
<td>mg/L</td>
<td>0.009 {Cr(III)}</td>
<td>0.0005</td>
<td>0.0009</td>
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<tr>
<td>Cu</td>
<td>mg/L</td>
<td>0.008 (3)</td>
<td>0.0023</td>
<td>0.0058</td>
</tr>
<tr>
<td>Fe</td>
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<td>0.01</td>
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<td>K</td>
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<td>12.8</td>
<td>17.8</td>
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<tr>
<td>Li</td>
<td>mg/L</td>
<td></td>
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<tr>
<td>Mg</td>
<td>mg/L</td>
<td></td>
<td>9.56</td>
<td>12.7</td>
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<tr>
<td>Mn</td>
<td>mg/L</td>
<td>1.5 (3)</td>
<td>0.0435</td>
<td>0.004</td>
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<td>Mo</td>
<td>mg/L</td>
<td>1</td>
<td>0.0362</td>
<td>0.063</td>
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<tr>
<td>Na</td>
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<td></td>
<td>35.4</td>
<td>33.8</td>
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<tr>
<td>Ni</td>
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<td>0.15m</td>
<td>0.006</td>
<td>0.0023</td>
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<tr>
<td>Pb</td>
<td>mg/L</td>
<td>0.20 (3)</td>
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<td>0.00014</td>
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408
<table>
<thead>
<tr>
<th>Sb</th>
<th>mg/L</th>
<th>0.02</th>
<th>0.0049</th>
<th>0.0051</th>
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<tr>
<td>Se</td>
<td>mg/L</td>
<td>0.002</td>
<td>&lt; 0.001</td>
<td>0.001</td>
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</table>
Appendix C

Force generated upon drying a GCL
Appendix C.1 Method.
- Standard used: Modified ASTM 6768.
- All tests conducted in x-roll direction.
- GCL specimen obtained from a hydrating GCL panel for 15 days under 2 kPa.
- Procedure involves gripping hydrated GCL specimens in a tensile testing machine and allow the specimens to dry.
- The gripped specimens are allowed to dry at a constant temperature of 22 degree Celsius and relative humidity of ~50%. The grips had no displacement with time.
- Recording interval was 8 seconds.

Figure C.1 Schematic of the test setup with a GCL sample.
**Installation:**

- Take the mass of the specimen.
- Attach the specimen to the upper grip of the tensile testing machine.
- Note the load generated due to the self-weight of the specimen.
- Grip the specimen on the bottom grip with minimum slack.
- Relax the pre-tensioning caused due to the gripping by adjusting the gauge length to match the recorded load generated due to self-weight of the specimen (max change required was 0.1 mm).
- Report the final gauge length (usually less than the initial).
- Allow the test to run till it meets the termination criteria (e.g., complete drying, load approaching to the dry mass of the specimen etc...).
- Remove specimen. Take measurements (% moisture, x-ray, etc...).

**Termination criteria:**

The first test was not terminated until there was not any significant change in the load within last 24 hours. Replicates were terminated when the calculated final load was achieved. Moisture content of the samples (placed next to the drying specimen) was measured daily. When the moisture content is close to the dry (off the roll) moisture content, it suggests that there will be not further significant shrinkage hence the test could be terminated.
Appendix C.2 Test results.
Table C.1 Summary of the test results.

<table>
<thead>
<tr>
<th>GCL*</th>
<th>1</th>
<th>100</th>
<th>100</th>
<th>100</th>
<th>100</th>
<th>200</th>
<th>500</th>
<th>800</th>
<th>100</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauge length (mm)</td>
<td>100</td>
<td>100</td>
<td>200</td>
<td>500</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>100</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Width (mm)</td>
<td>100</td>
<td>100</td>
<td>500</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>100</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Actual force (max.) (N)</td>
<td>51</td>
<td>37.5</td>
<td>84.2</td>
<td>252.5</td>
<td>129.6</td>
<td>157.5</td>
<td>135.2</td>
<td>163.3</td>
<td>141.3</td>
<td>39</td>
</tr>
<tr>
<td>Force (N/m)</td>
<td>510</td>
<td>375</td>
<td>401</td>
<td>418.5</td>
<td>421</td>
<td>505</td>
<td>647.8</td>
<td>787.5</td>
<td>676</td>
<td>816.5</td>
</tr>
</tbody>
</table>

* Refer to Chapter 2 and 3 for GCL properties.
Drying stress of virgin GCL1

100 mm gauge length 100 mm wide

Figure C.2 Stress generated upon drying virgin GCL1.
Drying stress of virgin GCL2

100 mm gauge length 100 mm wide

Figure C.3 Stress generated upon drying virgin GCL2.
Drying stress of virgin GCL2

100 mm gauge length 200 mm wide

Test 1 - Max: 83.7 N
Test 2 - Max: 84.2 N

Figure C.4 Stress generated upon drying virgin GCL2.
Drying stress of virgin GCL2

200 mm gauge length 200 mm wide

Test 1 - Max: 129.6 N
Test 2 - Max: 157.5 N

Figure C.5 Stress generated upon drying virgin GCL2.
Drying stress of virgin GCL2

800 mm gauge length 200 mm wide

![Graph showing stress generated upon drying virgin GCL2.](image)

Test 1 - Max: 141.3 N
Test 2 - Max: 163.3 N

Figure C.6 Stress generated upon drying virgin GCL2.
Drying stress of virgin GCL2

100 mm gauge length 500 mm wide

Test 1 - Max:252.5 N
Cyclic test
Moisture Content:
First cycle - 120%
All other cycles - 60%

Figure C.7 Stress generated upon drying virgin GCL2.
Drying stress of virgin GCL2

500 mm gauge length 200 mm wide

Test 1 - Max: 135.2 N

Figure C.8 Stress generated upon drying virgin GCL2.
Drying stress of virgin GCL2

Effect of width and gauge length

Dimension of the GCL sample in mm (gauge length x width)

100 x 100
100 x 200
100 x 500
200 x 200
500 x 200
800 x 200

Measured load per unit length (N/m)

200
400
600
800
1000

Figure C.9 Load vs. specimen dimension for GCL2.
Drying stress of virgin GCL3

100 mm gauge length 100 mm wide

Figure C.10 Stress generated upon drying virgin GCL3.
Drying stress of virgin GCL4

100 mm gauge length 100 mm wide

Test 1 - Max: 33 N
Test 2 - Max: 34.7 N
Test 3 - Max: 37 N

Cyclic test

Moisture Content:
First cycle - 210%
All other cycles - 80%

Figure C.11 Stress generated upon drying virgin GCL4.