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Abstract

Geosynthetic clay liners play a major role in optimising the hydraulic performance of today's barrier systems. Numerous research has been carried out to evaluate and enhance hydraulic performance of GCLs. However, there are still challenges in maintaining consistent performance at roll overlaps. This paper reviews the studies conducted to determine the liquid flow mechanism through the overlap, methodologies developed to assess the hydraulic performance and also how different factors affect the performance at the overlap. The preferential flow at the overlapping seam has been identified as a critical factor affecting the hydraulic performance and an emphasis on understanding the mechanism of the liquid flow is identified as important. Hence, the necessity of research to quantify the horizontal (transverse) flow in the overlap region is brought into discussion. A new development proposes a potential experimental and numerical method to quantify the preferential flow and factors affecting it in the overlapping region of GCLs.

Notation

V_t total volume of flow through GCL specimen for a time duration (m^3)

A_t area of the entire seamed or unseamed GCL specimen (m^2)

q_u vertical flow rate per unit area of unseamed GCL specimen (m^3/ m^2/s)

L_s total length of the seam (m)

q_p preferential flow rate per unit length of seam (m^3/ m^2/s)

Δt time interval during which the flow is measured (s)

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Introduction

Geosynthetic clay liner (GCL) is a geosynthetic product engineered to be used as a hydraulic barrier for water retention systems, waste containment facilities and mining applications reducing the cost of conventional material usage and providing better performance (EPA, 2001; Rowe, 1998; Benson et al., 2005; Daniel, 2012). It consists of a prefabricated layer of impermeable material typically bentonite supported by a geomembrane or incorporated between two layers of woven/ non-woven geotextile or geomembrane varying on the type of application. While the geotextiles or the geomembrane offer the capacity and strength to withhold loading, the low permeability and high swelling capacity of bentonite will act as a perfect hydraulic barrier in the field.

As the number of applications of GCL has advanced, the quality of the GCL product has improved to provide a more consistent and uniform product for industry. However many challenges are faced due to separation of panels on side slopes, separation of panels due to shrinkage resulting from temperature variations, punctures and wrinkles, installation faults, lack of performance or insufficient supplemental bentonite, liner design faults etc.(Müller and Wöhlecke, 2017; Thiel and Richardson, 2005; Fox et al., 1998). The research study carried out by Buckley, Gates and Gibbs (2012) clearly illustrated how the performance of GCLs vary depending on the application and environmental conditions; referring to GCL samples exhumed from different regions of Australia which has a diverse range of climatic conditions. As a result, researchers began to investigate the critical issues in manufacturing and installation which resulted in these failures (Rowe, 2014). Laboratory-scale permeameter cell testing and flow box model testing conducted today were developed as an outcome of these extensive research work. It was significant from these studies that the GCL panels struggle to maintain the optimum hydraulic performance expected at its overlaps (Mazzieri and Di Emidio, 2015; Rowe, Quigley and Petrov, 1997; Daniel, Trautwein and Goswami, 1997; Rowe, Brachman and Joshi, 2016; Egloffstein et al., 2012; Xiong, Gui and Ma, 2009).

In the research study carried out by Benson et al. in 2004, on a GCL sample exhumed from a lagoon, the flow box test results indicated that the applied dye primarily passes through the overlap area of the GCL indicating that its preferential flow is through the overlap (Benson, Jo and Abichou, 2004). Cooley and Daniel also observed and identified large flow rates collected through the overlaps intentionally made to be faulty compared to the non-overlapped portions of the GCL using the tank developed to measure the seam performance (Cooley and Daniel, 1995; Daniel, Trautwein and Goswami, 1997). Many large scale model tests and laboratory level element tests were also carried out to highlight and validate this shortcoming, the leakage or permeation at the GCL overlap (Daniel and Estornell, 1992; Benson, Jo and Abichou, 2004). Research confirms that the liquid flow at the GCL overlap is the main restraining factor which affects the product's ability to maintain the expected level of hydraulic conductivity in the field. Based on the observations from the field tests and the experimental results obtained from the model tests, the effectiveness of the overlaps is identified, and to some extent depends on the method of manufacture, overlap seam specifications and most importantly its performance criteria (Rowe, 2012). This paper focuses on research studies conducted on the important area of GCL overlap that is of interest to industry; how well the

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efficacy of the GCL overlap condition affects the performance of the overall product as a hydraulic barrier and provides future research directions on GCL overlap.

Liquid flow mechanisms

Research has been carried out to identify the flow rate passing through the overlap and to determine its hydraulic conductivity using flow box tests and permeameter cell tests (both model tests and element tests), but no specific analysis was carried out in these research to recognize the preferential flow mechanism at the overlap.(Daniel and Estornell, 1992; Mazzieri and Di Emidio, 2015; Daniel, Trautwein and Goswami, 1997; Parastar et al., 2017).

However, as research related to the overlap advanced, the flow rate collected from the experimental results was divided by the cross-sectional area to provide a hydraulic flux value which was easily comparable with the conventional hydraulic conductivity value. It was also identified that the hydraulic conductivity in the transverse direction differs from the hydraulic conductivity in the vertical direction because the transverse direction contains a geotextile-bentonite interface that vastly differs from the reinforced bentonite layer in the vertical direction (Kendall and Austin, 2014).

In a further study on the GCL overlap and the effect of the permeant liquid to the level of permeation through the seam, a coloured dye was introduced to identify the liquid flow mechanism at the overlapping section. Results as shown in the Figure 1 clearly depicted that a horizontal flow was preferred by the liquids than the vertical flow. (Mazzieri and Di Emidio, 2015)

Attempts to obtain a mathematical solution for the flow rate through the overlap of GCL have been made considering the transmissive flow of water and the effect of hydration at the seam. (Giroud, Thiel and Kavazanjian, 2004; Harpur, Wilson-Fahmy and Koerner, 1993; Chai et al., 2016; Malusis et al., 2018) Most of this research were related to a circular defect on the geomembrane laid on top of the GCL and the transmissive flow through the layers resulting from it (Mendes et al., 2010; Bannour et al., 2013; Bannour and Touze Foltz, 2014; Barroso et al., 2006; Müller and Wöhlecke, 2017; Timothy, 2017). However, no study was carried out to analyse the mechanism of the flow at the overlap. Athanassopoulos (2013) established a mathematical relationship between the vertical and horizontal flows at the overlap using a subgrade stone protrusion cell. In his study, he developed an empirical formula to include both the horizontal and vertical flows in the flow rate through the overlap seam (Figure 2).

The total flow through a seamed GCL specimen is developed in his study in Equation 1;

$$V_t = (A_t * q_u + L_s * q_p)\Delta t \tag{1}$$

where,

V_t= total volume of flow through GCL specimen for a time duration (m^3)

A_t=area of the entire seamed or unseamed GCL specimen (m^2)

q_u= vertical flow rate per unit area of unseamed GCL specimen (m^3/ m^2/s)

L_s= total length of the seam (m)

q_p= preferential flow rate per unit length of seam (m^3/ m^2/s)

Δt = time interval during which the flow is measured (s)

This study also concluded that the flow through a seamed GCL is slightly higher than the unseamed GCL depicting its horizontal direction flow.

Additional research specifying the measurement of preferential liquid flow through the GCL overlap could help address the failures occurring in the field.

Experimental and numerical techniques for assessing hydraulic performance of GCL overlap

The necessity to produce a consistent cost-effective product to the industry has encouraged researchers to study the hydraulic performance of GCLs since mid-1980s continuously, in order to improve the GCL manufacturing techniques and product chemistry.

Field testing

Samples of GCL were exhumed from the field in order to observe the leakages resulting in the failure of performance of the product using different field instruments such as lysimeters and infiltrometers.(Edil, Benson and Foose, 2001; Benson, Jo and Abichou, 2004; Rowe, 2012; Touze-Foltz, 2010; Benson et al., 2007; Rowe et al., 2017). Benson et al. (2004) describes one such field test carried out using sealed double ring infiltrometers (SDRIs) using the method described in ASTM D5093. The need for a laboratory method to study this research perspective became critical.

Element testing to replicate the field condition – development of the permeameter cell

The most common apparatus that was used to test hydraulic conductivity of saturated porous materials are permeameter cells. Various research was conducted using different types of permeameters to test GCLs which advanced into the flexible wall permeameter used today.(Cooley and Daniel, 1995; Petrov and Rowe, 1997; Salemi et al., 2016; Heyer, 1995; Garcin et al., 1995; Daniel and Estornell, 1992; Robert J. Petrov, 1997). With the development of research on permeability of GCLs ASTM Committee D35 released a standard to measure the rate of flow through GCLs, "Standard Test Method for Measurement of Index Flux through Saturated Geosynthetic Clay Liner Specimens using a Flexible Wall Permeameter". (ASTM, 2009)

However, no specific standard has been developed to test the overlapping condition of the geosynthetic clay liner. Researchers have adopted the general standard according to their own preferences across different research. For example, Mazzieri, et al. (2015) has placed an overlap area of the GCL for permeameter cell testing as per Figure 3 while Kendall and Austin (2014) have used two full layers of GCL overlapped on top of each other for testing. The former replicated a smaller scale of the actual field condition but the results were highly affected by the edge effects as the sample is comparatively small. In contrast, in Kendall and Austin (2014) method although the edge effect is reduced due to the full width seam, only the vertical flow at the overlap is represented by this method. The horizontal flow is neglected. An attempt to develop a separate permeameter test for the horizontal flow has been made by Kendall and Austin (2014), but it has not been validated.

These drawbacks have arisen from the lack of an established standard to test GCL overlaps and highlights the importance of research in this study area. In addition, the shortcomings of element testing in laboratory conditions shows the importance of a standard model test to replicate the field conditions to measure the performance of a Geo-synthetic clay liner.

Model testing – GCL flow box

Estornell and Daniel attempted to determine the hydraulic performance using a steel tank (Figure 4) which overcame many of the above discussed issues. Later, several other researchers modified the tank to evaluate many environmental concerns such as wet-dry cycles, freeze-thaw effect etc. These tanks were able to test large specimens of GCL which replicated the field condition. (Daniel, Trautwein and Goswami, 1997).

However, these tanks were not practically convenient as the sizes were very large and were not able to move, plus needed a lot of space and also could not test samples at higher compressive stresses. Cooley and Daniel developed a smaller acrylic tank specifically to test GCL overlaps but it was again limited to very low compressive stresses and created variable overlap widths due to its circular cross section.

Daniel, Trautwein and Goswami (1997) developed a new acrylic apparatus named GCL flow box to accommodate full width seams and high confining stresses. The setup and scale of device however requires a long time period of several months for experimental work. (Kendall and Austin, 2014) This is the current method and is often used to test hydraulic performance at the overlap.

Development of a numerical model

Several research studies on attempts to develop a numerical model using Finite Element

Modelling has been conducted to establish a methodology to validate the experimental results on hydraulic performance of the GCL overlap seam. However, most of this research was based on modelling of a common circular defect and the hydraulic flow through the hole/circular space or due to diffusion (Edil, Benson and Foose, 2001; Ghorbani, El-Zein and Airey, 2018; Bharat, 2014; Santhosh and Babu, 2014). Though equations and models were developed, it did not serve the actual scenario at the GCL overlap seam where the flow is identified as horizontal preferential flow.

Mathieu, Nassar and Didier (2004) introduced a Finite Element model using an FEM software called EAUSOL to simulate the nature of liquid flow and determine the effect of hydraulic head on permeability using a flow box test. This software has allowed the authors to vary the test conditions in the simulated flow box model to observe the effect of these changes to the hydraulic conductivity through the GCL overlap. No other specific studies conducted in this regard was identified in the past decade which could be due to the complications associated with simulation of experimental results related to the GCL overlap.

Factors affecting the hydraulic performance of the overlap

With the identification of the liquid flow mechanism through an overlap condition and development of methodology to assess the flow through the GCL overlap, the importance of a further step to identify the parameters which affect the liquid flow passing through the seam is identified. In the present context, considerable research has been conducted and continues to recognize and evaluate the effect of such parameters in order to improve the performance of the GCL overlap by addressing these limitations.

Type of GCL and properties of bentonite

Four types of GCLs ; adhesive bonded bentonite to upper and lower geotextiles, stitch bonded GCL, needle-punched GCL and adhesive bonded bentonite to an upper geomembrane layer have been in use for the past few decades (Kong et al., 2017; Xiong, Gui and Ma, 2009). The needle- punched GCL was identified by researchers to be the most effective, in minimising swell due to its fibre properties producing a significantly lower bulk void ratio than the fibre-free products. (Rowe, Quigley and Petrov, 1997; Lake and Rowe, 2000; Mazzieri and Di Emidio, 2015; Parastar et al., 2017).

Improvements to the GCL product such as application of modified bentonites in GCLs are also being investigated to improve the hydraulic performance as an effective barrier system.(Gitipour et al., 2015; Lee and Shackelford Charles, 2005; Koerner, 2013; Di Emidio et al., 2017; Bohnhoff et al., 2013; Scalia et al., 2014; Hosney and Rowe, 2017; Amadi and Alih, 2017; Parsa et al., 2018) Increases in hydraulic conductivity normally are associated with pore water conditions that contribute to diminish osmotic swelling in the interlayer of the montmorillonite mineral.(Shackelford et al., 2000; Jo et al., 2001; Scalia and Benson, 2011; Jo et al., 2005; Kong et al., 2017; Mazzieri and Di Emidio, 2015; Pirrion et al., 2012). These irreversible reactions occur at both low and high pH due to strong disequilibrium conditions and will also result in reduction of the self-seaming ability allowing water to permeate through the overlap seam. (Benson, Ören and Gates, 2010) Many factors such as duration of permeation, electrical conductivity, pH value, particle size distribution, concentration of permeant, prehydration effect have been investigated to measure the effect on the hydraulic

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performance of the GCL.(Jo et al., 2001; Shackelford et al., 2000; Jo et al., 2005; Malusis and Shackelford, 2002; Razakamanantsoa, Djeran-Maigre and Barast, 2016; Malusis, Kang and Shackelford, 2015)

However, the effect of these modifications to the GCL product and supplemental bentonite applied at the overlap needs to be examined independently from this research perspective. (Scalia et al., 2014; Gates, 2011).

Length of overlap and amount of supplemental bentonite at the overlap seam

The overlap length is a critical factor that affects the permeation of water through the overlap as less overlap length has resulted in separation of panels due to shrinkage as well as leakage of liquid through the joints (Thiel, 2006). The overlap length is varied between 75mm to 300mm with different types of bentonite adhesions. Several studies have identified that 300mm of overlap is conservatively sufficient to minimise the permeability of liquid flow at the seam to match the performance of the GCL itself. But it did not confirm a permanent bonding to restrict permeation at the overlap as the joint is not sealed. Addition of a supplementary amount of bentonite at the overlap was then experimented with comparison to a GCL overlap with no bentonite (Figure 5) (Rowe, Brachman and Joshi, 2016). Research identified that bentonite addition gave a significant reduction in permeation. (Cooley and Daniel, 1995; Rowe, 2012; Benson, Jo and Abichou, 2004).

These studies recognized that the amount of bentonite supplementarily added will allow reduction of the overlap length even up to 75mm by restraining the liquid flow using its own permeable characteristics and self-seaming ability.(Brachman et al.; Egloffstein et al., 2012;

Rowe, Brachman and Joshi, 2016; Yang et al., 2015) An extensive number of laboratory experiments have been carried out changing the two factors (overlap and amount of bentonite) to verify the fact that increase in overlap length and amount of bentonite resulting in a self-seam of the product, does reduce the permeability through the overlap (Yang et al., 2015; Egloffstein et al., 2012; Rowe, Brachman and Joshi, 2016; Benson, Jo and Abichou, 2004; Rowe, Brachman and Take, 2017).

The amount of bentonite and the method of adhesion of bentonite is still undergoing research; granular bentonite, piled bentonite, powdered bentonite, adhesive paste of bentonite are some of the research trials carried out in the past to get an optimum hydraulic performance at the overlap (Egloffstein et al., 2012; Abuel-Naga, Bouazza and Gates, 2013; Seiphoori et al., 2016).

Investigation using bentonite powder needled into the cover geotextile and overlap sealed by bentonite paste in the manufacturing stage was another method carried out in field conditions by industry experts to compare the improvement in performance (Kendall and Buckley, 2014).

Identification of best combination of overlap length and supplemental bentonite at a given GCL overlapping condition is therefore still open for debate.

Temperature effect

Exposure to air and sunlight due to insufficient cover in the early stages of a GCL application combined with the cationic exchange in the fresh bentonite layer going through the daily hydration-desiccation/wet-dry cycles lead to the formation of irreversible cracks and

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deformations in the GCL product (Pirrion et al., 2012; Touze-Foltz, 2010; Touze-Foltz et al., 2016; Podgorney and Bennett, 2006; Ghorbani, El-Zein and Airey, 2018). The desiccation effect combined with ion exchange results in irreversible damages to the geosynthetic product as it therefore would not re-swell to such a level that the GCL gains its original structure and is able to regain the expected low permeability level.(Touze-Foltz, 2010; Benson and Stephen, 2009; GRI, 2013; Koerner and Koerner, 2005; Egloffstein, 2001; Guyonnet et al., 2005; Bradshaw and Benson, 2014; Malusis and Shackelford, 2002)

The separated GCLs are observed to have a relatively high as-manufactured moisture content from 20-45%. This is to augment the additional moisture uptake, under the geomembrane exposed to sunlight (Koerner and Koerner, 2005). It has been measured in field that the increase in temperature may rise up to 70^{0}C on black geomembranes placed above GCLs. At the same time, the natural matric suction of bentonite in the GCL will draw moisture from the subgrade where the rate of suction will be site specific and depend on subgrade moisture conditions. Further, the uneven distribution of bentonite contributes to preferential flow paths when the bentonite dries and cracks (Bostwick et al., 2010). All these reasons lead to shrinkage of the GCL panel leading to panel separation (Figure 6). The magnitude of wetting and drying cycles, hence magnitude of shrinkage is therefore observed to vary substantially at different sites, different exposures and different time periods (Thiel, 2006; Rowe, Brachman and Take, 2017).

According to laboratory tests conducted by Koerner, et al. (2005), both the bentonite and geotextiles may shrink at 110^0 C, but at 60^{0}C only bentonite is involved in the shrinkage. This represents a maximum overlap loss of 93mm for a typical GCL roll width of 4.4m where the underlying soil would not be exposed even at a minimum overlap of 150mm (Koerner and Koerner, 2005). Egloffstein (1995) suggests that even a calcium concentration of 0.00000025M to 0.015M in pore water could result in cationic exchange of Na to Ca providing damage to the Bentonite seam by desiccation particularly in drier regions(Lin and Benson, 2000). Hence, it was identified that a combination of several mechanisms are involved in this shrinkage process (Koerner and Koerner, 2005). The reduction in the practical self-seaming ability of a GCL due to these effects will allow preferential flow of leachates to pass through the overlap seam. The alternative of improving bentonite mineral as a sealant itself should also be discussed as a topic for further research and resolution (Egloffstein, 2001).

Effect of confining load

The most common effect of panel shrinkage is due to wet-dry cycles taking place especially in cases of exposed GCLs, where the material attempts to move at the GCL seam where a shear force is generated. This tends to decrease the conventional non-bonded overlap distance or tends to breach the bentonite bond at the overlap seam and therefore result in gaps between adjacent panels (GRI, 2015).

On the other hand, in different applications of GCL, different types of loading may occur on top of the GCL product. For example, loading of leachate will increase the confining pressure on the GCL layer in a municipal land fill application. Experiments have been carried out to study the effect of variation of different overburden pressures and head effects with different GCL products, different amounts of bentonite on the overlap and different overlap widths. (Yang et al., 2015) Research has identified that bentonite hydraulic conductivity at the overlap seam reduces significantly on increase in confining pressure resulting from overburden pressure (Giroud, Thiel and Kavazanjian, 2004; Rowe, Quigley and Petrov, 1997).

Analysis has been carried out on how the impact of low, intermediate and high confining stresses affect the hydraulic conductivity of a given GCL product. A range of results for lower confining stresses lesser than 30 kPa were collected using flow box test results along with permeameter cell results in a varied stress region from low figures around 10 to 30 kPa to high pressure values up to more than 250 kPa as shown in Figure 7. (Bouazza, 2002)

The importance of recognising the effect of confining stress in controlling the advective flow through GCLs is continually being discussed in literature. The reduction in permeability of GCLs is attributed to lower bulk void ratios in GCLs and hence lower bentonite void ratios resulting from higher confining stresses.(Rowe, Quigley and Petrov, 1997; Bouazza, 2002) A better understanding on how to achieve the optimum confining load required to self-seam the overlap of a GCL barrier given the variable environmental conditions needs to be therefore established.

Association of GCL with a geomembrane – wrinkle effect

Studies conducted on deformations of the geomembranes associated with geosynthetic clay liners demonstrate changes in hydraulic characteristics at the joints of the GCL, especially with the presence of wrinkles on the material (Yang et al., 2015). Experiments have been carried out to quantify deformations of geomembrane wrinkles near overlaps in the underlying GCL when subjected to overburden pressure (Gudina et al., 2011).

It is identified that the loading on the geomembrane has an effect in the generation of wrinkles with time. The performance of the GCL overlap when it is parallel to or in line with a wrinkle depended on the width of the GCL seam relative to the deformed wrinkle (Figure 8). When overlap width of the seam was greater than the wrinkle when in line with the seam, there was no evidence of preferential flow observed. The flow through the GCL seam is most affected when perpendicular to a wrinkle. The presence and distribution method of bentonite, whether the powder is piled or the adhesive is applied uniformly also was identified to have an effect on the preferential flow. The adhesive bentonite showed a higher resistance to water flow than the piled bentonite in these research results.(Giroud, Thiel and Kavazanjian, 2004; Rowe, Brachman and Joshi, 2016; Joshi, Brachman Richard and Rowe, 2017; Prabeen, Kerry and I., 2017; Joshi, Rowe and Brachman, 2018). Research needs to be carried out on how to minimise the effect of wrinkles on the geomembrane at the GCL overlaps using optimal design considerations.

Implications for further research

Extensive research identifying the failure in maintaining the hydraulic performance at the geosynthetic clay liner overlap validates the importance of recognizing how to overcome the effects of failures occurring due to installation and development stages of a landfill design (Cooley and Daniel, 1995; Rowe, Brachman and Joshi, 2016; Yang et al., 2015; Daniel, Trautwein and Goswami, 1997; Kendall and Buckley, 2014; Rowe, Quigley and Petrov, 1997). This paper highlights several areas of research which could to be explored further to improve the overlap performance.

1. A clear understanding of the liquid flow mechanism through the GCL overlap seam needs to be identified. Although much research has been carried out to identify the liquid flow rate through the separated seam, the mechanism of liquid flow has not been taken into consideration. With the mathematical identification of a possible preferential flow in the horizontal direction in addition to the vertical flow, a possible research direction is to understand the impact of the ratio between the two flows; vertical and horizontal on hydraulic conductivity at the overlap seam.
2. Considering the standard method to test geosynthetic clay liners, the necessity of developing a specific element test method to measure hydraulic conductivity through the GCL overlap is recognized. Although different element and model tests have been carried out using different assumptions and environmental conditions, no standard method has been adopted to measure the liquid flow through the overlap seam. A new experimental method separating the horizontal and vertical flows through the GCL overlap seam using a flexible wall permeameter could be developed.
3. A possible relationship could then be developed for comparison of the element and model tests. Further enhancing the analysis, a numerical model could be developed replicating the overlapping condition incorporating vertical as well as horizontal flow direction in order to validate the experimental results.
4. Once the liquid flow mechanism is identified and a standard method for testing GCL overlaps is established, different factors affecting the GCL overlap hydraulic performance could be analysed separately using Finite element analysis modelling.

The need of a numerical model to simulate different field conditions is therefore recognised as important.

5. Develop new modified bentonite powders or pastes to be applied at the overlap seams to reduce the liquid flow passing through. The best combination of overlap length and supplemental bentonite at a given overlapping condition, given the different environmental conditions such as temperature, confining load etc. need to be analysed.
6. Considering the various environmental conditions affecting the GCL overlap failures, the temperature effect, confining load and the wrinkle effect were the most significant factors identified. Once an understanding of the horizontal flow is identified, both element and model tests could be carried out to identify the variation of hydraulic performance through the GCL overlap with the variation of each of these effects. The variation increase in temperature and wet-dry cycles, the confining load and both of these effects on developing wrinkles on the geomembranes on top of the seam could then be analysed to achieve a possible optimum arrangement for the GCL overlap

The improvement of the performance of GCL overlaps using the described developments of overlap length, supplemental bentonite and its characteristics can be used to reduce the effect of these environmental conditions occurring due to failure in proper installation and construction of liners. A better understanding of the liquid flow at the overlap seam can therefore be sought for the combination of these factors, allowing engineers to have better confidence in their barrier designs. The implications for the overlapping condition will hence allow the industry to achieve the best performance for a given specific GCL product. The

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major environmental concerns of contamination risk will be addressed and the reduction of material and rehabilitation costs will bring about major economic savings for the GCL industry.

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Figure 1. Test on GCL overlap permeated with NSW: (a) Schematic of interface flow through the overlap during dye-assisted permeation with rhodamine (b) image of the outlet filter paper stained with rhodamine. (Mazzieri and Di Emidio, 2015)

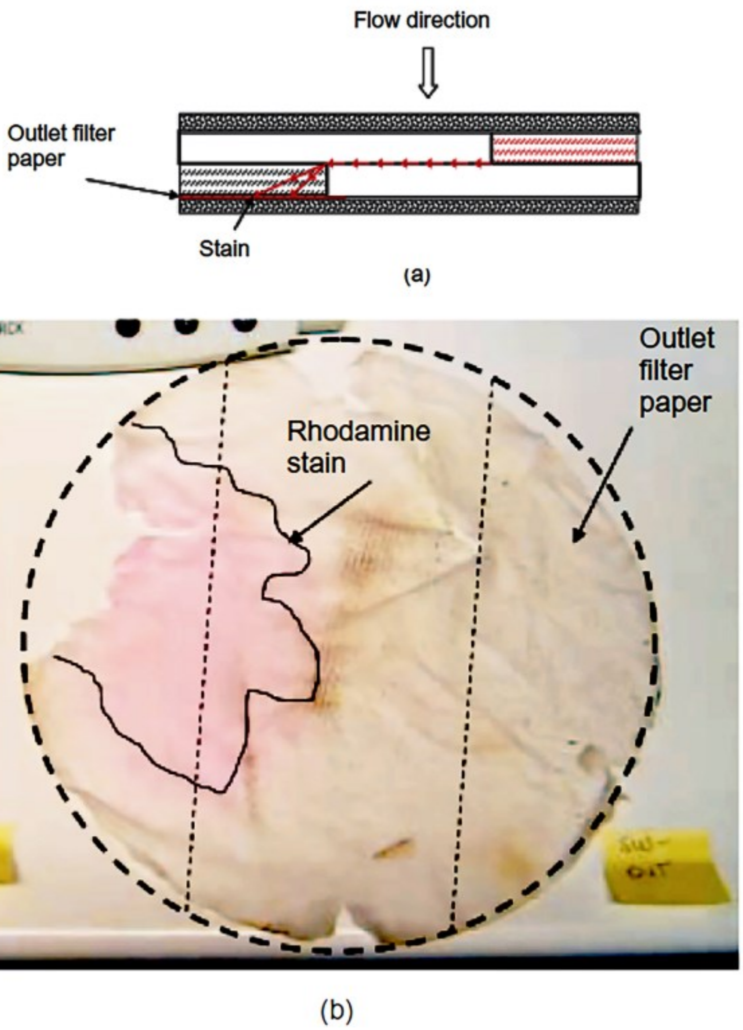

Figure 2. Schematic of preferential flow through GCL seam

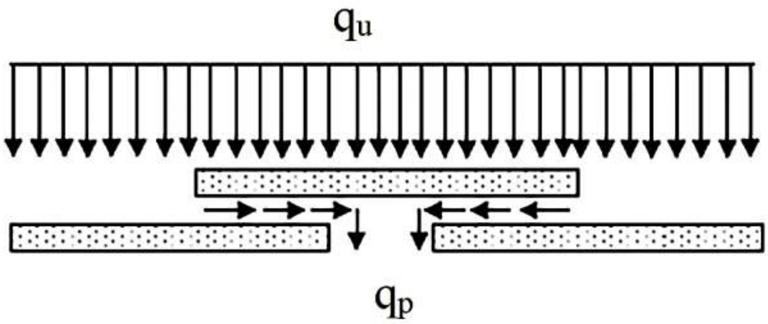

Figure 3. (a) A medium Scale flexible wall permeameter (b) Layout of permeability test on overlap seam (Mazzieri and Di Emidio, 2015)

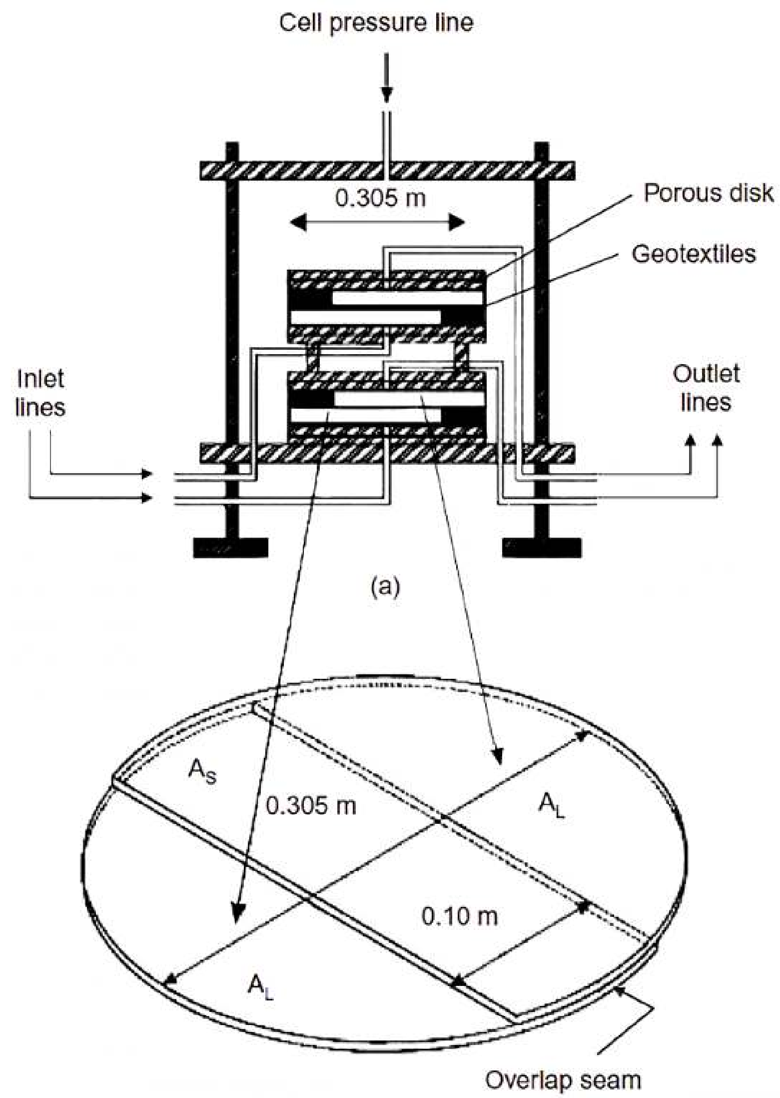

Figure 4. Tank used by Estornell and Daniel (Daniel, Trautwein and Goswami, 1997)

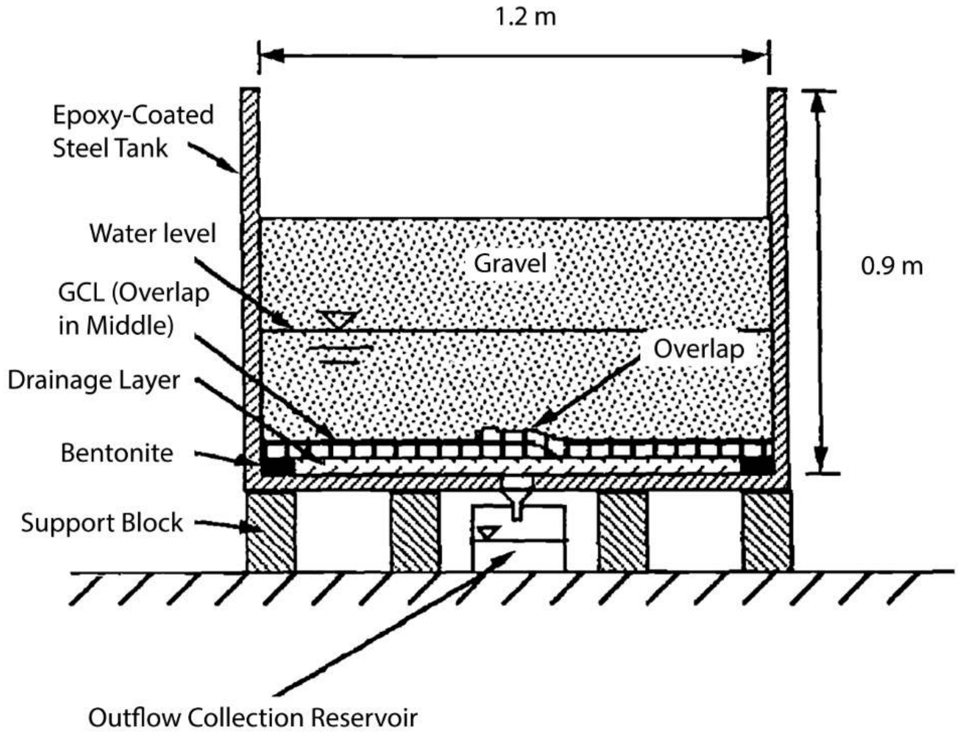

Figure 5. Reduction in flow due to the presence of supplemental bentonite at the seam of the GCL in perpendicular case with 150 mm wide seams tested in 0.59-m test cell (Rowe, Brachman and Joshi, 2016)

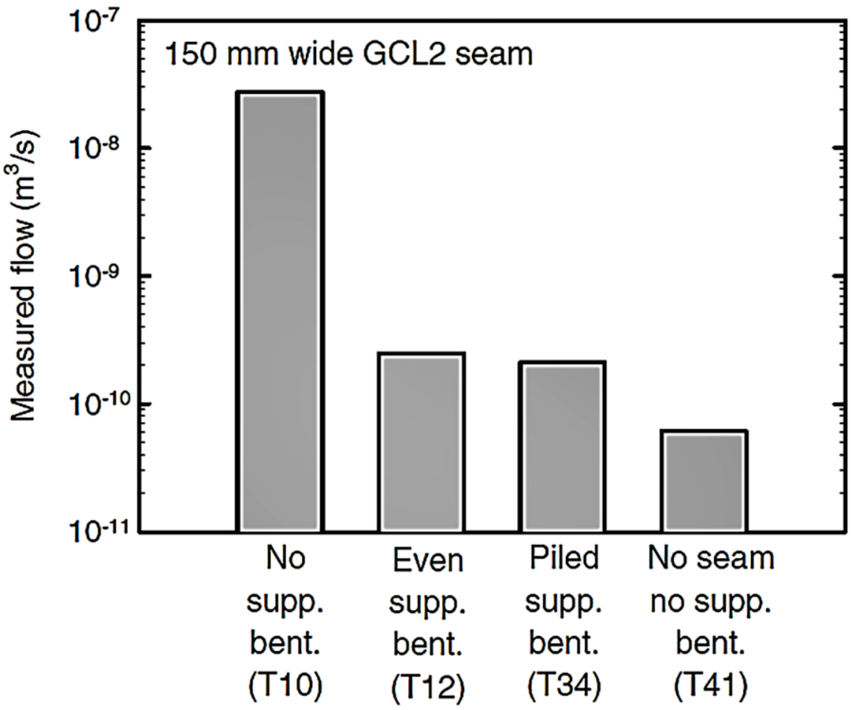

Figure 6. Photograph showing gap in GCL panels after removal of geomembrane (Thiel and Richardson, 2005)

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Figure 7. Variation of hydraulic conductivity versus confining stress (Bouazza, 2002)

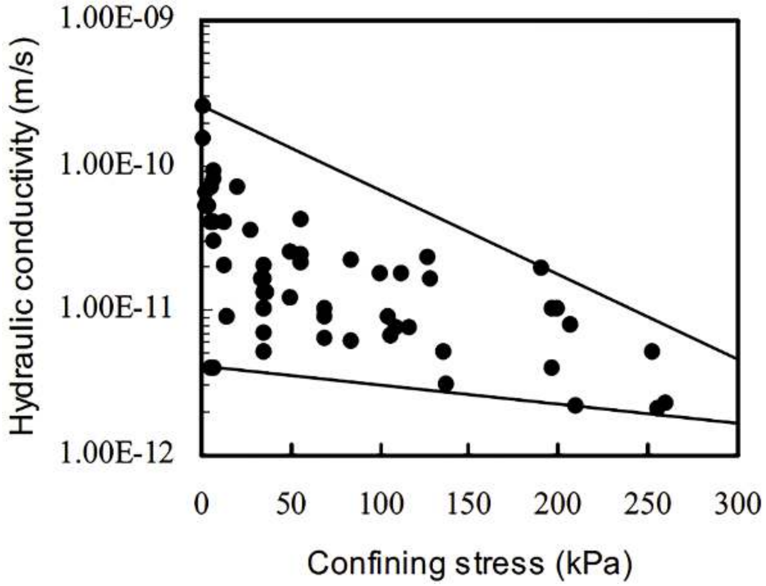

Figure 8. Cross section showing geomembrane wrinkle and overlapped GCL seam: (a) wrinkle on top and parallel to GCL seam; (b) wrinkle perpendicular to GCL seam (Rowe, Brachman and Joshi, 2016)