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Liquid Flow Mechanism at a Geosynthetic Clay-Liner Overlap

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ABSTRACT

Geosynthetic clay liners (GCL) perform a significant role in hydraulic barrier applications such as waste and liquid containment structures in geotechnical engineering. Although continuous research is carried out to evaluate and enhance the hydraulic performance of the geosynthetic clay liners, it has been identified that GCL overlaps still struggle to maintain this optimum level of performance which can be attributed to many factors. This paper presents a study conducted on identifying the mechanism of liquid flow at the GCL overlap. A numerical model of the model-scale flow box test was developed in SEEP/w software where the material properties were input using element scale permeameter cell test results. The flow rate obtained from the model was then compared with the flow rate of the actual flow box test. It was identified that the element scale cell tests did not capture the horizontal preferential flow through the GCL overlap; hence, created a gap between the results.

INTRODUCTION

Geosynthetic clay liners are presently used as a substitute for composite liner applications in waste and liquid containment structures especially as a hydraulic barrier to reduce contamination in soil and groundwater aquifers. Continuous research is being carried out to evaluate and enhance the hydraulic performance of the GCLs where a standard laboratory testing method has already been established to test GCL hydraulic conductivity (ASTM D5887). As a result, a high quality barrier product of hydraulic conductivity ranging from 1×10^{-11} to 1×10^{-12} m/s is being produced by industry at present. However, instances occur where the product has failed in maintaining the developed optimum level of hydraulic conductivity at its seam where the GCL panels are overlapped, after being installed in the field.

The importance of studying the hydraulic performance of the product at its overlapping condition has been recognized by researchers. Insufficient overlap length, insufficient supplemental bentonite applied, installation faults, temperature effect, confining load etc. are some of the identified reasons affecting the hydraulic performance at the overlap region. (Cooley et al., 1995; Rowe et al., 2016; Rowe et al., 1997; Thiel et al., 2005; Yang et al., 2015) Limited research has been carried out to identify the mechanism of flow through this GCL overlap. This research is needed in order to provide a solution for the performance failure in line with the factors affecting it.

Cooley and Daniel were two of the pioneers who researched the GCL seam performance. They developed a large 1 m × 1 m tank in the laboratory model test scale to artificially create an overlap and observed large flow rates passing through the overlaps compared to the non-overlapped portions of the GCL (Daniel et al., 1997). This model test named "Flow box" is able to replicate a model-scale sample of GCL overlaps. Researchers such as Estornel and Daniel (Daniel, 1997) and Mazzieri et al. (2015) conducted several attempts to replicate this overlap condition in the element scale permeameter cells specified in the standard element test method ASTM D5887 (ASTM, 2009) used for GCL hydraulic performance testing. These attempts failed due to the edge effects that were encountered due to the small and circular cross-section which could not incorporate a full overlap seam width. The effect of overlap length and the supplemental bentonite applied at the overlap seam was also looked into in literature as a major component affecting the liquid flow through the GCL overlap. (Benson et al., 2004; Rowe, 2012; Rowe, et al., 2016; Yang, et al., 2015)

However, as reflected from the GCL overlap sample with Rhodamine dye injected in Mazzieri, et al. (2015)'s study it was identified that there is preferable horizontal flow over the vertical flow at the overlapping seam of a GCL which needs to be studied further. Attempts to obtain a mathematical solution for the flow rate through the overlap of GCL were made time to time considering the transmissive flow of water and the effect of hydration at the seam (Giroud et al., 2004; Harpur et al., 1993; Parastar et al., 2017). Athanassopoulos (2013) developed an empirical relationship between the vertical and horizontal flows at the overlap using a subgrade stone protrusion cell.

The total flow through a seamed GCL specimen is developed in this study as follows;

$$V_t = (A_t * q_u + L_s * q_p)\Delta t$$

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 the flow in the horizontal direction at the overlap.

Kendall (2014) further observed that the hydraulic conductivity in the transverse direction differs from the hydraulic conductivity in the vertical direction because the transverse direction contains a fibre-bentonite interface that vastly differs from the reinforced bentonite layer in the vertical direction (Kendall et al., 2014).

Even though the horizontal flow at the GCL overlap seam was identified and the flow rates passing through the overlap has been tested, no research has been carried out to identify and measure the liquid flow mechanism at this point. The standard ASTM D5887 method only specifies tests for general hydraulic conductivity tests on GCLs. 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 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, 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) in the same research study, but was not clearly validated.

As a next step in finding a solution, Mathieu et al. (2004) modelled the flow box test using EAUSOL software and attempted to identify the flow path at the GCL overlap seam using the vector directions of the water flow. However, that is the only study where an attempt to use numerical modelling to solve this issue has occurred.

The lack of clear understanding on the liquid flow mechanism and a standard measurement technique on quantifying the preferential flow through the GCL overlap seam has brought in the importance of this research study into focus. This paper reports on how the liquid flow mechanism at the geosynthetic clay liner overlap could be determined combining the use of laboratory scale experimentation and numerical modelling techniques.

MATERIALS AND METHOD

The Geosynthetic clay liner samples contains powdered bentonite sandwiched between a non-woven cover geotextile (270g/m^2) and a woven carrier geotextile (110 g/m^2), made from polypropelene and were bonded by needle-punching. The major mineral component in the bentonite is montmorillonite mineral (70% smectite approximately) as determined by X-ray diffraction. (QUT CARF laboratory testing)

Laboratory Testing

A series of model tests were carried out using a large scale model box of 0.5m × 1m × 1m dimensions quite similar to the “Flow Box” developed by Daniel (1997). Permeability tests are conducted for a series of standard GCL overlap samples with supplemental bentonite applied at the seam along with a baseline GCL experiment. The model box was confined with 300mm of stone (approximately 6 kPa effective confining stress) and a hydraulic head of 3.5m. Another set of element scale tests are carried out to validate the flow box results using the standard permeameter cell specified in ASTM D5887. The standard permeameter cell is a 100mm diameter circular cell given an effective confining stress of 27.5kPa and the same hydraulic head of 3.5m. Figure 1 shows a schematic representation of the two element and model scale setups used for this study.

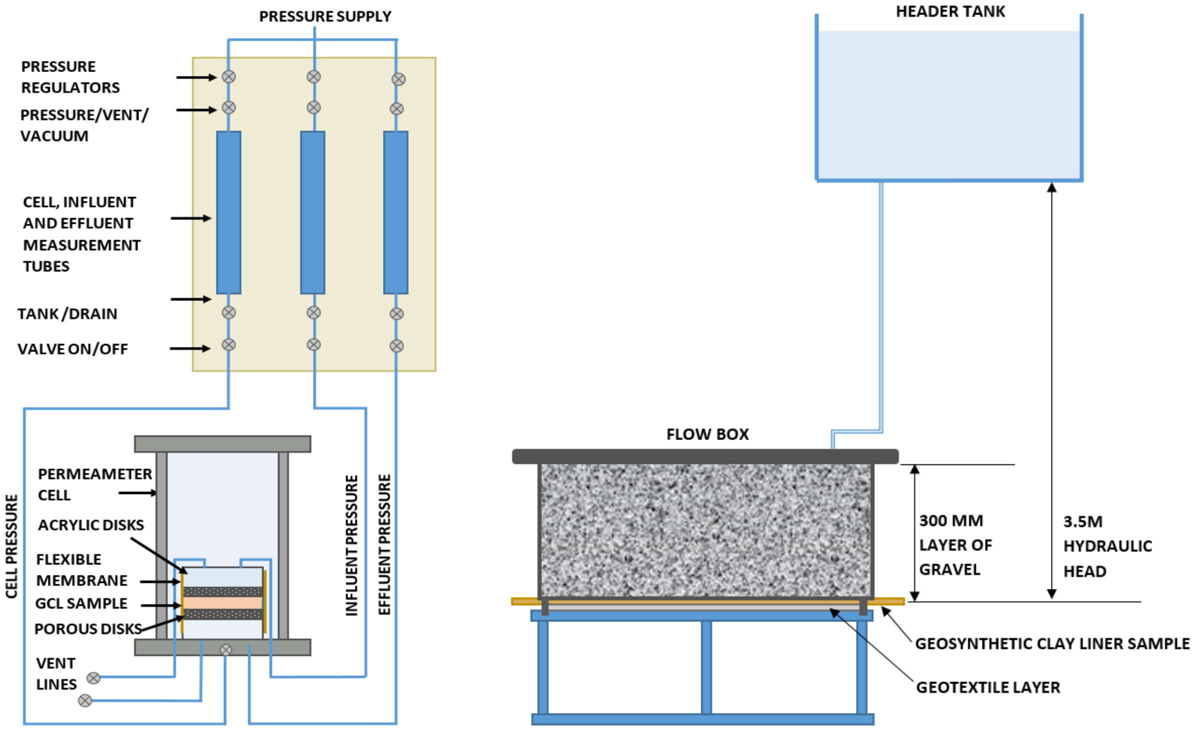

Figure 1 – (i) Element Scale – Standard Permeameter cell test (ii) Model Scale – Large

The numerical model was developed for the GCL overlap based on the same laboratory conditions applied for the model-scale flow box. The cross-section of 0.5 m width was hence illustrated in the model with the bentonite impregnated 300mm GCL overlap with a hydrated bentonite thickness of 12 mm obtained from the actual flow box test results. The GCL overlap was first modelled with an interface layer of bentonite between the two GCLs, which clearly illustrated the preferential flow through the overlap seam when a higher conductivity is input as a material property for the interface (Figure 2).

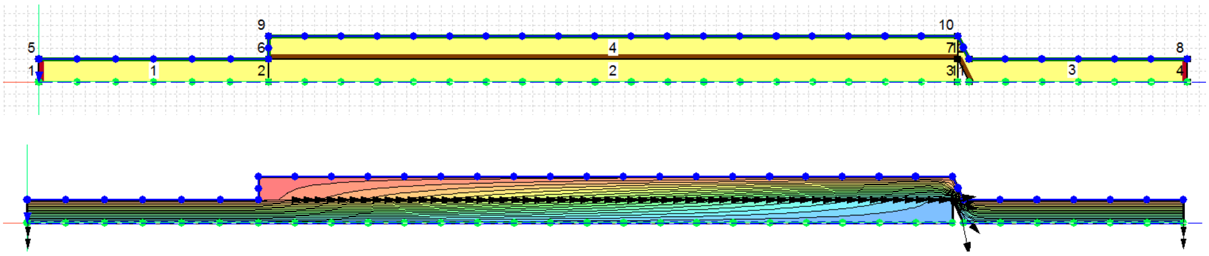

Figure 2 – GCL cross-section modelled with an interface layer of supplemental bentonite

However, this model could not be used as the hydraulic conductivity through the supplemental bentonite impregnated onto the overlap which is replicated by the interface could not be separately measured in the laboratory scale. Further, even though the overlap could be tested in the flow box, there was no standard test method to measure the hydraulic performance of the GCL overlap in the element scale permeameter cell to be compared with for FE model validation.

In order to validate the model with experimental data, the cross section of an overlap was divided into two areas for analysis. The two areas that were considered are illustrated in

Figure 3. Hydraulic conductivity tests were carried out first for the single layer of GCL (Section 01) and then two layers of GCLs cut from an overlap area to replicate the overlapping condition (Section 02) in the permeameter cell setup.

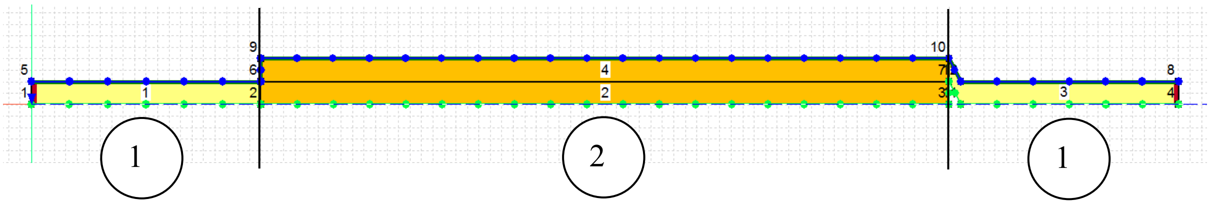

Figure 3 – The GCL overlap model for flow box showing 3 sections for comparison with element scale permeameter cell test results

The results of the two element level tests were used as the input material properties for the numerical model developed in the SEEP/w analysis for the GCL overlap. The flowrate derived from the numerical study was then compared with the actual flow rate measured by the actual flow box overlap test for analysis.

RESULTS AND DISCUSSION

Model-scale testing

The flow box and the permeameter cells were setup under laboratory conditions as shown in Figure 4.

Figure 4 – Laboratory test setups; (i) Model scale Flow box setup (ii) Element scale Permeameter cell setup

Firstly a standard overlap hydraulic conductivity test was carried out using the flow box. The standard overlap consisted of 300mm overlap of two GCL sheets with supplemental bentonite impregnated onto it on the overlap seam area. A hydraulic head of 3.5m was applied onto the model box and with a confinement stress of 6kPa using a 300mm gravel layer. Table 1 provides the results of the test carried out on the flow box.

Table 1 – Flow box test results

Hydraulic conductivity (m/s)	Flow rate through the GCL overlap at 3.5m head (m^3/s)
2.29×10^{-11}	2.09×10^{-9}

Numerical Modelling using element scale test results

Next, an attempt was made to replicate the actual experimental condition of the flow box test in SEEP/W analysis in GEOSLOPE software. The flow box cross-section in the numerical model was scaled to the same dimensions of the actual flow box as described and the hydraulic conductivity of the GCL sample calculated from the flow box test results (Table 1) was input as the material property of the product. Figure 5 shows the cross-section of the GCL overlap developed using the software.

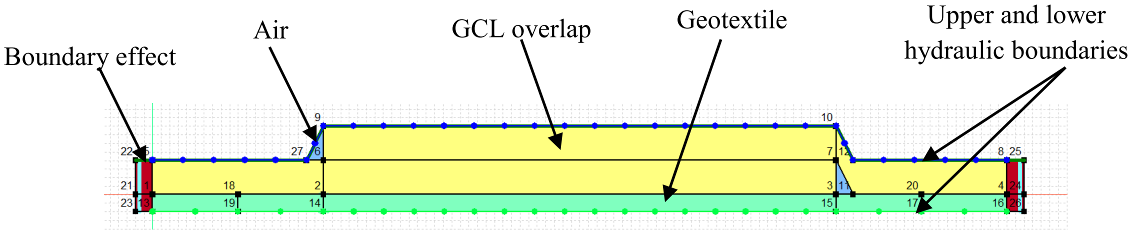

Figure 5 – Features assigned to the flow box model in GEOSLOPE SEEP/W analysis

“Air” was defined with a higher hydraulic conductivity for areas trapped with air due to the overlapping condition. The geotextile added to the bottom of the GCL layer to filter the water flowing through the sample into the collection bag was also added to replicate a model much similar to the actual case in FE analysis. An external permeable boundary layer was added to the wall lines of the box to incorporate the side wall leakage errors. A trial and error method was used to derive the hydraulic conductivity of the boundary layer of the box in order to obtain the expected flow rate calculated from the actual flow box test.

Once the numerical model is calibrated using the actual flow box results, it is ready for use in the analysis. The results of the calibrated flow box model confirmed the literature, depicting the higher flow at the GCL overlap. The results obtained are provided in Figure 6.

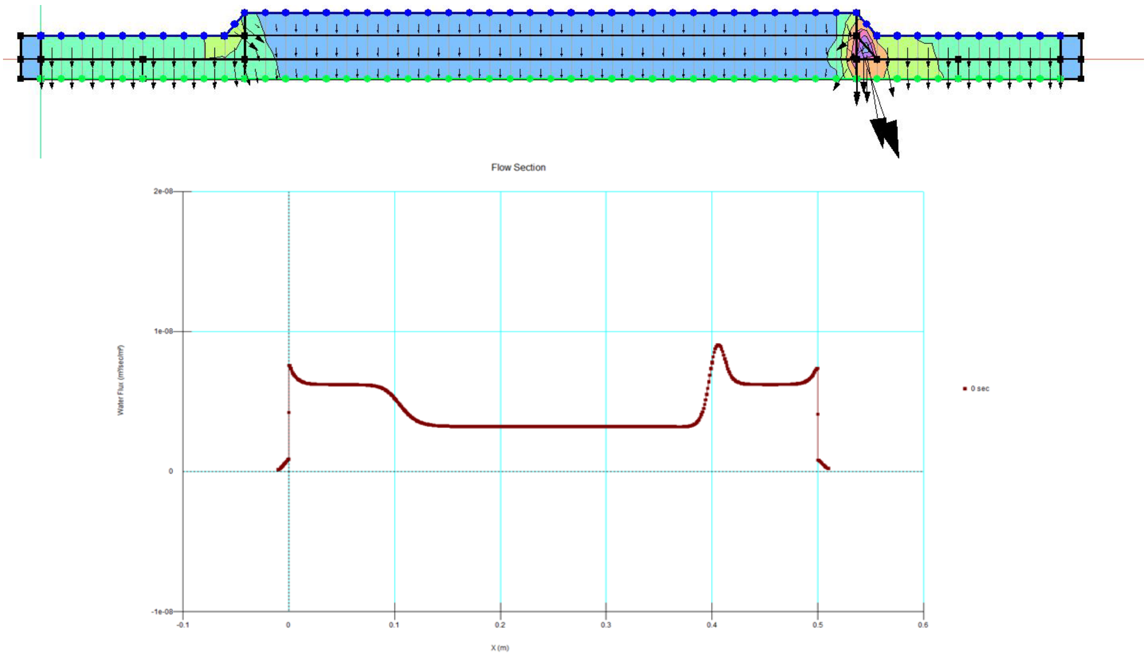

Figure 6 – FE model depicting the higher flow at the GCL overlap (1) Cross-section of the flow box in FE model (2) Graphical representation of the flow through the GCL overlap in the FE model

As described in the method, the flow box was segmented into 3 sections, two single layers and one double layer of GCL as illustrated in Figure 7. This allowed the overlap created in the flow box to be modelled replicating the single layer and double layer GCL hydraulic conductivity tests carried out in the element-scale permeameter cell.

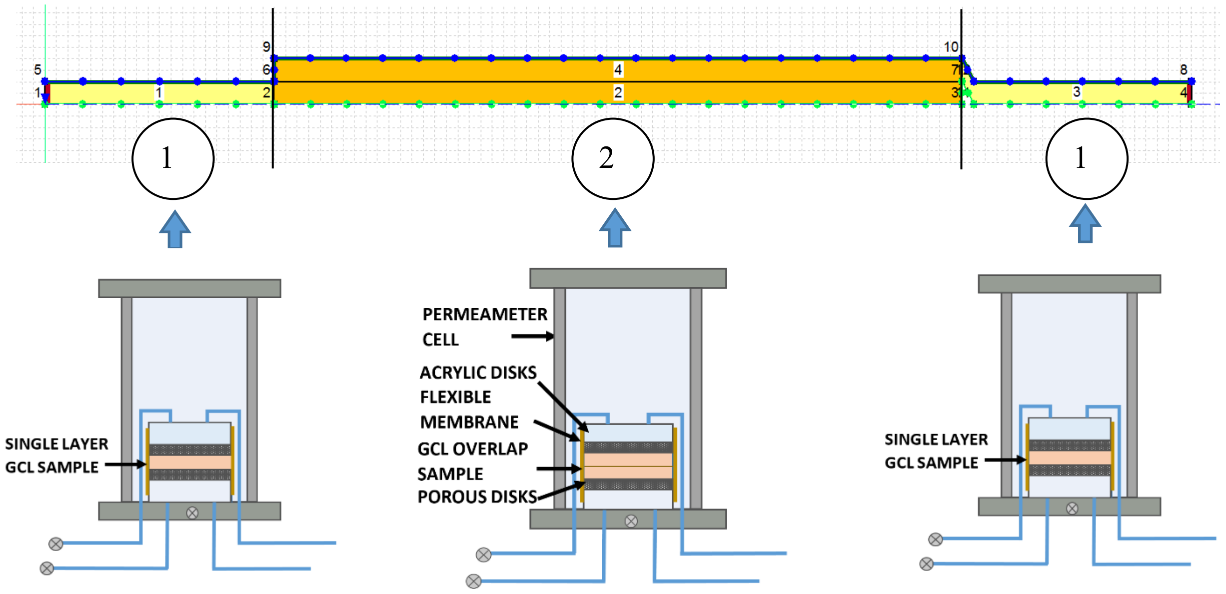

Figure 7 – The three element scale permeameter cell tests carried out to be compared with the flow box results

The two element-scale tests illustrated above were conducted in the laboratory permeameter cells and the results obtained are as shown in Table 2.

Table 2 – Permeameter cell test results

Permeameter cell tests	Permeability (m/s)
Single GCL layer	1.37×10^{-11}
Double GCL layers	1.29×10^{-11}

The hydraulic conductivity values of the single layer and double layer GCL samples were input into the numerical model as material properties separating the GCL material into two sections as shown in Figure 6. The model was rerun for these new material properties and the flow rate obtained is as shown in Table 3.

Table 3 – Comparison of flowrates obtained from FE model and laboratory model test

Flowrate of the laboratory flow box test (m^3/s)	Flowrate obtained from FE model (m^3/s)
2.09×10^{-9}	1.27×10^{-9}

A flowrate considerably less than the actual experimental flow rate was observed in the FE model. The variation in flow rate was approximately 40% of that of the experimental results.

Considering the previous literature and data analysis carried out on the hydraulic performance through the GCL overlap, the expected study result was also that the actual flow box results would have a higher flow rate than the value obtained from the model. The gap was identified as a result of the inability of element scaled permeameter cell tests to take the horizontal flow at the GCL overlap into consideration.

The higher flow rate generated in the GCL overlap test conducted in the flow box highlighted the fact that there is an additional flow through the overlap that is not captured from the element tests carried out in the research study. Even though an element test is conducted using two layers of GCLs to represent the overlap area of the GCL seam, it does not seem to capture the horizontal preferential flow identified through the model-scale testing as the two layers do not replicate the open ended overlap due to the membrane confinement. The analysis on previous literature confirmed this idea with the emphasis on the horizontal preferential flow.

Next Steps

Findings of this study hence emphasizes the necessity of developing a separate laboratory element test method to measure the horizontal direction preferential flow through the GCL overlap seam. Once this method is developed, the hydraulic properties for the horizontal flow along overlap can accurately be determined. Then, these properties can be incorporated into the numerical model to get a better agreement with the flow box test results (flowrate). Once the element scale laboratory tests and the numerical model to replicate the GCL overlap seam are verified, further studies could be carried out to enhance the performance of the overlap seam by conducting more research on overlap material characteristics. The numerical model will be important in this aspect for further analysis as the experimental conditions could be altered easily using the model for different test conditions. Hence, the gap in GCL overlap performance could be addressed to improve barrier performance.

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