Effect of confining stress on the transient hydration of unsaturated GCLs

Effet de la contrainte de confinement sur l'hydratation transitoire de GCLs insaturés

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ABSTRACT: Geosynthetic clay liners (GCLs) are often used within composite landfill liner systems in combination with a geomembrane to provide an effective barrier. In order for the GCL to function as a barrier, however, it must hydrate from its initially low moisture content. With the geomembrane above the GCL limiting moisture uptake from the surface, the GCL must hydrate by taking moisture from the foundation soil below. Numerical simulations of hydration showed that in an isothermal closed system, the foundation soil sets the suction value towards which the GCL migrates. In this paper the impact of normal stress on the rate of hydration and equilibrium moisture content is investigated numerically. The laboratory tests were completed with 2 kPa normal stress, however, in a landfill, GCL hydration could occur at significantly higher normal stresses. Therefore the question arises whether additional normal stress will aid or hinder GCL hydration. The results showed the impact of normal stress is to constrain swelling of the GCL which will reduce the equilibrium moisture content as well as reduce the time to achieve equilibrium. This provides additional motivation to cover the composite barrier system in a timely manner within the construction process.

RÉSUMÉ : Les géosynthétiques bentonitiques (GSB) sont souvent utilisés en combinaison avec une géomembrane dans la conception des sites d'enfouissement pour fournir une barrière étanche. Pour assurer sa fonction d'étanchéité, un GSB doit s'hydrater suite à l'installation puisqu'il possède un faible taux d'humidité initial. La géomembrane qui recouvre le GSB limite la reprise d'humidité du GSB. L'hydratation doit donc se faire en utilisant l'humidité du sol au-dessous de la barrière. Des simulations numériques de l'hydratation ont démontré que dans un système fermé isotherme, le sol de fondation fixe la valeur de succion vers laquelle l'humidité migre vers le GSB. Dans cet article, les effets de la contrainte normale sur la vitesse d'hydratation et sur la teneur en humidité à l'équilibre sont étudiés numériquement. Les essais en laboratoire ont été réalisés avec une contrainte normale de 2 kPa. Cependant, dans un site d'enfouissement, l'hydratation du GSB pourrait se produire à des contraintes normales beaucoup plus élevées. Les résultats ont montré que l'impact de la contrainte normale est de contraindre le gonflement du GSB, ce qui réduira la teneur en humidité à l'état d'équilibre ainsi que le temps nécessaire pour atteindre l'état d'équilibre.

KEYWORDS: Geosynthetic clay liner, hydration, numerical simulations, parametric study, landfill, barrier systems

1 INTRODUCTION

Geosynthetic clay liners (GCLs) are often used in combination with a geomembrane (GMB) as a composite landfill liner system. For a GCL to function as a hydraulic barrier, however, it must hydrate from its initially low moisture content. The source of this moisture cannot be from the atmosphere as the GMB barrier is installed on top of the GCL. Instead, a GCL must hydrate with moisture from the foundation soil below the GCL. This is not to say that the GMB does not play a significant role in defining the hydration behaviour of a GCL. If the surface of the GMB is left exposed to solar radiation during construction of the landfill liner, peak daily temperatures have been observed in the range of 60-75 °C for black GMBs (Pelte et al. 1994; Chappel et al., 2012; Rowe et al., 2012). These daily thermal cycles have been shown in the laboratory to suppress the ability of GCLs to significantly hydrate (Rowe et al. 2011).

If best practice is followed and the GMB is covered in a timely fashion with a granular protection layer or leachate collection system, the combination of a lack of direct contact with solar radiation and the thermal insulation provided by these layers of granular material will result in a much less severe thermal regime allowing GCL hydration to occur. Because these layers are designed to be as thin as possible (i.e. maximising landfill volume), GCL hydration in this scenario could be viewed as occurring under low confining stresses and relatively isothermal conditions. Research quantifying the rate of GCL hydration under these conditions was performed by Rayhani et al. (2011) which showed that GCLs readily hydrate from the subsoil under these conditions with the rate of hydration and final equilibrium water content of the GCL varying on the initial moisture content of the foundation soil.

The key to quantifying the moisture uptake and retention behaviour of GCLs is the material's unsaturated water retention curve (WRC). The water retention behaviour of GCLs at low confining stresses has recently been quantified using measurements of GCL suction using high capacity tensiometers and relative humidity sensors (Beddoe et al., 2010) for four geotextile-encased GCLs containing granular bentonite (Beddoe et al., 2011). The results of this study have indicated that the method of GCL manufacture, in particular the presence or absence of a scrim reinforced nonwoven carrier geotextile and thermal treatment, can have a significant impact on the water retention behaviour of GCLs. Using the water retention curves (WRCs) defined by Beddoe et al. (2011), Siemens et al. (2012) performed an unsaturated numerical modelling parametric study of the experimental isothermal hydration experiments of Rayhani et al. (2011). The results of this analysis are shown schematically in Figure 1. The underlying foundation soil was observed to act as a suction boundary condition. As a result, the soil followed a drying path, whereas the GCL followed its wetting path until an equilibrium suction value was reached. Due to the relatively small mass of water required to hydrate the GCL compared to the mass of moisture held in the soil column, the equilibrium suction value was observed to be that represented by the foundation soil's initial moisture content.

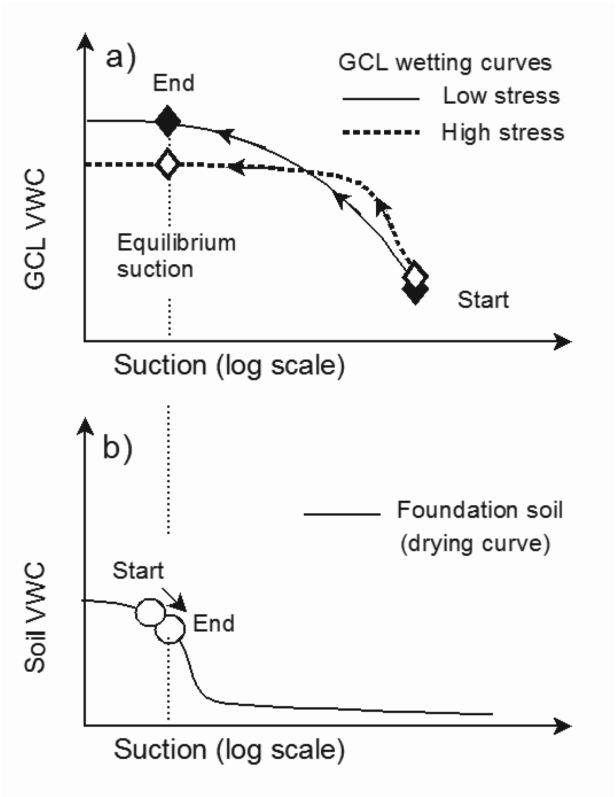


Figure 1. Unsaturated paths followed during closed hydration of a GCL placed on a foundation soil.

Although it is possible for hydration to occur under the conditions previously described, it is also possible that GCL hydration may occur later in time after construction when it is subjected to the higher confining stress associated with waste placement. Based on the effect of higher normal stress on other geomaterials (e.g., Fredlund and Pham 2006) it is hypothesised that confining stress will have a similarly significant impact on the WRC of the GCL and its hydration behaviour. In particular, the increased confining stress will reduce the height of the GCL after it is fully swollen to its saturated moisture content when compared to a similar GCL at a nominal 2 kPa confining stress (Figure 1). A GCL hydrated at high confining stress will therefore have a lower void ratio than a GCL hydrated at low confining stress. This change in the pore structure of the encased bentonite of the more confined GCL will result in a reduction in the GCLs saturated conductivity and an increase in the air entry value of the GCL from the values measured at low confining stress.

Despite there being clear indications that confining stress will significantly impact the WRCs of GCLs, there is currently a paucity of WRC data for GCLs at higher confining stresses (the one exception being the two GCL specimens tested by Southen and Rowe, 2007). As a result, the practical impact (if any) of confining stress on the magnitude and rate of hydration is not immediately clear. However, data exists that describes the water retention behaviour of GCLs at low confining stress, and the consolidation behaviour of saturated GCLs to confining stress. In this paper we report a numerical sensitivity analysis to quantify the potential impact higher normal stress could have on the rate of hydration of GCLs to assess whether it is likely to have any practical impact on the hydration behaviour of GCLs assumed in landfill design.

2 MODEL DESCRIPTION

The effect of confining stress on the moisture uptake of GCLs was investigated for a typical geotextile-encased GCL consisting of a woven cover and a non-woven carrier geotextile with the material properties listed in Table 1. The water retention behaviour of this GCL has been quantified at a low (2 kPa) confining stress by Beddoe et al. (2011). The WRC relationship for this GCL and a typical silty-sand foundation soil are listed in Table 2 and plotted in terms of volumetric water content against suction in Figure 2.

The material properties for the GCL at high confining stress (Figure 2 and Table 2) were estimated from experimental results. Southen and Rowe (2007) reported drying WRCs for the GCL at 100 kPa vertical stress, which allowed comparison with the low stress data. Comparing the fitted curves indicated an increase in the ‘a’ parameter of 100 kPa was necessary to match the results (Table 2). Beddoe et al. (2011) compared WRCs of various GCLs and reported that at suction values greater than approximately 3000 kPa, the WRCs were similar. Therefore the ‘a’ parameter for the wetting curve was increased by two orders of magnitude as listed in Table 2. The ‘m’ and ‘n’ parameters were adapted to ensure the WRC agreed with other GCLs for higher suction values. Lake and Rowe (2000) reported on the compressibility and swell behaviour of GCLs. The results were used to estimate the height and saturated porosity of the hydrated GCL at 100 kPa vertical stress. Finally conductivity data obtained at various confining stresses (Rowe and Hosney, 2013) was used to estimate the saturated conductivity at 100 kPa.

The finite element model (Figure 3) procedure was described in detail earlier (Siemens et al. 2012) and a brief summary will be given here. The initial moisture conditions are set in the GCL and foundation soil and then the model steps forward in time under closed conditions. As-manufactured the GCL is at nominal moisture content and approximately 10^5 kPa suction. The soil is at a suction corresponding to its initial moisture content. During closed isothermal hydration the foundation soil undergoes minor drying while the GCL approaches the suction boundary condition provided by the soil. At equilibrium the system achieves a hydrostatic state.

Table 1. Properties of GCL1

Property		*GCL*
Average GCL mass per unit area (g/m^2)	*Measured*	4679
	Minimum Acceptable Roll Value	3965
Carrier Geotextile	*Type*	W
	Mass per unit area (g/m^2)	120
Cover Geotextile	*Type*	NW
	Mass per unit area (g/m^2)	240
Bentonite	*Montmorillonite content (%)*	50-55
	As-delivered form	Fine granular
Structural	*Needle-punched*	Yes
	Thermally treated	Yes

Table 2. GCL and foundation soil Fredlund and Xing fitting parameters for water retention curves and saturated hydraulic conductivity values.

Parameter		*GCL 2 kPa*	*GCL 100 kPa*	*Soil*
Fitting parameters	*a (kPa)*	13.10	1310	6.73
	n	0.84	3.20	1.95
	m	0.51	0.32	0.78
	ψ_r *(kPa)*	2559	2559	5856
Saturated VWC	*(%)*	0.73	0.55	0.39
K_{sat}	*(m/s)*	1.5×10^{-11}	3.5×10^{-13}	9.5×10^{-4}

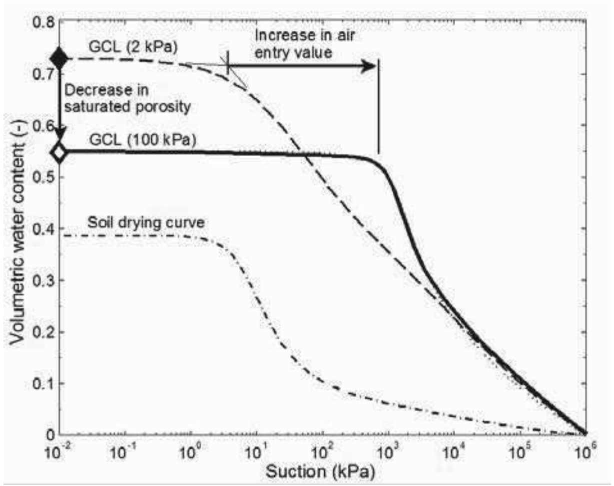


Figure 2. WRCs for the soil as well as the GCL at low and high confining stress.

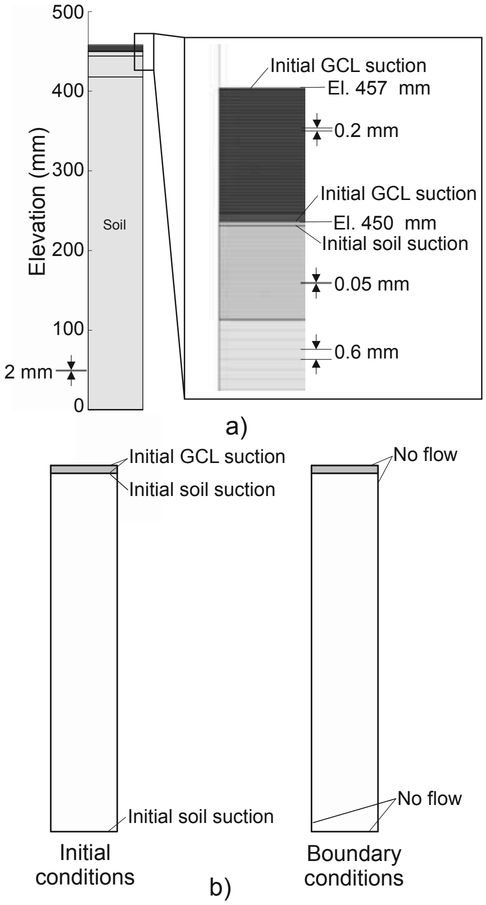


Figure 3. Finite element model and boundary conditions.

3 RESULTS

3.1 *Typical Model Results – GCL on Soil at GWC=16%*

A typical model result is illustrated in Figure 4. The low confining stress model (Siemens et al. 2012) is also included for comparison. The foundation soil has an initial suction of 27.6 kPa while the GCL initial suction is set to 362,000 kPa. These conditions are representative of a foundation soil compacted to a constant moisture content with the GCL immediately installed following compaction. In Figure 4a both GCLs start at their initial low VWC and increase to similar equilibrium moisture content with the higher confining stress model achieving equilibrium in a shorter duration. From Figure 4b, both GCLs plot along their wetting curves and the reason for the similar equilibrium VWC is apparent. The soil provides the suction level to which the GCLs migrate. For the suction level applied in this model, the GCL WRCs of the 2 kPa and 100kPa cross, which results a similar equilibrium VWC.

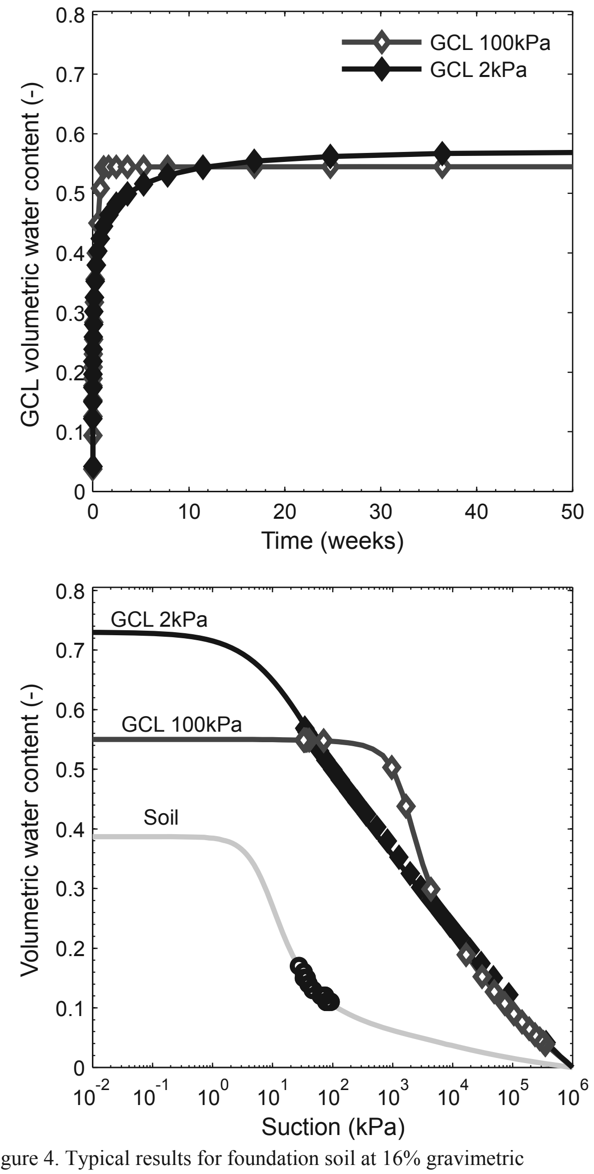
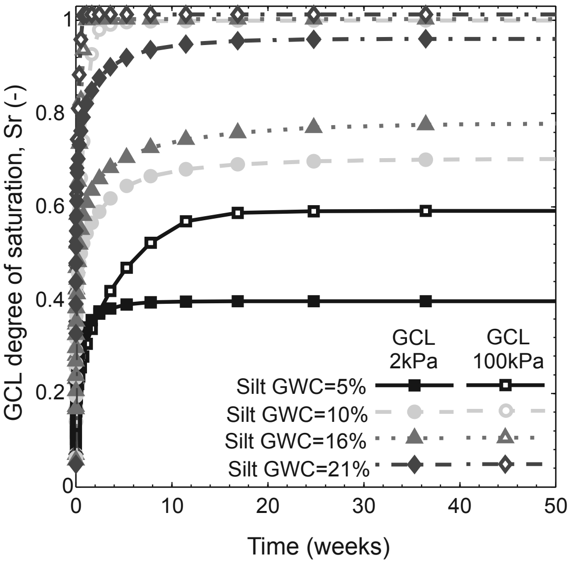


Figure 4. Typical results for foundation soil at 16% gravimetric moisture content: a) GCL volumetric water content versus time and b) unsaturated paths plotted on WRCs.

3.2 *Model Results*

The calculated uptake of moisture during GCL hydration is shown in Figure 5a in terms of degree of saturation versus time. Relationships are shown for GCL hydration occurring at either 2kPa or 100 kPa normal stress for a range of four foundation soil moisture contents. As observed by Siemens et al. (2012), the equilibrium degree of saturation of a GCL increases with foundation moisture content. The effect of normal stress can be observed by comparing the hydration behaviour at 2 kPa (closed symbols) and 100 kPa (open symbols). For each of the four foundation moisture contents examined in this study, the GCL hydrating at a higher confining stress was observed to achieve a higher degree of saturation than the unconfined GCL. The magnitude of this difference is shown in Figure 5b expressed as the ratio of Sr_{100kPa}/Sr_{2kPa} at their equilibrium state of hydration. This data indicates that although GCLs at both confining stresses will achieve their near-fully saturated state on the wettest of foundation soils, at progressively lower foundation moisture contents, the GCL hydrated under 100 kPa confining stress will be at an increasingly higher degree of saturation.



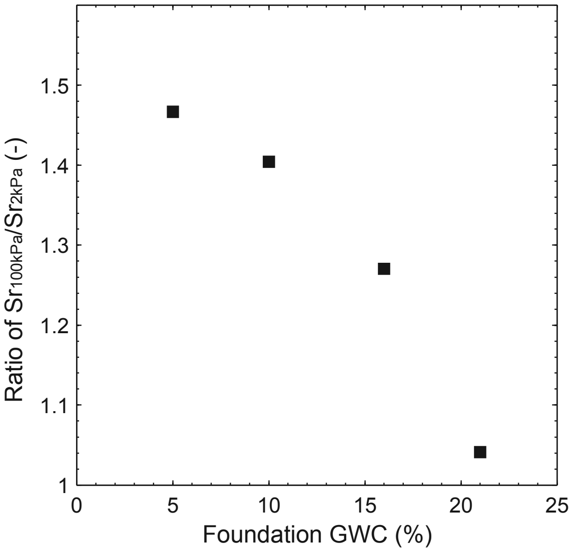


Figure 5. Effect of GCL confinement on hydration: a) GCL degree of saturation, Sr versus time and b) ratio of Sr_{100kPa}/Sr_{2kPa} versus foundation gravimetric water content.

4 CONCLUSIONS

The lack of unsaturated water retention curve data for GCLs at high confining stresses has made the assessment of the effect of confining stress on the magnitude and rate of hydration currently unclear. In this paper, existing data describing the water retention behaviour of GCLs at low confining stress has been combined with data describing the consolidation behaviour of saturated GCLs to perform a numerical sensitivity analysis to investigate whether higher confining stresses are likely to have a practical impact on the hydration behaviour of GCLs in landfill design.

The numerical analyses indicate:

1. GCLs hydrating at high confining stresses will hydrate faster than a GCL at lower confining stresses for lower suction ranges. GCLs at higher confining stresses have the benefit of having a higher suction where the saturated hydraulic conductivity is achieved and their thinner thickness results in a shorter flow path distance.
2. For a given foundation soil moisture content, a GCL hydrating at a higher confining stress will achieve a higher degree of saturation than an unconfined GCL. The magnitude of this difference is a function of the foundation moisture content. This is due to the change in shape of the WRC resulting from the decrease in saturated VWC and increase in air entry value.

The objective of the parametric study was to assess the likely impact of confining stress on the hydration of GCLs in landfill liner applications. The results of these analyses indicate that confinement will play a significant role on both the rate and magnitude of hydration in GCLs, warranting further laboratory studies to experimentally quantify the WRCs for typical GCLs at a higher confining stress. In the absence of this specific information, the analyses indicate that the use of WRCs defined for GCL hydration at low confining stress will be generally conservative (i.e. underpredict) the rate and magnitude of hydration for GCLs at higher confining stresses.

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