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Published in:
Proceedings of the 2nd Symposium on Coupled Phenomena in Environmental Geotechnics (CPEG2), Leeds, UK 2017

Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

THM analysis of compacted clay liner response to baled municipal waste

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ABSTRACT: Heat is generated in municipal waste containment facilities due to the chemical and biochemical evolution of waste. Sometimes it is required to check if the level of heat generated during the deposit lifetime may damage or reduce the isolating properties of the liners. That verification relies on appropriate evaluation of heat and moisture transfer through the barrier as well as the evolution of stress fields. This paper presents an example of such verification based on a coupled thermo-hydro-mechanical (THM) analysis for the case of a compacted clay liner designed to isolate a deposit of baled municipal waste. The evaluation of the different boundary conditions for the analysis is discussed in detail. The case study corresponds to a deposit of baled waste and the evaluation of thermal loadings on the lining is performed using thermal discrete elements.

KEYWORDS: municipal waste, compacted clay liners, T-H-M, Desiccation cracking, DEM.

1 INTRODUCTION.

A compacted clay liner (CCL) is an essential item in many impermeabilization schemes used in municipal solid waste (MSW) facilities. Albrecht & Benson (2001) provided clear evidence of drying induced damage in CCL, apparent as orders of magnitude increases in permeability subsequent to drying-wetting cycles. They also identified high plasticity, low compaction energy and high water content on compaction as risk factors.

Most studies of CCL desiccation have focused on cover layers exposed to atmospheric interaction. However waste biochemical evolution results in heat generation within the fill. This heat may be directly exploited as an energetic resource (Coccia et al. 2013) and may help to optimize bioreactor performance (Megalla et al. 2015). On the other hand historical predictions of temperature evolution for the MSW at the contact with the lining are also a necessary input to perform detailed studies of geomembrane service life (Rowe & Islam, 2009) or liner desiccation (e.g. Zhou & Rowe, 2005).

1 .1 *Baled MSW deposits*

Intense efforts have been made to minimize the volume and environmental impact of municipal waste disposal schemes. A technique that is sometimes adopted is that of baling. Baling involves wrapping up in plastic pre-processed municipal solid waste (MSW) for intermediate or long term storage. Baling has the advantage of producing compacted waste, requiring less storage space. Baled waste is also easier to transport and handle. An overview of the pros and cons of baling may be found in Baldassaro et al (2003).

MSW bales are typically wrapped in low-density polyethylene (LDPE). There are two main types of bales: rectangular and cylindrical, both generally weight around 1 mT and have meter-sized dimensions. Baled waste can be disposed of in long-term or temporary deposits, frequently as an intermediate storage to incineration. Long-term deposits, leading to bale-landfills, have been used in countries such as USA, Lebanon, Iceland, New Zealand, Italy and Spain (Nammari, 2006). When long-term storage of baled MSW is envisaged, liners and other protective design features similar to those applied in regular MSW deposits need to be engineered. An idealized scheme of a baled MSW deposit is shown in Figure 1.

Most research on baled waste has focused in environmental and/or safety aspects, such as the biochemical evolution of waste inside the bales, the heating potential on incineration or the self-combustion hazard (Nammari, 2006; Passamani et al. 2016). Little attention has been paid instead to geo-environmental problems such as slope stability, thermal loads on the lining and the consequent potential of desiccation cracking of the clay liner.

1 .2 *DEM*

The discrete element method (DEM) is now extensively used in geomechanics for the exploration of fundamental soil and rock behaviour (O'Sullivan, 2011). Although the best-known applications of the method are in single-phase mechanical problems, extension to multi-phase (e.g. Climent et al. 2014) or thermal (El-Shamy et al. 2011) problems is relatively straightforward. Direct application of the method to large-scale boundary value problems is certainly possible (e.g. Ciantia et al. 2016) but, to overcome computational limitations, generally requires the use of carefully designed upscaling or coarse-graining techniques.

Baled MSW deposits offer a favourable setting for DEM-based analysis. Due to the relative large dimensions of the bales, it is feasible to establish a one-on-one map in which each bale is represented by a single element without incurring in excessive computational costs. In this communication we illustrate this point by presenting thermal analyses of baled MSW.

1 .3 *Case description*

The analyses described below were inspired by studies for a potential long-term deposit. The deposit in question was planned to recover a pre-extant quarry. The site was approximately elliptical in plan with a 350 m long-axis and

200 m short-axis. The maximum planned height of the deposit above its base is 110 m, and the maximum height above its surroundings is 75 m. The bales to be stored were shaped as cuboid (1.1 m x1.1 m x1.65 m). The waste wrapped was the output of a plant where MSW underwent mechanic-biological treatment (MBT).

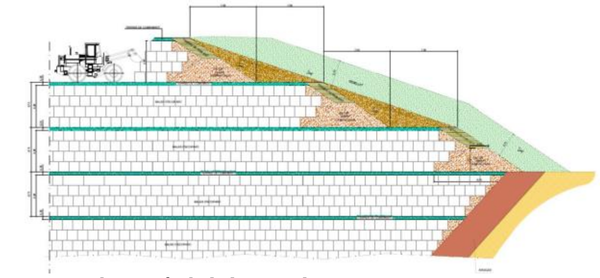


Figure 1 Scheme of a baled MSW deposit.

2 THERMAL LOADING ANALYSYS

2 .1 *Heat generation in MSW*

Heat is generated in MSW deposits as a by-product of the biochemical evolution of the waste. The evaluation of heat generation potential from direct thermochemical analysis of the waste is quite complex and prone to large error, and empirical approaches based on field observations are currently favoured (Yesiller et al. 2015). From these observational studies, equations such as

$$H = A\left[\frac{Bt}{B^2 + 2Bt + t^2}\right]\exp\left[-\left(\frac{t}{D}\right)^{\frac{1}{E}}\right] \quad (1)$$

may be proposed to describe the elementary heat source per unit volume. Another useful outcome of these studies is the identification of heat conduction as the dominant mechanism involved in heat transfer, some 20 times larger than convection (Yesiller et al. 2005). This allows a relatively simple numerical analysis based on the heat conduction equation. Currently those analyses are typically performed numerically using finite elements (Hanson et al. 2008; Rowe et al. 2010; Megalla et al. 2015). None of this studies, however, has dealt with the case of baled MSW for which DEM offers an interesting alternative.

2 .2 *Thermal modelling using DEM*

Heat transfer analysis in DEM is based on a discretized version of the heat transfer equation (Itasca, 2014) in which each particle acts as a heat reservoir and each contact as a heat conduit. The energy balance for each particle is expressed as

$$Q_v = m_b C_v \frac{\partial T}{\partial t} + \sum_{p=1}^{N} Q^p \quad (2)$$

Where m_b stands for particle mass, C_v for the constant-volume specific heat assigned to the particle, Q_v for heat source power and Q^p for the heat flow through contact *p*. This, in turn, is obtained using

$$Q^p = -\frac{\Delta T}{\eta^p l^p} \quad (3)$$

where ΔT is the temperature gradient between contacting particles, l^p the branch vector of the contact and η^p the thermal resistivity per unit length assigned to the contact.

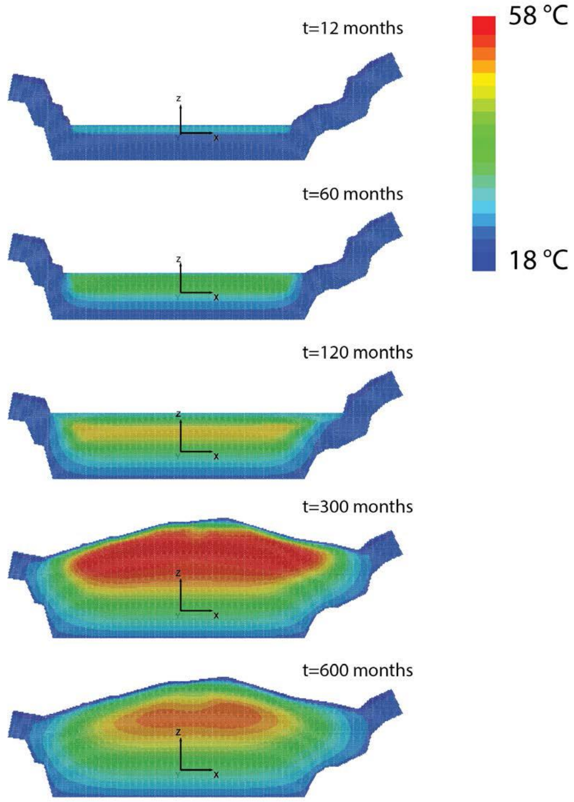


Figure 2 Temperature evolution in the analyzed section

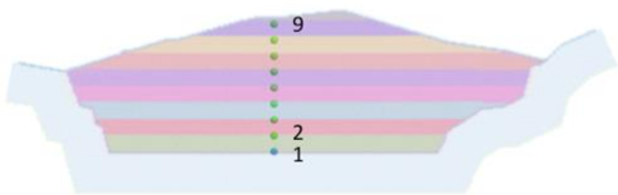


Figure 3 Observation points for temperature

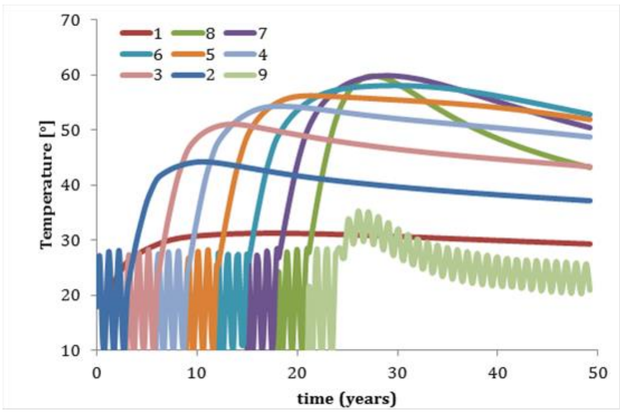


Figure 4 Temperature evolution at observation points

2 .3 *Thermal model of baled MSW deposit*

Thermal boundary conditions are represented by a constant temperature at the lower boundary -deduced from the local geothermal gradient to be 19°C at 25 m below ground. At the upper boundary a sinusoidal simplification of local annual atmospheric mean temperature oscillation is applied. The oscillation limits are 6°C and 30°C.

The upper boundary is a moving boundary, to represent the progressive filling of the deposit. The model is raised in 9 steps; at each step a layer of 9 bales height is activated. This is equivalent to total operation period of 27 years for the particular case considered here.

For initial estimations the heat generation function (1) was used for each bale with parameters given in Table 1. These parameters were adjusted taking into account the composition of the MBT urban waste that was considered for the site. This was dominated by plastics (30%) and textile/paper (55%), with an estimated methanogenic potential of approximately 70 Nm^3/t.

Table 1 Parameters for heat source function (eq. 1)

A	*B*	*D*	*E*
W/m^3	-	-	-
5.5	2200	1200	0.83

For identical spheres in hexagonal packing an analytical relation may be established between the equivalent continuum conductivity, *k*, and contact resistivity, *η*,

$$\eta = \frac{1}{k\sqrt{2}R^2} \tag{4}$$

This allows to exploit data on conductivity available from other MSW deposits (e.g. Yesiller et al. 2015). The parameters used in the simulation are presented in Table 2

Table 2 Material parameters for the thermal simulation

C_v	*k*	*η*
J/(kgK)	W/mK	K/(Wm)
5.5	2200	1200

2 .4 *Thermal analysis: results*

The model results indicate an evolution of temperature within the deposit that peaks somewhat below 60°C and has its maximum in the upper part of the section (Figure 2). These observations are in line with observations of temperature evolution on other MSW deposits (Hanson et al. 2010).

Temperature evolution history at individual bales may be easily extracted from the model (Figure 3, Figure 4). In the particular case being analysed the temperature at the layer in contact with the liner - point 1- raises to 30°C quickly and is maintained at that value with little variation throughout the period under study. This kind of local temperature evolution may then be used as input in analysis of liner integrity.

4 LINER RESPONSE ANALYSES

4 .1 *Methodology*

Coupled THM analyses are well established in the field of radioactive waste disposal to analyse the effect of thermal loads on containment barriers (Gens et al. 2009). However, the thermal loadings and material characteristics present on those problems differ significantly from the ones pertaining to MSW deposits. There have also been many studies focusing on GCL response to thermal loading (Southern & Rowe, 2005; Azad et al, 2012; Rowe & Verge, 2013). The study of GCL under waste generated thermal load is more infrequent with Zhou & Rowe (2005) being the most significant exception.

A coupled THM analysis is performed with CODE_BRIGHT (Olivella et al. 1996) a FE code developed for the analysis of boundary value problems. CODE_BRIGHT solves simultaneously the balance equations of momentum, air mass, water mass and internal energy. The solution should comply with constitutive laws that include Darcy's law, Fick's law, Fourier's law a water retention relation and a mechanical constitutive law. The solution is restricted by thermodynamic equilibrium relations: Henry's law and the psychrometric law.

4 .2 *Model description*

Following Zhou & Rowe (2005) the geometry of the model idealizes a section of the lining, including a compacted clay liner of 90 cm lying over a 30cm layer of sand (Figure 5). Horizontal displacements at the vertical boundary are cero, as well as vertical displacement at the bottom. At the bottom boundary air pressure is kept at 100 kPa, temperature at 18 °C and suction at 65 kPa, equivalent to a water table located at 7.8 m beneath the upper boundary. That upper boundary is where a geomembrane will be located and the boundary conditions there are no water flow, air at atmospheric pressure and a temperature history given by the DEM analysis given in the preceding section (Figure 6).

The initial conditions (Table 3) assume that net stress and total stress are both coincident and geostatic. Also a k_0 of 1 is used, following the laboratory observations of Wijeyesekera et al. (2001).

In the analysis presented below permeability is described using the Kozeny relation, water retention properties using the Van Genuchten (1980) formulation and the stress-strain relation of the soil through the state surface model of Lloret & Alonso (1985).

$$\frac{\Delta e}{1+e} = a_1 \Delta \ln(-p') + a_2 \Delta \ln\left(\frac{s+p_{ref}}{p_{ref}}\right) + a_3 \Delta\left[\ln(-p')\ln\left(\frac{s+p_{ref}}{p_{ref}}\right)\right] + \alpha_T T \tag{5}$$

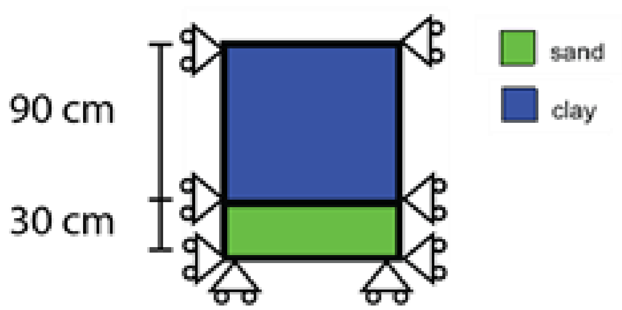


Figure 5 Model geometry and mechanical BC

Table 3 Initial Conditions for THM analysis for both clay and sand

Suction	*Gas Pressure*	*T*	σ_v	κ_0
[kPa]	[kPa]	[°]	[kPa]	[-]
16	100	18	Geostatic	1

Table 4 Model material properties

	G_s [-]	$\gamma_{d,max}$ [kN/m³]	ω_{opt} [-]	$S_{r,opt}$ [-]	e [-]	n [-]	γ_w [kN/m³]	γ_{sat} [kN/m³]
Clay	2.7	16.2	19	0.83	0.605	0.377	0.43	19.90
Sand	2.65	20.1	8.9	0.80	0.293	0.227	0.35	22.33

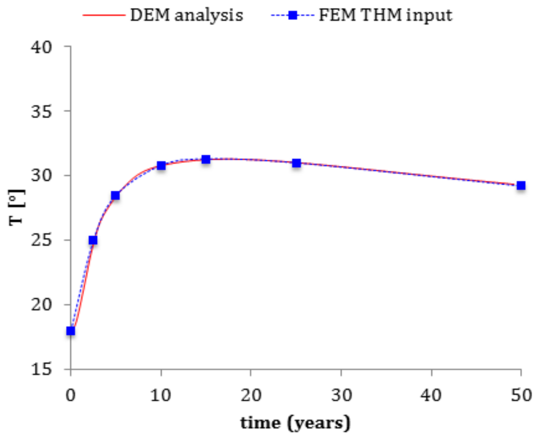


Figure 6 Temperature history at the upper face of the CCL

Table 5 Material Hydro-Thermic models and properties

Property	Model	Clay	Sand
Water Retention Curve	$S_e = \frac{S_l - S_{rl}}{S_{ls} - S_{rl}} = \left(1 + \left(\frac{P_g - P_l}{P}\right)^{\frac{1}{1-\lambda}}\right)^{-\lambda}$	$\lambda = 0.3$ $P = 18kPa$ $S_{rl} = 0$ $S_{ls} = 1$	$\lambda = 0.3$ $P = 0.26kPa$ $S_{rl} = 0$ $S_{ls} = 1$
Permeability	$\mathbf{q}_l = -\mathbf{k}\left(\frac{k_{rl}}{\mu_l}\right)(\nabla P_l - \rho_l g)$ $k_{rl} = \sqrt{S_e}\left(1 - \left(1 - S_e^{1/\lambda}\right)^{\lambda}\right)^2$	$\mathbf{k} = 4.3\text{e-}15 \cdot \mathbf{I}$ $\lambda = 0.5$ $S_{rl} = 0$ $S_{ls} = 1$	$\mathbf{k} = 7.5\text{e-}9 \cdot \mathbf{I}$ $\lambda = 0.4$ $S_{rl} = 0$ $S_{ls} = 1$
Heat conduction	$i_c = -\lambda \nabla T$ $\lambda = \lambda_{sat}\sqrt{S_l} + \lambda_{dry}\left(1 - \sqrt{S_l}\right)$	$\lambda_{dry} = 0.3$ $\lambda_{sat} = 1.3$ [W/m°C]	$\lambda_{dry} = 0.256$ $\lambda_{sat} = 2.84$ [W/m°C]

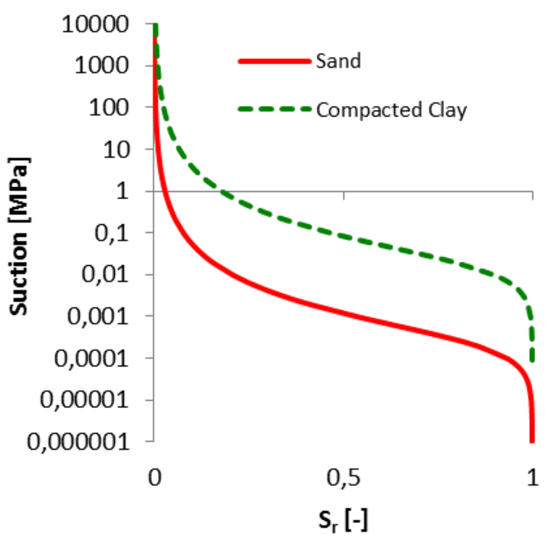


Figure 7 Water retention curves for sand and clay

Table 6 Specific heat and phase densities

Property	Units	Liquid	Clay	Sand
Specific Heat	$Jkg^{-1}K^{-1}$	1000	1000	800
Density	kgm^{-3}	1000	2700	2650

Table 7 Non-linear elastic model parameters

Sand	Clay
$a_1 = \frac{-\kappa}{1+e} = \frac{-0.009}{1+0.605} = -0.005$	$a_1 = \frac{-\kappa}{1+e} = -5.7e-3$
$a_2 = \frac{-\kappa_s}{1+e} = \frac{-0.015}{1+0.605} = -0.009$	$a_2 = \frac{-\kappa_s}{1+e} = -5.7e-4$
$a_3 = 0.003$	$a_3 = 2.8e-5$
$\alpha_T = 3.33*10^{-6}$	$\alpha_T = 3.33*10^{-6}$

4 .2 *Model outputs*

The main results of the analysis for the case described in the previous section are summarized in Figure 8, Figure 9 and Figure 10.

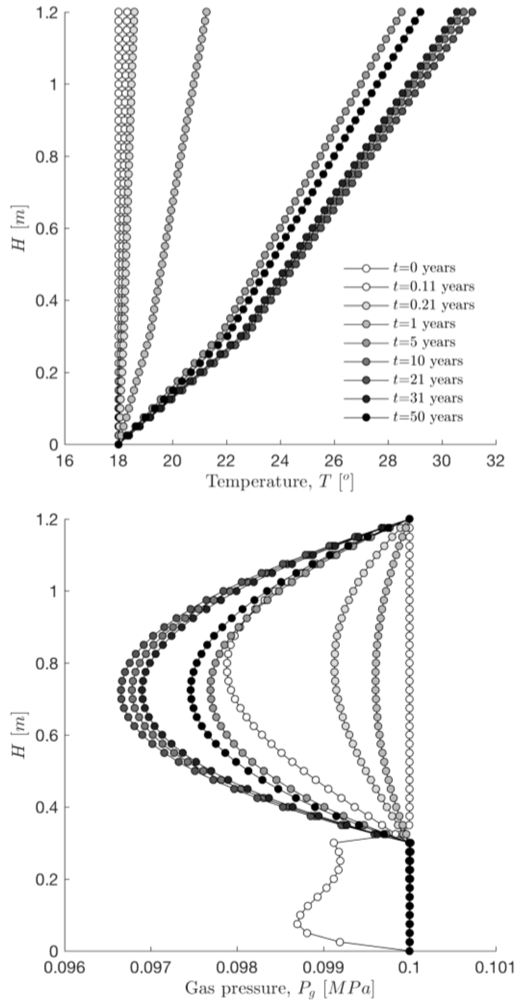


Figure 8 Temperature and gas pressure evolution with depth

The evolution of the temperature reflects the conditions imposed at the boundaries, being significantly higher in the clay than in the sand. This heating is initially accompanied by desaturation, which reduces the initial moisture content of the clay by about 6 percentage points. This drying reduces the initial horizontal stress by 400 kPa, which would still correspond to a positive tensile stress of 270 kPa if the final load of the baled deposit is considered.

The changes are relatively fast, reaching the equilibrium moisture level about 5-10 years from the start of the simulation (Figure 8). This temporal development is logical if one takes into account the temporal evolution of the temperature (Figure 6), which dissipates very slowly after the initial rise. Since the increase rates of the mechanical loads applied to the lining is lower, transient situations may occur where unloading due to desiccation may draw the clay into traction. Although such tensile stresses may induce cracking and an increase of permeability in the clay, the subsequent load increase far exceeds the 60 kPa that Albrecht and Benson (2001) indicate as level of load capable of sealing possible existing cracks.

The level of drying obtained in the analysis is not just function of the temperature history imposed but aspects such as the position of the water table have a big influence on the results. In particular the above calculation was repeated by changing only the suction condition at the base to 25 kPa, which represents a position of water table at about 4 m depth below the geomembrane. This, despite not affecting the evolution of the temperatures in the clay barrier, has a big impact on its drying history. The humidity in this case is reduced by only two percentage points and the horizontal stress reduction does not exceed 150 kPa (Figure 10b). In this case there is no doubt that no tension cracks would develop in the clay.

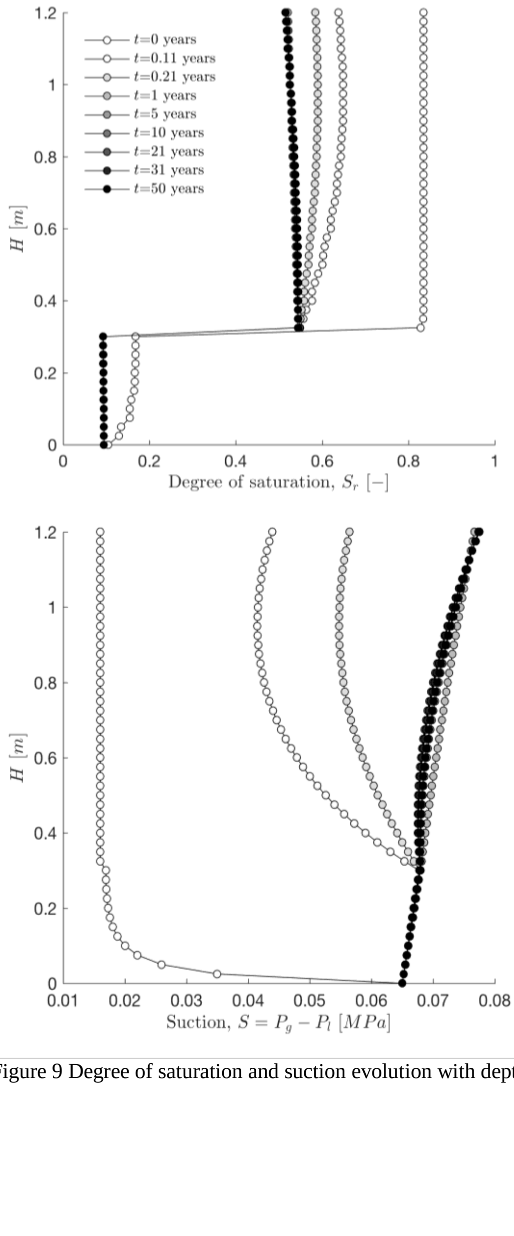
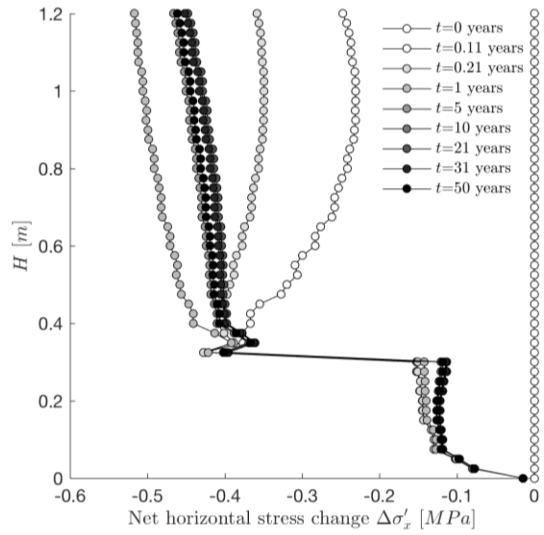
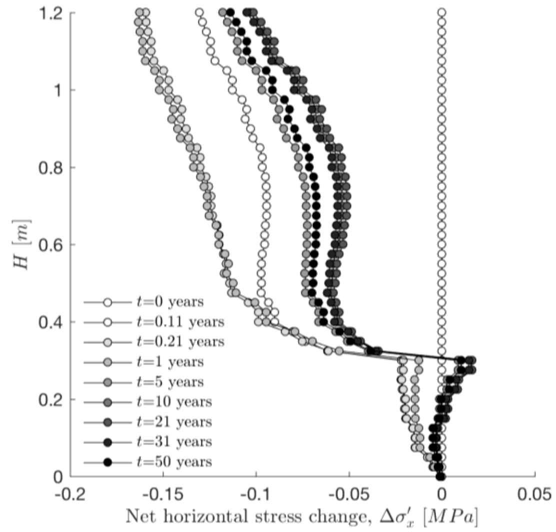


Figure 9 Degree of saturation and suction evolution with depth



a) Water table=7.6m



b) Water table=3.7m

Figure 10 Temperature evolution at observation points

5 CONCLUSION

THM coupled analysis have several applications in the field of MSW engineering. Here we have focused on a small scale problem, which is the response of compacted clay liners to the temperature history of the deposit. The evaluation of such temperature history was done by means of a separate model, in which a discrete element method was applied to represent a large scale problem.

For the cases studied here the most significant control of CCL response to thermal heating was the depth to water table beneath the CCL. When the water table was close to the liner there was no room for significant desiccation. Even for cases with a relatively deep water table the conditions were not conducive to cracking.

5 ACKNOWLEDGEMENTS

The work described in this paper was partly funded through the first Author's Junior Research Fellowship at Imperial College and the EU funded GEO-RAMP RISE project (H2020-645665-GEO-RAMP). Participation of the third author is supported by the Industrial Doctorate program of the Generalitat de Catalunya

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