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Gas breakthrough and emission through unsaturated compacted clay in landfill final cover

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ABSTRACT

Determination of gas transport parameters in compacted clay plays a vital role for evaluating the effectiveness of soil barriers. The gas breakthrough pressure has been widely studied for saturated swelling clay buffer commonly used in high-level radioactive waste disposal facility where the generated gas pressure is very high (in the order of MPa). However, compacted clay in landfill cover is usually unsaturated and the generated landfill gas pressure is normally low (typically less than 10 kPa). Furthermore, effects of clay thickness and degree of saturation on gas breakthrough and emission rate in the context of unsaturated landfill cover has not been quantitatively investigated in previous studies. The feasibility of using unsaturated compacted clay as gas barrier in landfill covers is thus worthwhile to be explored over a wide range of landfill gas pressures under various degrees of saturation and clay thicknesses. In this study, to evaluate the effectiveness of unsaturated compacted clay to minimize gas emission, one-dimensional soil column tests were carried out on unsaturated compacted clay to determine gas breakthrough pressures at ultimate limit state (high pressure range) and gas emission rates at serviceability limit state (low pressure range). Various degrees of saturation and thicknesses of unsaturated clay sample were considered. Moreover, numerical simulations were carried out using a coupled gas–water flow finite element program (CODE-BRIGHT) to better understand the experimental results by extending the clay thickness and varying the degree of saturation to a broader range that is typical at different climate conditions. The results of experimental study and numerical simulation reveal that as the degree of saturation and thickness of clay increase, the gas breakthrough pressure increases but the gas emission rate decreases significantly. Under a gas pressure of 10 kPa (the upper bound limit of typical landfill gas pressure), a 0.6 m or thicker compacted clay is able to prevent gas breakthrough at degree of saturation of 60% or above (in humid regions). Furthermore, to meet the limit of gas emission rate set by the Australian guideline, a 0.6 m-thick clay layer may be sufficient even at low degree of saturation (i.e., 10% like in arid regions).

1. Introduction

Biodegradation (i.e., anaerobic activities) of municipal wastes produces a large amount of landfill gas, namely CO_2 and CH_4. The landfill gas may emit into the atmosphere and hence endanger the lives of nearby residents. Although gas collection systems have been widely used, landfill gases cannot be collected completely (McBean et al., 1995; EPA, 1999). To minimize emission of landfill gas to the atmosphere, a common approach to isolate municipal wastes from the environment is to construct an engineered cover over landfills. Compacted clay has been widely used for landfill final cover systems due to its relatively low saturated water permeability (Albright et al., 2004; Benson et al., 2007; Barnswell and Dwyer, 2012). Although saturated permeability is a key parameter for assessing the feasibility of compacted clays used as hydraulic barriers in landfill final covers, it is not sufficient to evaluate the performance of compacted clay barriers as gas barriers in terms of gas breakthrough pressure and emission rate at different weather conditions. This is because landfill covers are unsaturated in service (Weeks and Wilson, 2005; Zhan et al., 2014). Infiltrated rainfall water can increase the degrees of saturation of soil but improbable to render it fully saturated. This implies that it would be non-conservative to consider a saturated compacted clay for impeding gas flow since unsaturated soils typically favor gas flows than saturated soils. Several studies have been carried out to investigate the effects of different factors (e.g., moisture content, cover thickness, temperature and methane flow rate) with regards to

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methane oxidation rate in biocovers (Perdikea et al., 2008; Abichou et al., 2014; Sadasivam and Reddy, 2015; Mei et al., 2015; Zhang et al., 2015). For example, Perdikea et al. (2008) investigated the performance of thin biocovers for oxidizing methane emissions in a bioreactor landfill under various moisture contents, cover thicknesses, methane flow rates and compost-to-sawdust ratios by conducting column experiments. Generally, suitable biocover materials require high soil porosity for better gas exchange in order to facilitate the penetration of oxygen from the atmosphere and methane supply from landfills (Huber-Humer et al., 2011). Thereby, the permeability of biocovers is typically high since the permeability is mainly governed by soil porosity. To the authors' knowledge, there is no available study on low permeability soils like compacted clay to explore its feasibility as gas barrier in terms of preventing gas breakthrough and emission in landfill covers under various clay thicknesses and degrees of saturation.

To investigate gas breakthrough pressure of clay at ultimate limit state (high gas pressure), water-saturated swelling clay has been widely tested (Tanai et al., 1997; Galle, 2000; Graham et al., 2002; Harrington and Horseman, 2003; Hildenbrand et al., 2002), due to its applicability in nuclear waste disposal which generally locates hundreds of meters below the ground surface. The measured gas breakthrough pressure of saturated swelling clay is very high (in the order of MPa). The reported value may not be applicable to a compacted clay in the landfill cover due to several reasons. Firstly, as illustrated above, compacted clay in the landfill cover is usually unsaturated. Effects of degree of saturation on gas breakthrough pressure in the context of landfill cover are not known. Secondly, although landfill gas pressure can reach up to 50 kPa at some extreme condition (Wei, 2007), field monitoring results suggest that landfill gas pressure is typically less than 10 kPa (McBean et al., 1995). Compared with typical gas pressures observed in nuclear waste disposal, gas pressure in municipal waste landfill is much lower. The huge difference in gas pressure may affect test results, for example, due to change in the compressibility and density of gas.

For the gas emission rate at serviceability limit state (low gas pressure), Moon et al. (2008) carried out a series of gas permeability tests on oven-dried clayey soil using a permeameter. Based on their measurements, they concluded that compacted clay may not be sufficient to prevent landfill gas emission. It should be pointed out that the available guidelines for designing landfill covers utilizes gas emission rate rather than gas permeability. For example, Australian guideline (Carbon Farming Initiative (CFI), 2013) allows for a maximum methane emission rate of 63 ml/m^2/min. The gas emission rate should be strongly affected by not only gas permeability of soil, but also the thickness and degree of saturation of soil layer. Moon et al. (2008) only tested dry triaxial size soil specimens, which are much smaller than the typical thickness of compacted clay (or fine-grained soil) layer in a landfill (i.e., 0.3–1.5 m) (EPA, 1999). To fully understand the efficiency of unsaturated compacted clay on minimizing gas emission, it is necessary to investigate the influence of clay thickness and degree of saturation.

In this study, two series of gas breakthrough tests at a pressure range of 0–50 kPa and two series of gas emission rate tests at pressure range of 0–20 kPa were carried out on unsaturated compacted Kaolin clay by using one-dimensional soil column. Three clay degrees of saturation (40%, 60% and 80%) and two clay thicknesses (0.4 m and 0.6 m) were considered. The numerical modeling is carried out to better understand the experimental results by extending the clay thickness and varying the degree of saturation to a broader range that is typical at different climate conditions. As far as the authors are aware, this is the first study to investigate the feasibility of unsaturated compacted clay as a gas barrier in landfill covers under various degrees of saturation and clay thicknesses. The results can improve our understanding of gas breakthrough and emission in unsaturated compacted clay and hopefully provide useful insights to the optimum design of landfill cover systems.

2. Theoretical considerations

2.1. Gas breakthrough in unsaturated soil

According to Galle (2000), gas breakthrough pressure of soil cover can be determined from the relationship between landfill gas pressure and gas emission rate. Fig. 1 shows a conceptual diagram illustrating the relationship between gas emission rate and gas pressure for unsaturated soils. It can be seen that when gas pressure is low (i.e., lower than point *A* shown in the figure for the clay), gas emission rate is almost negligible. This may be because for unsaturated clay, the soil pores occupied by gas may not be interconnected to form a gas flow pathway. Only the process of gas diffusion takes place in this pressure range (Graham et al., 2002). When gas pressure increases up to a threshold value (point *A*), gas emission rate increases dramatically. The sudden increase of gas emission rate is mainly because some isolated pores may be forced to be continuous, resulting in a much higher gas flow. Point *A* is referred to as the breakthrough point and the corresponding pressure as gas breakthrough pressure.

It should be pointed out that the gas breakthrough pressure of unsaturated soil is different from the well-known air-entry value of soil. The latter one is defined as the matric suction, which is the difference between pore air pressure and pore water pressure, where gas starts to enter the largest soil pore. The entrance of gas into the soil pores does not necessarily induce a dramatic increase of gas flow rate.

2.2. Gas emission rate in unsaturated soil

By considering the compressibility of gas, Scheidegger (1974) modified the Darcy's law to calculate gas emission rate in soil:

$$Q = \frac{k_g A \left(P_{in}^2 - P_{out}^2\right)}{2\mu H P_{out}} \quad (1)$$

where Q is the volumetric emission rate (m^3/m^2/s); k_g is gas permeability of soil (m^2); μ is dynamic viscosity of gas which is equal to 1.76×10^{-5} Pa s for air at 20 °C; A is cross-section area (m^2); H is thickness of soil (m); P_{in} is absolute inflow gas pressure (Pa); and P_{out} is absolute outflow gas pressure (Pa). It is well recognized that k_g of unsaturated soil is strongly dependent on the degree of

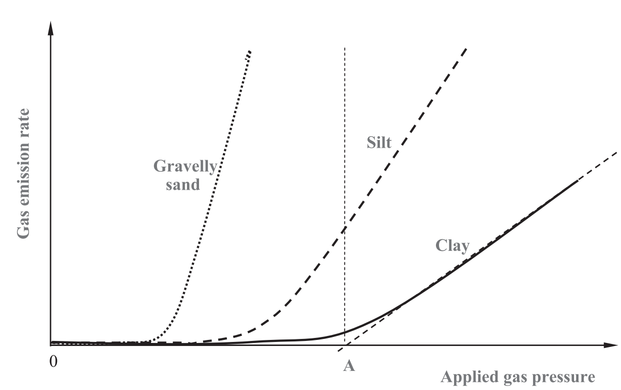

Fig. 1. Schematic diagram showing the relationships between gas emission rate and gas pressure of silt, gravelly sand and clay.