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PRESSURE FIELD TESTS TO INFER PERMEABILITY OF WASTE BODIES UNDER IN SITU AERATION

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ABSTRACT: This paper presents the preliminary results of field trials conducted to investigate the air permeability of waste at the Braambergen landfill located near the city of Almere, the Netherlands. Pressure variations were monitored in surrounding wells during air extraction tests using differential pressure transducers. The magnitude of the pressure response to gas abstraction indicates suitability of the method to investigate waste permeability and the swiftness of the pressure response indicated good connectivity within the investigated well field. The obtained air permeability values showed a trend where permeability decreased as the distance between two wells increased, suggesting higher permeability in closer proximity to a well. Although the values are comparable to those reported in other landfills, the differences can be explained by the influence of site-specific factors on permeability.

Keywords: Permeability, aeration, pressure test

1. INTRODUCTION

An ambitious experiment in the Netherlands employs the in-situ stabilization techniques of aeration and leachate recirculation to reduce long-term emissions from landfills and bring them out of aftercare within the next decade (Vereniging Afvalbedrijven 2014). This experiment entailing three large-scale pilot projects started in 2017, is world-leading and potentially transformative for the landfill industry in developing and demonstrating a new approach to post-closure management. Within the context of the experiment, projects are carried out on three landfills in the Netherlands: Braambergen (province Flevoland), Wieringermeer (province North-Holland), and De Kragge II (province North-Brabant). One of the key challenges to successful in-situ stabilization is the preferential flow of gas and water through the heterogeneous and anisotropic waste body, possibly limiting spatial outreach of air flow and hence the spatial extent of the stabilization effect (Gebert et al 2022; Meza et al 2022). Pressure field tests can be used to determine the interconnectivity of aeration wells and the permeability within the waste body.

Air permeability in landfills plays a critical role in the management and performance of these waste disposal sites. Air movement within the landfill body directly affects the processes of gas generation, migration, and control (Jain et al 2005). Understanding and assessing air permeability is crucial for designing effective landfill gas management systems and evaluating potential environmental impacts. Air permeability refers to the ability of air to flow through the waste mass and other materials present in the landfill. The permeability of the landfill is influenced by various factors, including the composition and compaction of the waste, the presence of liners or covers, and the overall site design. Assessing and monitoring air permeability in landfills typically involves conducting permeability tests, where flow rate and changes in pressure over time are monitored (Wu et al 2012; Jain et al 2005).

This paper reports results of experiments conducted at Braambergen landfill, The Netherlands, with the goal to determine the permeability of the landfill body by conducting air abstraction tests tests on vertical gas wells. The results of these tests will contribute to a wider suite of experiments, including gas tracer tests (e.g. Imhoff et al 2003) aimed at determining how effective the landfill aeration is at accessing and treating all areas of waste within the landfill body.

2. MATERIALS AND METHODS

2.1 Site description

The Braambergen landfill is located near the city of Almere in the province of Flevoland, the Netherlands (Figure 1). The pilot project consists of four compartments: 11 Noord (11N), 11 Zuid (11Z), 12 Oost (12O), and 12 West (12W). These compartments were operational from 1999 to 2008 and cover an approximate surface area of 10 hectares (Meza et al 2022).

Since 2017, the Braambergen landfill has been undergoing in-situ stabilization through aeration. A network of 332 wells has been drilled across the four compartments, with well spacing ranging from 15 to 20 meters. These wells are operated in low-pressure aeration since 2019, enabling overextraction of gases as well as combined air injection and extraction processes on individual wells. The depth of the wells is 10 to 12 m from the surface, with a filter screen in the lower 1.8 meters. This filter screen acts as a barrier, allowing the passage of the gas while preventing the entry of unwanted materials, such as sediment or larger particles. By using these filter screens, gas can be extracted or monitored from within the landfill, decreasing the risk of contamination or clogging. The depth of the wells ensures that aeration reaches a significant distance in the lower parts of the landfill, allowing for effective extraction or monitoring of the gas production.

The in-situ aeration technique being employed at the Braambergen landfill aims to stabilize the waste mass and reduce long-term emissions. By introducing controlled air flow into the landfill, it facilitates the decomposition of organic waste and promotes the conversion of landfill gas, which primarily consists of methane, into carbon dioxide. This process helps to mitigate greenhouse gas emissions and improve the overall management of the landfill site (Meza et al 2022).

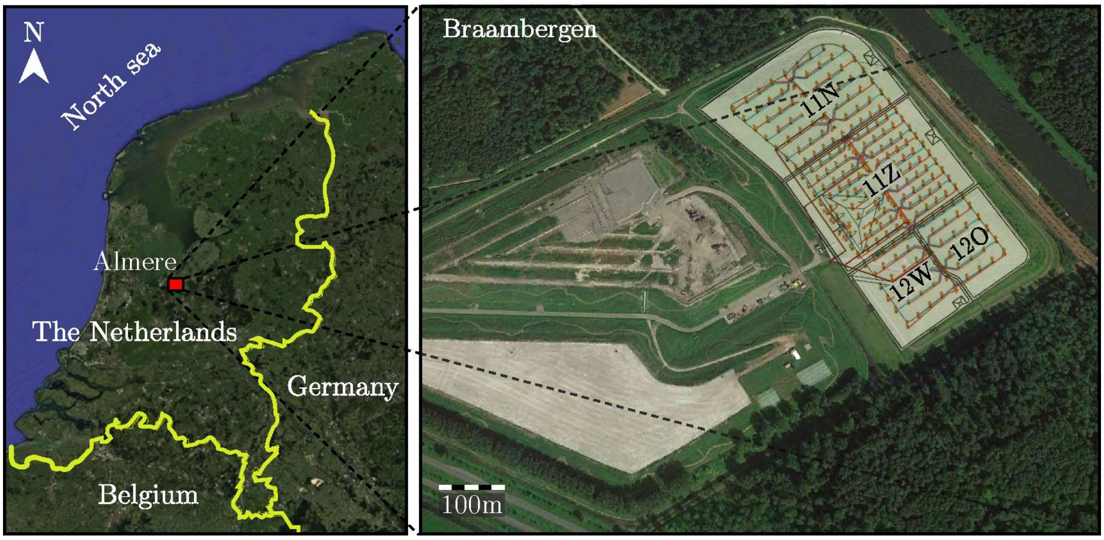

Figure 1. Braambergen landfill location, the four compartments that are aerated and the network of wells.

2.2 Pressure field tests

At the Braambergen landfill, gas pressure field tests were conducted in December 2022 on groups of wells to assess the impact of different operating conditions of in-situ aeration and the extraction process specifically. In compartment 11N of the landfill (Figure 1), air extraction from the wells was carried out using a small portable blower (Dutair model DB200). During the air extraction tests, the blower was connected to a central well, aiming to generate pressure variations within that well. Simultaneously, changes in pressure were monitored in eight surrounding wells located at radial distances ranging from 14 to 41 meters from the aeration well.

The purpose of these gas pressure field tests was to evaluate the effectiveness and spatial extent of the in-situ aeration process. By monitoring pressure variations in the surrounding wells, it is possible to assess the propagation of pressure changes and the influence of aeration on gas flow patterns within the landfill body. This information helps to understand the interconnectedness of the wells and the overall permeability distribution within the waste mass.

To measure pressure variations, differential pressure transducers and HOBO dataloggers were utilized. The pressure transducers used in the monitoring system were analogue Honeywell TruStability® differential pressure transducers with a measuring range of 70 mbar. The compensated pressure range of these transducers was between 10% and 90%, which provided an effective measuring range of -40 to +40 mbar. To connect the pressure transducers to the dataloggers, each transducer was connected via 15 meters of cable and a junction box. The power for the transducers was supplied by a single 9V battery located in the junction box. This setup allowed for remote and continuous monitoring of the pressure variations within the wells.

Each pressure sensor was connected to an individual wellhead using a short length of flexible tubing. The HOBO dataloggers were responsible for recording and storing the pressure data over time, enabling further analysis and interpretation.

Figure 2 provides a visual representation of the setup configuration used during the tests, as well as an example of a monitoring well equipped with a pressure sensor. This configuration allows for efficient and precise monitoring of pressure variations within the landfill wells during the testing period.

Figure 2. Test equipment utilized during the experiments.

Table 1 represents the configuration of the air abstraction tests. The first column lists the abstraction wells, the second column indicates the air flow rates (in m³/h) extracted from the abstraction well during each experiment and the third column presents the duration of the test. The subsequent columns indicate the spatial distances (in meters) between the abstraction well and the corresponding monitoring wells. The spatial distribution of the abstraction and monitoring wells, over compartment 11N, is shown in Figure 3.

Table 1. Configuration of the air abstraction tests.

Abstraction Well	**Air Flow (m^3/h)**	**Duration (minutes)**	**Distance from abstraction well to monitoring well (m)**								
			Dn3	**Dn5**	**D4**	**D5**	**E4**	**E5**	**Cn4**	**Dn4**	**En4**
Dn5	58.2	46	41.0	-	33.7	15.3	30.9	13.3	31.0	20.5	26.7
Dn3	57.9	60	-	41.0	13.3	31.1	15.5	33.7	26.5	20.5	30.7

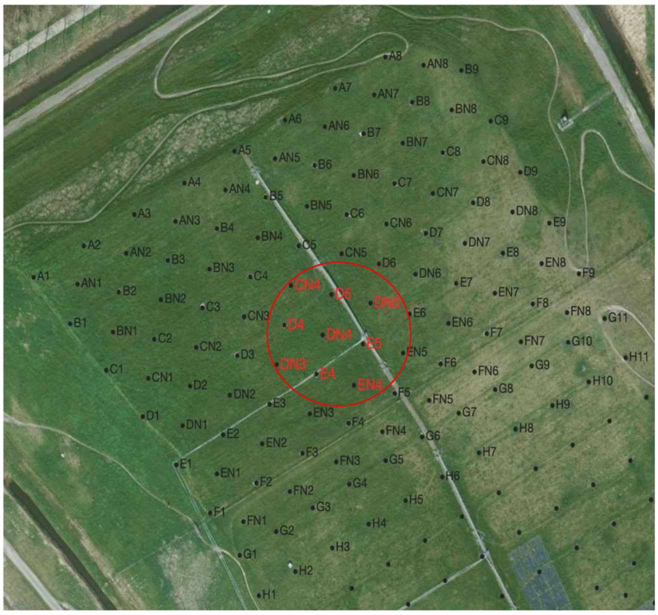

Figure 3. Distribution of aeration wells over compartment 11N. The red circle highlights the abstraction and monitoring wells listed in Table 1.

2.3 Determination of air permeability

The aeration well field at Braambergen, is typically operated using overextraction. All wells are put under suction to draw atmospheric oxygen into the waste through the permeable top cover. In this way, the landfill domain shares some similarities with a leaky aquifer in terms of the behavior of fluids and gases within its domain. Therefore, when it comes to analyzing gas pumping tests in the landfill domain, certain principles from aquifer analysis can be applied.

Following the description given by Baehr and Hult (1991) the landfill can be described as a domain separated from the atmosphere by a confining unit (Figure 4) where the upper confining unit (top cover) is leaky and less permeable to air than the domain. The bottom boundary is formed by the water table (impermeable to air). Emulating the leaky aquifer theory of Hantush (Hantush and Jacob, 1955), leakage through the confining unit is assumed to be distributed across the whole upper domain.

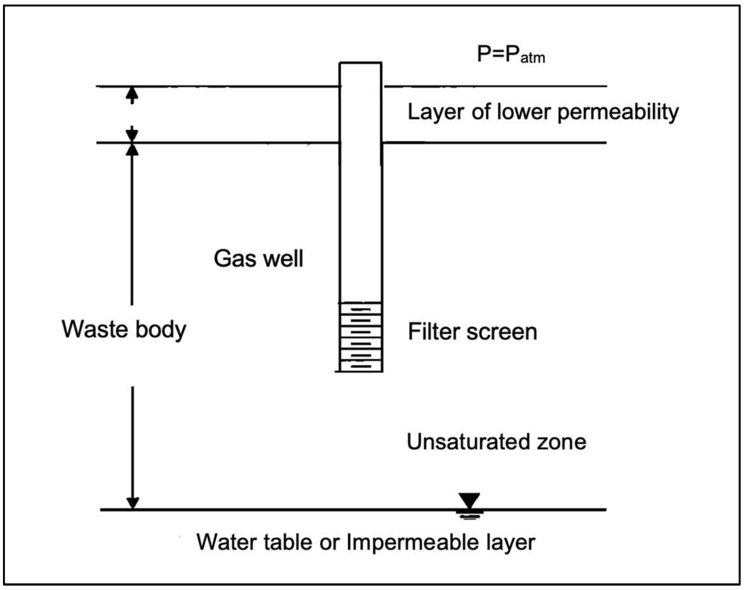

Figure 4. Landfill domain representation as an unsaturated zone separated from the atmosphere by a layer of lower permeability.

The Hantush inflection point method for analyzing short - to medium - duration groundwater pumping tests was adapted for use in gas pumping tests. It involves plotting the drawdown of the well during the extraction versus time on a logarithmic scale. The Hantush inflection point, corresponds to the point on the curve where the drawdown changes from a straight line to a concave curve. At the inflection point, the relationship between the drawdown and the slope of the curve is given by:

$$2.3*sp/\Delta sp=K0(r/L)*\exp(r/L) \tag{1}$$

Where:
Sp is the inflection point drawdown (m)
Δsp is the slope of the curve at the inflection point.
K0 is the Modified Bessel function of the second kind and zero order.
r is the radial distance from the center of the abstraction well to the monitoring well (m).
L is the leakage factor (m).
exp(r/L) is the exponential function.

Once the slope Δsp is obtained the transmissivity of the waste body can be calculated as follow:

$$KD=2.3*q*\exp(r/L)/(4\pi*\Delta sp) \tag{2}$$

Where:
KD = T is the transmissivity in m^2/d
q is the pumping rate or extraction rate during the pumping test (m^3/d).

The permeability (k) is obtained as follows:

$$k=T*\mu/(\rho*g*D) \tag{3}$$

Where:
k is the permeability in m^2
T is the transmissivity in m^2/d
μ is the air viscosity in kg/(m*s)
D is the thickness of the vadose zone in m
ρ is the density of the air in kg/m^3
g is the acceleration due to gravity (m/s^2)

3. RESULTS AND DISCUSSION

Figure 5 shows the pressure variation observed in the monitoring wells during the abstraction tests. These clearly indicate that during both tests, all the surrounding wells responded to air abstraction. The immediate drop in pressure suggests that gas was successfully extracted from the wells and indicates good connectivity within the well field. Furthermore, when the extraction was stopped, the pressure in the monitoring wells swiftly recovered. This rapid pressure recovery further reinforces the indication of good connectivity within the well field. The data in Figure 5, shows a variation in the pressure response in monitoring wells, which ranged between -0.8 to -1.8 mbar. As demonstrated in Figure 6, which shows the maximum measured pressure change plotted against distance from the extraction well, there is a correlation between pressure and distance, with less of a response as distance increases.

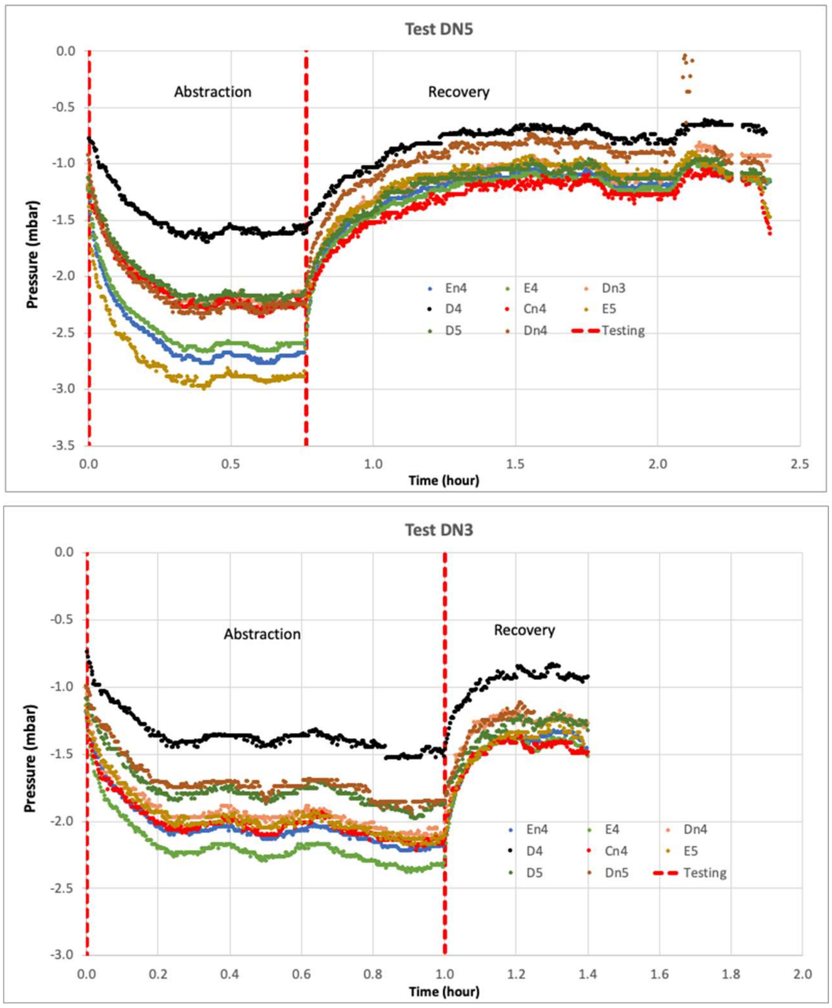

Figure 5. Pressure response of the sensors located in the monitoring wells during the abstraction tests. The red dashed lines indicate the duration of the abstraction test.

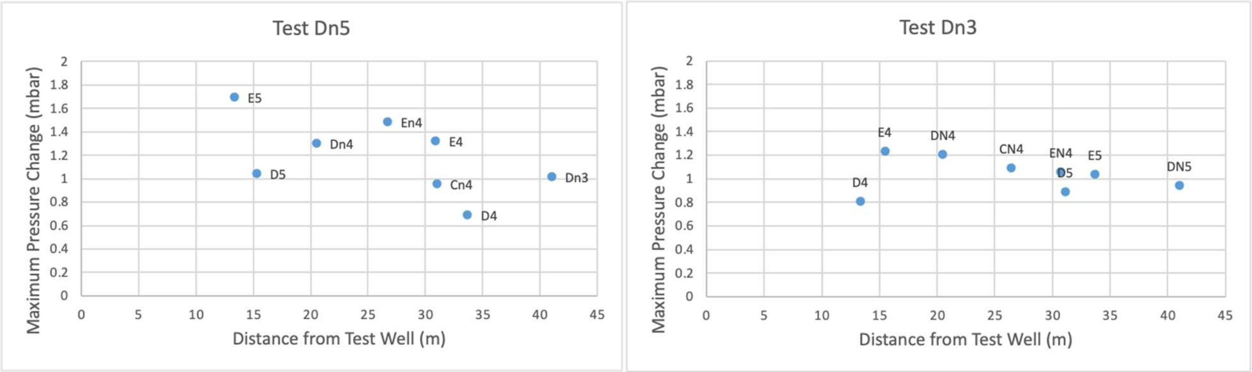

Figure 6. Maximum pressure variation (mbar) per well according to the distance to the abstraction well.

The permeability of the waste, between the abstraction well and each monitoring well, was obtained for both tests (Test Dn5 and Test Dn3). Permeability values as presented in Table 2 and Figure 7, according to the Hantush method, were obtained by using the Matlab toolbox Hytool (Renard, 2017).

Table 2. Field air permeability of the waste body of Braambergen landfill.

Abstraction Well	Permeability (m^2) * 10^{-11}										
	Dn3	Dn5	D4	D5	E4	E5	Cn4	Dn4	En4	Mean	STD
Dn3	-	4.32	7.26	3.73	5.30	5.10	6.48	5.89	4.71	5.35	1.16
Dn5	2.08	-	2.43	2.77	3.00	3.49	2.63	3.32	3.22	2.87	0.48

Figure 7 shows the air permeability values of the waste body between the abstraction well and each monitoring well according to their distance to the abstraction well. There is a slight trend, observed in both tests, where the permeability values increase as the distance to the abstraction well decreases. This trend suggests that the air permeability tends to be higher in closer proximity to the wells and decreases as the distance away from a well increases. This may be due to increased probability of direct preferential channels developing in close proximity to a well resulting in higher permeability values. As the distance increases, the air flow pathways may become more convoluted, leading to a decrease in permeability. Increased distance between a pair of wells being tested may result in more lower permeability waste contributing to the average permeability value recovered.

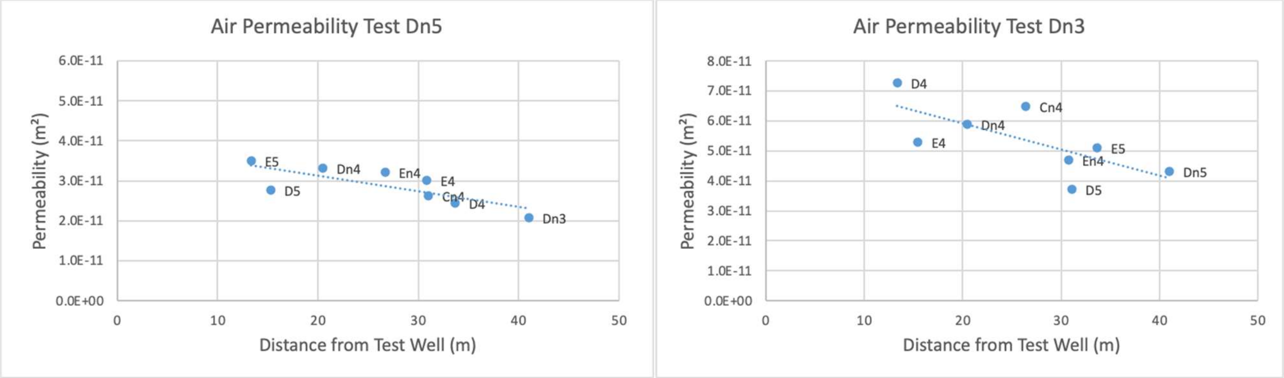

Figure 7. Air permeability k (m^2) values obtained from each monitoring well vs distance to the abstraction well.

The permeability values obtained are in the same order of magnitude to the ones presented by Jain et al (2005) where the mean permeability was 1.3 x 10^{-11} m^2. Moreover, if the obtained permeability values are compared to the ones obtained by Wu et al (2012), those are one order the magnitude larger. The average value presented by Wu et al (2012) is 1.87 x 10^{-12} m^2. Permeability in landfills can vary significantly depending on the specific site conditions, including factors such as waste composition, compaction, moisture content, age of the landfill, and the presence of liners or barriers. These factors can affect the arrangement and connectivity of void spaces, resulting in different permeability values.

The approach used in this paper is different from the approach of Jain et al (2005) and Wu et al (2012), who looked at the pressure change in the extraction/injection well, which can be influenced by factors such as well losses. Well losses refer to the hydraulic losses that occur within a well, including frictional losses along the wellbore and losses due to turbulence or other factors. These additional factors introduce complexities and potential uncertainties in the measurement.

By using monitoring wells, which are not directly involved in the extraction/injection process, the method presented in the paper avoids the need to account for well losses. The pressure changes measured in the monitoring wells can be considered more reliable indicators of the aquifer response, as they are less affected by the specific characteristics of the extraction/injection well.

An important point to consider is that during the experiments the aeration system of the landfill was in operation. The potential effects of this on the experiments and results presented in this study have not yet been quantified and could be the explanation of the differences in the average air permeability values obtained during both experiments.

More field tests are needed to cover the whole extension of the landfill. The results presented in this paper only considered the compartment 11N. Compartment 11Z is known to have groundwater tables above the filtered part of the aeration wells (Gebert et al., 2022), which should reflect in lower permeability values. Compartment 11Z exhibits distinct characteristics compared to compartment 11N. This includes lower flow rates, higher variability in CH_4 concentrations, and higher ratios of CH_4 to CO_2, indicating a higher prevalence of anaerobic processes (Meza et al, 2022). Given these differences in operational conditions and gas composition, it is reasonable to expect that the air permeability values in compartment 11Z may deviate from those obtained in compartment 11N. The variations in flow rates, gas concentrations, and anaerobic processes can impact the distribution and movement of air within the landfill, potentially influencing air permeability.

Additionally, it is worth noting that landfill conditions can change over time, and factors such as waste settlement, compaction, and degradation can further influence air permeability. Therefore, ongoing monitoring and periodic reassessment of air permeability values are crucial to capture any changes in the landfill's behavior and optimize management strategies accordingly.

4. CONCLUSIONS AND OUTLOOK

This study presents preliminary results of field trials to investigate the air permeability of waste at the Braambergen landfill. Pressure data, collected in several gas wells during air abstraction in two main wells, have been used to estimate air permeability values of the waste body at the compartment 11N of Braambergen. The values obtained are similar to the ones obtained for other researchers in different landfills. The magnitude of the pressure response to gas abstraction indicates the suitability of the method to investigate waste permeability. The swiftness of the response indicated good connectivity within the investigated well field. Whether the calculated permeabilities are sufficient to allow for effective aeration of the waste body, needs to be studied further.

Further testing is needed, not only at 11N, but also around all compartments of the landfill to determine the variability of waste body permeability. In order to determine how effective aeration of the whole waste body is, further tests including tracer gas tests need to be conducted at the site.

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