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LANDFILL GAS MIGRATION MODELLING – A PREQUISTE FOR DETERMINING ENVIRONMENTALLY COMPATIBLE GAS GENERATION RATES

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SUMMARY: Landfills containing organic matter pose an environmental risk for many decades. This is also the case for the landfill Heferlbach, which has been filled until 1974 with more than 200,000 tons of waste. Since no liners have been installed at this site, landfill gas generation represents a potential hazard to the surrounding environment. In particular, the risk for methane migration into adjacent buildings was the main reason for remediating the landfill via in-situ aeration (currently ongoing). This paper aims to evaluate the risk of methane migration/accumulation in the surroundings of landfills. Thereto a 2-dimensional mathematical model allowing for simulating convective, dispersive and diffusive transport of landfill gas has been developed and subsequently applied. The modelling results demonstrate that landfill gas migration is to a large extent driven by diffusion and thus highly sensitive to the air filled porosity of the surrounding subsurface. Moreover, it was shown that even for a worst case scenario potential methane accumulation in the basement of neighboring buildings are non-hazardous and well below the explosive limit of 5 vol-%.

1. INTRODUCTION

Landfills containing significant amounts of organic matter pose an environmental risk for many decades after closure. Besides the generation of leachate containing high amounts of salt and organic pollutants, the production of landfill gas (consisting of methane and carbon dioxide) endangers the surrounding environment. In case of landfill gas, negative environmental impacts (emissions of the greenhouse gas methane) are observed even on a global scale. According to IPCC (2006) about 3 to 4% of global anthropogenic greenhouse gas emissions originate from waste disposal sites.

Whereas leachate emissions and their potential impact on the environment (groundwater) have been investigated in numerous studies (Barker et al., 1988; Barlaz et al., 2002; Han et al., 2014; Porowska, 2015), research on landfill gas migration and associated risks are rather underrepresented (Kjeldsen and Fischer, 1995; Nastev et al., 2001). In many cases only the flow of CH_4 and CO_2 within the landfill has been the subject of modelling efforts, thereby assessing the influence of gas wells (in particular their design and operation) on the amount of landfill gas collected and emitted

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via the landfill cover (Martín et al., 2001; Xi and Xiong, 2013).

A clear linkage between source of emissions (waste), migration and potential impact on the receiving environmental media, as it has been accomplished for landfill leachate (Hjelmar et al., 2001; Laner et al., 2010), has not been established for landfill gas so far. Such linkage however is crucial for assessing the environmental compatibility of landfills and their emissions as demonstrated by Laner (2011).

Hence, the present study aims at evaluating the impact of landfill gas generation and migration on receiving environmental media (e.g. methane accumulation in the cellar of adjacent buildings or within the top cover of the landfill). By comparing the potential impact of gas migration with acceptable levels for the particular affected media, recommendations regarding environmentally acceptable landfill gas generation rates are derived.

As site specific conditions are not only determinant for the migration of landfill gas but are also decisive for acceptable levels of methane or carbon dioxide concentrations in receiving media, a case study landfill was chosen to illustrate the developed approach.

2. MATERIALS AND METHODS

2.1 Landfill Heferlbach

The case study landfill Heferlbach is located close to the city of Vienna in Austria (48° 08' 46" N, 16° 31' 21" E). Between 1965 and 1974 more than 200,000 tons of waste were disposed of at the site, of which almost two-thirds can be classified as municipal solid waste MSW and the remaining part as construction, demolition and excavation waste. The landfill covers a surface of about 66,000 m². Hence, the average deposition height of the waste (including the landfill cover) is only about 3.5 m (see Figure 1).

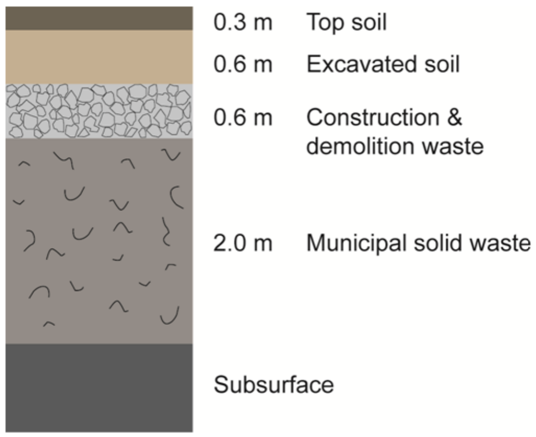

Figure 1. Average depth profile of the landfill Heferlbach (Brandstätter et al., 2013)

Since no liners have been installed (neither at the bottom nor lateral nor at the top), leachate emissions but also landfill gas generation still represent a potential hazard to the surrounding environment. The local hydrogeological situation however (leachate infiltrating into the subsurface is immediately diluted by the underlying groundwater aquifer of the river Danube) renders groundwater pollution to a subordinate priority. Thus, the risk for methane and carbon dioxide migration into adjacent buildings (see Figure 2) was considered as the main reason for remediating the landfill via in-situ aeration, which was initiated in 2012. Since then, the waste deposit has been aerated using horizontal air injection pipes.

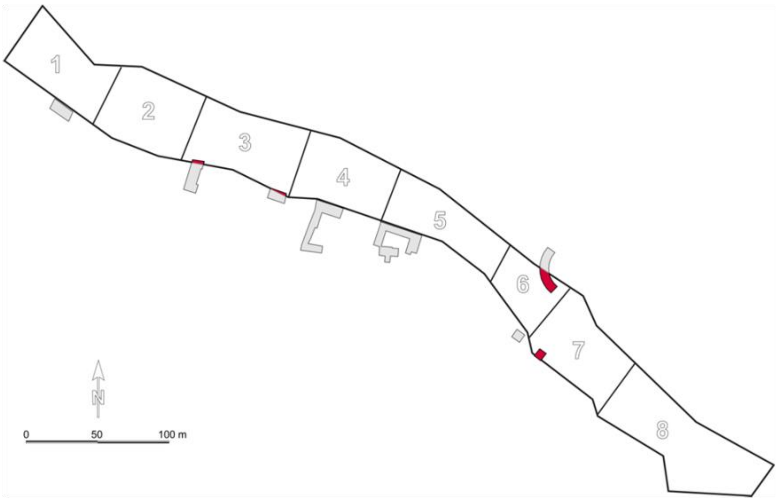

Figure 2. Map of the landfill Heferlbach. Numbers indicate sections for on-going in-situ aeration, the grey shaded structures indicate buildings, where the red shades represent building parts directly located on the landfill (Brandstätter et al., 2013)

The aeration of the waste aims to decompose/stabilize the organic matter still present in the landfill and thereby decrease the potential for future landfill gas generation (after air injection has been terminated) to an "environmentally acceptable" level. In the frame of the present paper, it is attempted to assess such acceptable level of gas generation via gas migration modelling. Thereby specific site conditions (profile of landfill, waste composition and its reactivity, distance to adjacent buildings etc.) are taken into account.

2.2 Gas Migration Modelling

Landfill gas migration in wastes and the adjacent soil and subsurface is governed by pressure and concentration gradients. Pressure-driven movement of fluids and gases is known as advection, whereas concentration driven migration as diffusion.

According to porous medium fluid dynamics the following convection-dispersion equation (in conjunction with the conservation of mass) can be formulated:

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(\theta_{air} \cdot D_{eff}\frac{\partial c}{\partial x}\right) - v \cdot \frac{\partial c}{\partial x} + G \tag{1}$$

where c is the concentration of the gas species in the gas phase [g/m³], t is the time [s], x is the coordinate [m], θ_{air} is the air filled porosity [m³/m³], v represents the advective gas velocity [m/s], G is the generation rate of the gas species [g/m³], and D_{eff} is the effective dispersion coefficient [m²/s], which can be calculate as follows:

$$\theta_{air} \cdot D_{eff} = D_L \cdot |v| + \theta_{air} \cdot D_g \cdot \tau_g \tag{2}$$

D_L represents the longitudinal dispersion [m], $|v|$ is the absolute value of the advective gas velocity [m/s], D_g is the molecular diffusion coefficient in air [m²/s] and τ_g is a tortuosity factor [-]. The latter accounts for the longer connecting path imposed by obstacles within porous solids relative to that for motion in unconstrained free space (Zalc et al., 2004). According to (Millington and Quirk, 1961) the tortuosity factor τ_g can be estimated as follows:

$$\tau_g = \frac{{\theta_{air}}^{7/3}}{n^2} \quad (3)$$

where n represents the total pore space [m³/m³].

The advective gas velocity v can be calculated using Darcy´s law as:

$$v = \frac{k_a}{\mu} \cdot \frac{\partial P}{\partial x} \quad (4)$$

where P is the gas pressure [Pa], k_a is the soil-air permeability [m²] and μ is the dynamic viscosity of air [Pa*s]. Equation 4 ignores the compressibility of gases and thus changes in gas density. But since observed gas pressure differences at landfills (due to landfill gas generation or short time changes in atmospheric pressure) are generally well below 3 kPa (Gebert and Groengroeft, 2006; Spokas and Bogner, 1996), which is only about 3% of the atmospheric pressure, the error made by this simplification is small.

A brief evaluation of available numerical tools for simulating gas migration in porous media based on the equations given above, showed that the program HYDRUS-2D (Šimunek et al., 1996) considers all equations and offers large flexibility with regard to the definition of flow domains and boundary conditions. In addition, it provides a rather user-friendly interface. Although HYDRUS-2D was originally developed by the US Salinity Laboratory in Riverside to simulate water flow and solute transport in variably saturated porous media, it may also be applied to trace the movement of gases due to pressure and concentration gradients. However, when applying HYDRUS-2D for gas transport modelling the following limitations and simplifications need to be accepted:

- incompressibility of gases (tolerable due to rather small pressure differences)
- constant air-filled porosity of the porous media over time (changes can only be simulated via different scenarios)
- constant air permeability of the porous media over time (changes can only be simulated via different scenarios)

For simulating gas migration into the surroundings of the Heferlbach landfill, the profile illustrated in Figure 3 (left side) and a corresponding model set up (including the definition of the flow domain) for HYDRUS-2D are chosen (Figure 3 – right side). The definition of the flow domains “Atmosphere” and “Basement” are necessary in order to allow for a dilution of the landfill gas emitted into air and thus ensure a realistic concentration gradient for the landfill gas component investigated (methane). In particular, the dilution of the landfill gas component emitted has been implemented in HYDRUS-2D via a first order decay function. For instance, methane generated in the landfill and migrating into the “Atmosphere” or “Basement” is there virtually converted (applying a first order decay) into a second gas. The amount this second gas accumulating in the atmosphere or in the basement represents the amount of methane emitted from the landfills to both media and is defined as an output of the modelling in HYRUS-2D. The chosen modelling approach assures a realistic concentration gradient of the landfill gas components (e.g. methane) between waste and potentially affected environmental media.

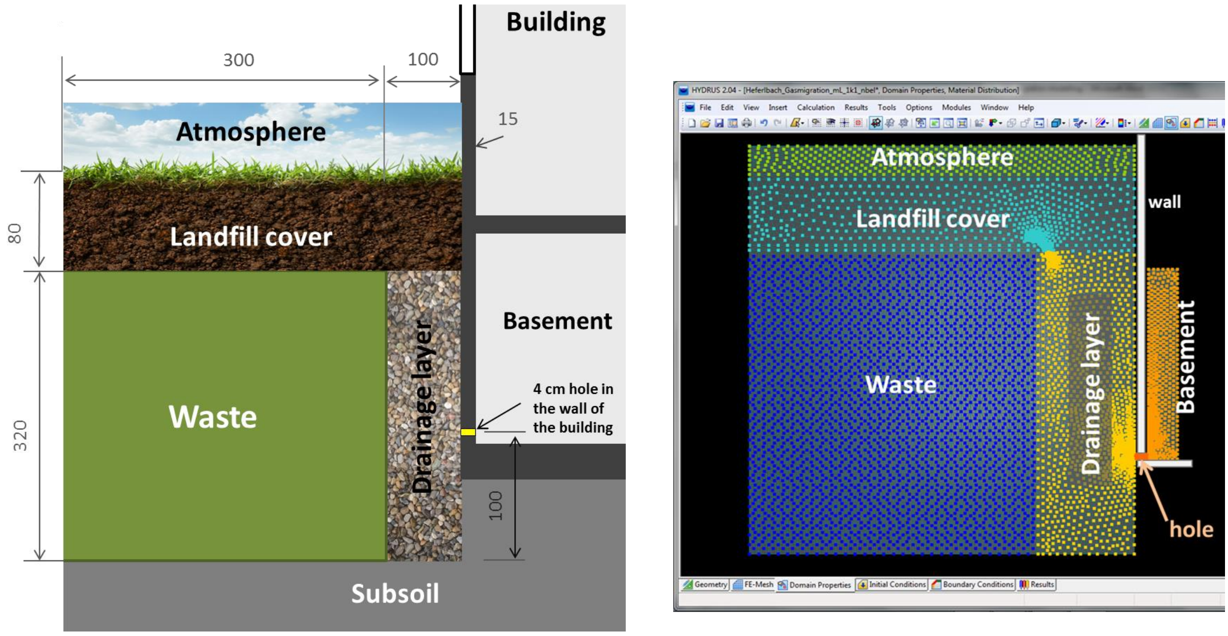

Figure 3. Profile of the Heferlbach landfill modelled (left) and its implementation (flow domains defined) into the software HYDRUS-2D (right)

The generation of gas within the landfill has been implemented in the model via a simple source term (amount of landfill gas produced per finite element and time period), which has been applied for the whole waste domain. Advective outflow of the landfill gas may occur via the upper boundary of the "Atmosphere" and the lateral boundary of the "Basement". The relative gas pressure at these boundaries is set to zero (representing atmospheric pressure), whereas for the waste domain excess pressure is inevitably provided by HDRUS-2D as a result of the defined production (inflow) of landfill gas.

For assessing environmentally acceptable landfill gas generation rates, various scenarios are analyzed. Different sets of parameters for the gas permeability k_a the porosity n, and the air field porosity θ_{air} of the landfill cover, the drainage layer and of the outer basement wall of neighbouring buildings have been defined to reflect a range of possible combinations and their effects on gas migration/accumulation (e.g. in the basement). Thereby causal correlations, such as decreasing air filled porosity θ_{air} and reduced soil-air permeability k_a are taken into account. The scenario simulation results indicate "best-case" and "worst-case" estimates as well as most probable outcomes given the various parameter settings chosen (see Table 1). The modelling results (e.g. methane accumulation in the basement of adjacent buildings) are subsequently compared to limit values for indoor air quality and safety standards defined by national guidelines and problematic scenarios (i.e. parameter combinations) are identified.

Table 1 summarizes the required input data of HYDRUS-2D and gives ranges for the parameter values finally used. It should be noted that some input data may not be directly inserted into the entry mask of the software, but rather represent the database used to determine the input values required for HYDRUS-2D.

For the molecular diffusions coefficient of methane in air a value of $2.1*10^{-5}$ m²/s is applied. This coefficient gets drastically lowered in porous media depending on the total porosity n and the air-filled porosity θ_{air} (see equation 2 and 3).

Table 1. Ranges for the main input parameter required to simulate landfill gas migration

Flow domain	Soil-air permeability k_a *(in vertical direction)*	Ratio between horizontal & vertical permeability	Porosity n	Air filled porosity θ_{air}
Unit	*[m²]*	*[-]*	*[m³/m³]*	*[m³/m³]*
Waste	$10^{-13} - 10^{-15}$	0.3 – 3	0.4 – 0.5	0.12 – 0.18
Landfill cover	$10^{-12} - 10^{-14}$*	0.3 – 3	0.4	0.04 – 0.20*
Drainage layer	$10^{-11} - 10^{-14}$*	0.3 – 3	0.4	0.04 – 0.20*
Hole	$10^{-9} - 10^{-10}$	1	1	1
Atmosphere & basement	$>10^{-8}$	1	1	1

** small values represent rather wet conditions with high water contents, whereas larger values can be considered as representative for dry conditions with low water contents and thus high soil-air permeability*

Landfill gas generation (implemented as inflow into the waste domain) is modelled using two different rates: (a) 1 m³ of landfill gas per ton waste and year, and (b) 0.15 m³/ton/a. The higher rate (a) refers to the maximum landfill gas generation at the site prior to in-situ aeration. It is derived from landfill simulation reactor experiments using waste samples from the landfill being rich in organics. The lower generation rate (b) is based on results from laboratory tests running for two years. During these tests, waste samples taken from the landfill were continuously aerated. The observed reduction in total landfill gas generation (during incubation tests over 21 days) after 2 years of aeration in comparison to untreated waste samples is used to assess the lower range of landfill gas production in this study. This rate should reflect the maximum gas generation of the waste after thorough aeration (i.e. post-remediation stage).

3. RESULTS AND DISCUSSION

Altogether 40 scenarios (different combinations of material characteristics, absence and presence of holes in the outer wall of the basement, different gas generation rates) for landfill gas migration were modelled. The results of these modelling efforts are illustrated in the Figures below.

For assessing the environmental compatibility of potential gas migration/accumulation two points of compliance PoC are defined (see Figure 4). They represent points where certain criteria, defining the acceptable level of contamination for the affected environment, have to be fulfilled.

- PoC1 considers the maximum tolerable impact of landfill gas migration in the basement room of an adjacent building. In order to mitigate explosion risks, the maximum methane concentration in the room is limited to 3 vol-%. For the simulations we assume a volume of the basement room of 3 m³ per m² outer wall adjacent to the landfill. This geometry in conjunction with the assumption that a complete air exchange of the cellar room occurs once every two weeks (very conservative approach), results in an "air volume" available for diluting intruding methane of 80 m³ per m² outer wall and year.
- PoC2 considers the maximum methane concentration in the soil air of the landfill cover. In the present study the maximum allowed concentration of CH_4 was arbitrarily set to 5 vol-% at this point.

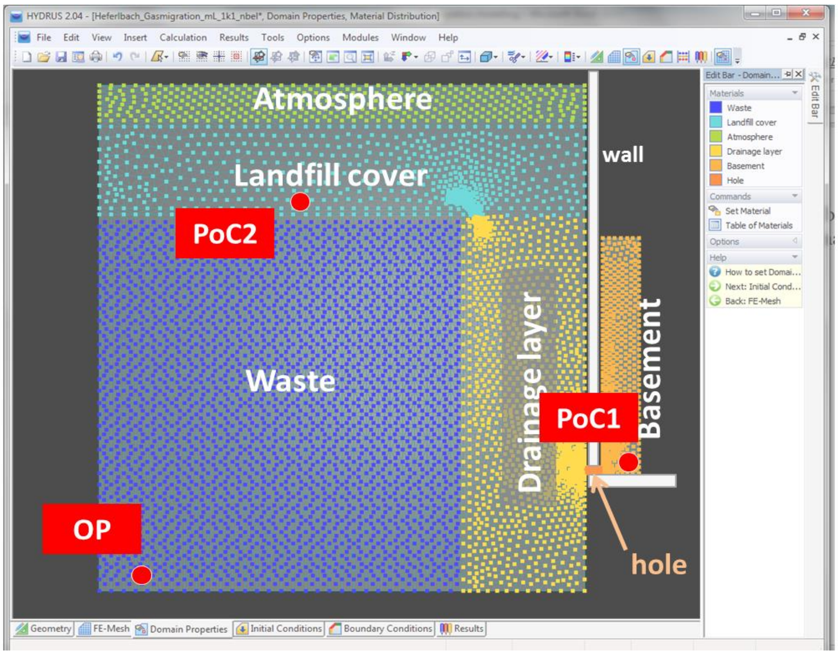

Figure 4. Point of compliances PoC1 & PoC2 and observation point OP for evaluating the environmental compatibility of landfill gas production and migration

In addition to the two PoCs, the methane content at an observation point OP located at the bottom of the waste body is investigated. For this observation point the methane concentration is calculated, but not compared to limit values, as such values do not exist for air present in the waste body itself. In case that at any point in the future the landfill might be considered as "natural environment" again, for this OP an alike limit value as for PoC2 (5 vol-%) is to be expected.

In Figure 5 methane concentrations for the whole domain simulated are exemplary illustrated. Red colours indicate high contents of methane (up to 50 vol%), whereas blue colours represent low concentrations.

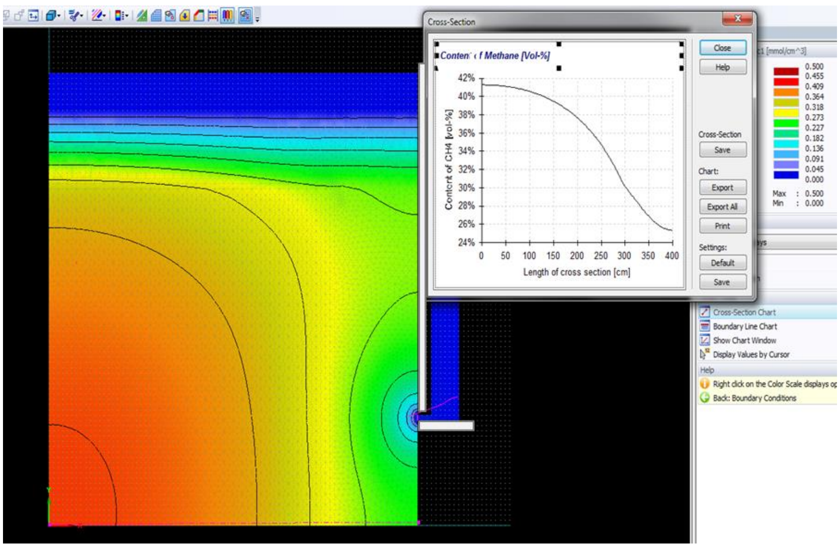

Figure 5. Schematic illustration of model results generated (methane concentration over the flow domain modelled). The XY-line-plot represents the concentration gradient at the bottom - screenshot of the software HYDRUS-2D

The main outcomes of the landfill gas migration modelling (methane concentrations at the different points of compliance and at the observation point located at the landfill bottom) are summarized in Figure 6 and 7. The results indicate that in any case (even if there is a hole of 200 cm² per m² outer wall of the cellar, and unfavorable conditions for the release of landfill gas via the landfill surface exist, such as a high water content of the landfill cover) the limit value of 3 vol-% methane in the cellar room of an adjacent building (PoC1) will not be reached. The highest concentration observed at PoC1 for the different scenarios investigated is 2%.

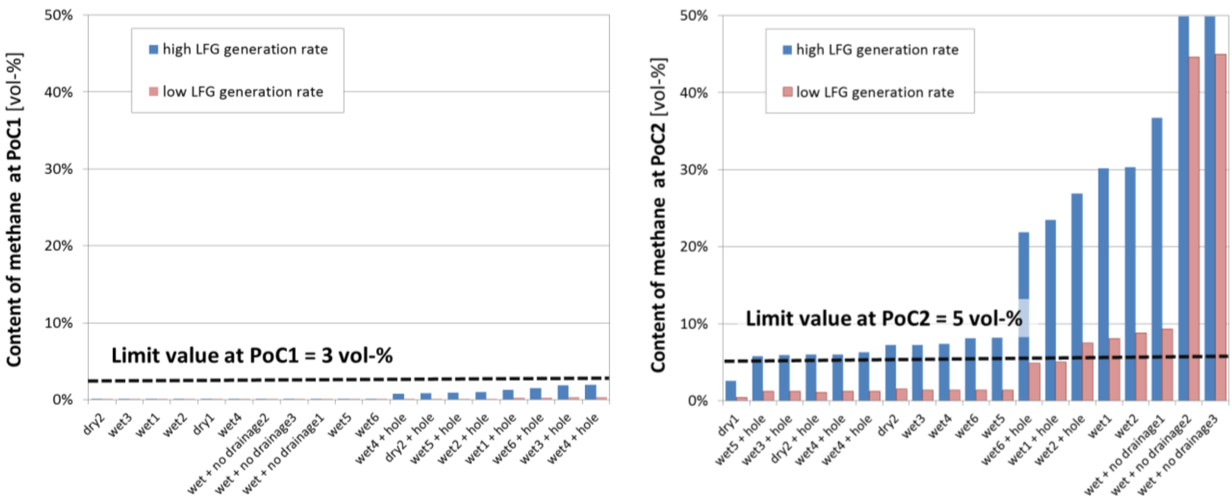

Figure 6. Content of methane (given in vol-%) at the points of compliance for different scenarios modelled. Left: PoC1 (cellar room adjacent to the landfill), right: PoC2(lower part of landfill cover).

With respect to the methane content at PoC2, the outcomes of the simulations demonstrate that for the high landfill gas generation rate (1 m³/t/a) the limit value of 5 vol-% will be exceeded in any case. Only for very favourable conditions - low water content of the landfill cover and thus high gas permeability and significant diffusion – the methane content at PoC2 is expected to be below the limit value. On the contrary, this is not the case for thelow landfill gas generation rate of 0.15 m³/t/a. Here the target value of 5 vol-% methane in the landfill cover can be complied with in most cases. Only in the absence of a vertical drainage layer or if the air filled porosity θ_{air} of the landfill cover drops below 0.03 m³/m³ (almost full water saturation of the soil) methane contents above 5 vol-% might be observed.

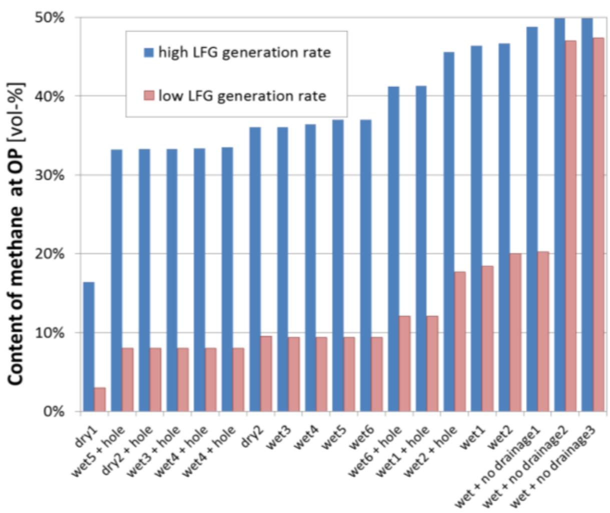

Figure 7. Content of methane at the landfill bottom (observation point OP) for the different scenarios modelled (given in vol-%)

For the observation point OP at the bottom of the waste deposit, the simulated methane content ranges from 16 to 50 vol-% for the high landfill gas (LFG) generation rate, and it is between 3 and 47 vol-% for the low LFG generation rate. Contents of methane below 5 vol-% are only observable for rather dry conditions (air filled porosity of landfill cover soil and waste are above 0.18 m³/m³) and therewith associated high gas diffusion rates.

In general, the results of the simulations demonstrate the significance of the air filled porosity θ_{air} (and thus the water content) of the landfill cover and the drainage layer for the methane concentration at the different points of compliance. A sufficient air permeability of the cover layer may sustain low methane concentrations in environmental media adjacent to the waste even at higher rates of LFG generation.

5. CONCLUSIONS

Landfill gas migration into the surrounding environment (e.g. cover soil, drainage layer, cellar room) is driven by pressure and concentration gradients. A two dimensional flow model implemented using the HYDRUS-2D software demonstrated that neighboring buildings of the Heferlbach landfill are not endangered of gas migration and unacceptable methane accumulation in the basement. Even a worst case scenario (high rate of landfill gas generation, presence of holes in the outer cellar wall, short distance (1 m) between cellar wall and degradable waste, high water content of cover soil and thus low air permeability, biweekly air exchange in the cellar room) revealed that the maximum methane concentration in the basement is less than 2 vol-% and thus well below the lower explosive limit of 5 vol-%. This result indicates that the methane explosion risk in buildings bordering the landfill does not justify the on-going in-situ aeration of the waste, as LFG generation rates observed prior to aeration, would not lead to explosive gas mixtures in adjacent cellar rooms.

With regard to the soil air composition in the landfill cover (PoC2), the on-going in-situ aeration of the landfill may is expected to reduce methane concentrations by about factor 5. This implies that in most cases methane contents in the soil air will be well below 5 vol-% after the landfill gas production rate of the waste has been reduced to 0.15 m³/t/a via in-situ aeration.

For the gas present in the pore space of the landfill, methane contents can hardly be reduced to less

than 10 vol-%. Even after long-term aeration of the waste high water contents of the landfill cover or clogging of the vertical drainage layer may result in methane contents well above 15 vol-%.
In summary, the outcomes of the present study demonstrate that landfill gas migration is to a large extent driven by diffusion. Thus, it is highly sensitive to the air filled porosity of the surrounding subsurface. This implies that the water content of the surrounding soil represents a crucial parameter when assessing the risk of landfill gas migration, since the porous water reduces the available air space. From a design and management perspective, this finding reveals that sustaining high air contents in the landfill cover and surrounding soil by using coarse material and draining soil water, may be sufficient for mitigating risks associated with the generation of methane and carbon dioxide at many old landfill sites.

AKNOWLEDGEMENTS

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