QUANTIFICATION OF LONG TERM EMISSION POTENTIAL FROM LANDFILLS

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SUMMARY: Novel approaches for the after-care of Municipal Solid Waste (MSW) landfills are based on technological measures to reduce the long term emission potential in a short time period. Biological degradation in landfills is a means to significantly reduce the long term emission potential. Leachate emission to the groundwater is considered to be one of the largest long-term impacts related to landfilling. Currently we are starting up a research program, partly subsidized by the Dutch Technology foundation STW, aimed towards developing a frame work which allows for a quantitative assessment of the long-term emission potential of a landfill. The research program is closely connected to demonstration-projects which will be carried out by the Dutch landfill operators Afvalzorg and Attero. These projects aim to demonstrate the reduction of long-term emission potential by a combination of leachate recirculation and landfill aeration.

This project aims to develop an original and efficient measurement, monitoring and modeling framework for 1) quantification of the long-term emission potential of landfill bodies (with and without stabilization) and 2) optimization of the applied landfill stabilization technology for reducing the emission potential. Three sub-projects will be carried out within the STW subsidized program:

1. Integration of high resolution geophysical measurements with 3D process modeling to obtain 3D-time lapse images of processes in the landfill body;
2. Quantification of bio-geochemical heterogeneous activity in full-scale landfills;
3. Integrated modeling and up-scaling of landfill processes and heterogeneity;
4. In addition to the above mentioned projects which are going to start in the first half of 2011, a PhD-project started in September 2010 focusing on quantification of the flow processes controlling the long-term emission potential.

1. INTRODUCTION

Research in the last couple of decades has provided us with a signficant amount of knowledge about the processes taking place in the landfill body and how these processes lead to emissions towards the environment of the landfill [Kjeldsen et al. 2002; Haarstrick et al. 2004; Kindlein et al. 2006; Beaven 2008]. This knowledge has lead to the development to approaches which lead to an enahanced stabilization of the landfill body. Two main approaches can be identified: 1) Infiltration and recirculation of landfill leachate stimulating the anaerobic degradation of solid organic matter leading to an enahced methane production and 2) stimulated aeration of the landfill body leading to enhanced degradation of organic matter by creating local aerobic conditions.

Two Dutch landfill operators plan to start demonstration projects the coming year within the frame work of the Dutch Foundation for Sustainable Land filling. The goal of these projects is to demonstrate a two step approach to landfill stabilization. First, an anaerobic step (based on infiltration and recirculation of leachate) is used to produce as much methane as possible in order to capture and use this methane for energy production. Once the efficiency of the methane production has decreased, a second step is foreseen in which the landfill body is aerated. This will cause part of the remaining fraction of organic material and especially organic nitrogen to degraded and be removed from the landfill body. After these two steps, it is expected that the bio-geochemical conditions within the landfill cause the emission potential to be minimal. The preparatory findings for these demonstration projects have been described by [Heimovaara et al. 2010].

A major fundamental issue, resulting in major operational difficulties, is that bio-geochemical conditions in landfills are spatially very heterogeneous. Leachate recirculation improves the degradation under methanogenic conditions by reducing the effects of this heterogeneity. However, the volume of the landfill body that is stabilized is uncertain and it may be that parts of the landfill body still contain an unknown but significant amount of emission potential. The objective of this project is to develop a cost-effective methodology for quantifying the remaining long-term emission potential of full-scale landfills currently in operation, that at the same time can provide information for optimal management of the engineering methods for reducing emission potential.

Understanding and quantifying the consequences of landfill body heterogeneity is an essential part of this new methodology. The approach is based on innovative measurement and monitoring tools on the landfill scale, combined with probabilistic modeling techniques describing the coupled transport and degradation processes occurring in the landfill body. With these tools we will be able to obtain a quantitative assessment of the remaining emission potential as well as an assessment of the rates of emission under different scenarios, both during and after stabilization treatment. The tools will be integrated in application protocols. One for providing information for optimal application of engineering methods for enhanced landfill stabilization and another for estimation of the long-term emission potential.

The methods and tools developed in this project are to be used by landfill operators in order to implement and operate landfill stabilization techniques in the most optimal sense (lowest cost and highest efficiency). On the other hand, the methods will also be used to develop indicators for long-term landfill emission potential and behavior. These indicators provide guidance to the authorities and regulators for the development of (new) policies and regulations that allow for a significant reduction in after-care. As such the deliverables of this project will be essential for adopting and implementing a risk-based-approach for landfill after-care. Sustainable after-care of landfills is much to be preferred as the burden will be relieved for the future generations, in addition the total cost for society will be less than a non-sustainable eternal after-care approach.

The aim of the paper is to introduce the project. This is done by defining the problem, identfying the goals of the project and giving an outline of the approach. First a description is given of the underlying conceptual model of the landfill, the waste present, and the processes occurring in the landfill body. Then the research program, to be carried out by 3 PhD-students and 1 Post Doctoral researcher is presented.

2. PROBLEM DESCRIPTION

The rates at which the bio-geochemical reactions occur within a landfill depend on the local conditions [Reinhart 1995; Kjeldsen et al. 2002; Kindlein et al. 2006]. Optimal degradation of organic matter requires (a) presence of sufficient water for the initial hydrolysis of the organic waste into small dissolved organic molecules, (b) neutral pH-conditions, (c) not too high salinity,

(d) sufficient presence of nutrients for micro-organisms to grow, and (e) presence of electron-acceptors. These conditions are highly variable throughout the landfill body due to land-filling history, differences in waste type, differences in local landfill topography, different waste ages etc. As a result the bio-geochemical conditions and amount of degradation are heterogeneous throughout the landfill: organic matter can be fully degraded in some parts of the landfill while in other parts of the landfill no degradation has taken place at all (fully dry pockets without any hydrolysis).

The main hypothesis underlying this project is that heterogeneity in degradation in landfill bodies is due to a lack of mobile water in the non-degraded zones. When it is too dry, hydrolysis, being the first (and often rate limiting) step for bio-degradation, will not occur. On the other hand, in fully saturated conditions with stagnant leachate, hydrolysis can easily occur but in the first steps of bio-degradation organic acids are produced which reduce the pH. Sometimes accumulation of these acids leads to toxic pH levels for the micro-organisms limiting further bio-degradation. Mobile water in both these cases would reduce the negative effects due to increasing moisture contents, flushing and dilution of the organic acids and the transport of additional nutrients towards the active zones. Therefore, optimal conditions for bio-degradation require both sufficient and moving water throughout the waste body.

Full-scale application of landfill stabilization technology, however, is severely limited by the fact that it is very difficult to know the distribution of the effectiveness of measures throughout the landfill body. As a result, only qualitative estimations can be given over the effect of different stabilization approaches. As a consequence, regulators are reluctant to accept these approaches as alternative after-care measures. In addition, full-scale projects tend to have a large trial and error component, which considerably increases costs.

3. GOAL OF PROJECT AND UNDERLYING CONCEPTS

This project aims to develop an original and efficient measurement, monitoring and modeling framework for 1) quantification of the long-term emission potential of landfill bodies (with and without stabilization) and 2) optimization of the applied landfill stabilization technology for reducing the emission potential. The ambition of the project is to quantify the long term emission potential of a landfill body and provide tools to assess the uncertainty in this quantification

Quantification should be based on an understanding of landfill heterogeneity, water and gas flow patterns through the landfill and how these flow patterns influence the local bio-geochemical processes. In order to achieve this we require methods with which we can link measurement data to the processes occurring so that we can make statements at the scale of a full-scale landfill cell. The following conceptual ideas underly the academic research program supporting the full-scale demonstration projects:

- A landfill cell can be considerd to be a highly heterogeneous body of waste material where the composition and properties of the waste is highly variable in space. Waste material cannot be considered to be similar to soil and as a result direct implementation of soil based models and concepts for flow of water and gas may lead to erroneous results. Waste material often has an internal porosity (i.e. paper, cardboard, but also waste in plastic bags) with a capillary action that significantly differs from the bulk properties of the waste.
- Compaction of the waste has a signficant effect on the distribution of properties throughout the landfill body. Besides a large heterogeneity in material properties, compaction of waste will lead to layers of different density and as a result a large anisotropy in relative hydraulic and gas permeability. Combining this with the fact that landfills are unsaturated systems, water will generally flow along preferential flow paths. A major part of the water present in the

landfill body will have very low flow rates. Experiments at full scale landfills indicate that most flow occurs in the order of 10% to 20 % of the pore volume [Johnston et al. 1996; Johnson et al. 1998; Johnson et al. 1999; Rosqvist & Bendz 1999; Rosqvist & Destouni 2000; Johnson et al. 2001; Rosqvist et al. 2005] .

- Data from bioreactor landfills indicate a strong impact of recirculation on the biodegradation of the Solid Organic Material present in the waste. Up to 90 % of the organic material present can be converted. These high values are obtained although flow seems to occur in only 10 to 20% of the pore space? "Slow" diffusion of water and solutes, apparently, plays a very significant role in stimulating the degradation of organic material. Currently the feedbacks between the degradation of organic material, the flow of water and the transport of (dissolved) solutes and gases are not very well understood [Luning et al. 2006].
- Landfill aeration causes local oxidation of the waste body during the active phase which leads to an increased stabilization rate. After the active phase has finished, diffusion of reduced material from the non-oxidized regions will reduce the oxidation level (i.e. the migration of methane throughout the landfill body). It is clear that the aeration leads to a more stable situation (less organic matter, less future settlement, etc.). However, anaerobic conditions will be restored throughout the landfill, after a period of time. What the impact of these gradual changes in redox conditions is on the long term development in the quality of the leachate is currently not known. Another question in this respect is to what extent ventilation of the landfill body occurs through the preferential flow paths.
- It is clear that landfill stabilization will never be able to completely stabilize the total waste volume in a short time? Waste enclosed in a plastic bag will not be influenced by processes occuring outside the plastic bad, waste embedded in highly hydrophobic material will also be isolated. In the long run, however, plastic may degrade or hydrophobicity may slowly be overcome and as a result the contamination present in this waste will start to migrate and potentially impact leachate quality.

4. APPROACH

In order to achieve the ambitions of this project: the development and use of an original and efficient measurement, monitoring and modeling framework in order to quantify the long-term emission potential of landfill bodies we will carry out four sub-projects:

1. Modelling of preferential flow in landfill bodies (PhD)
2. Integration of high resolution geophysical measurements with 3D process modeling to obtain 3D-time lapse images of processes in the landfill body (PhD)
3. Quantification of bio-geochemical heterogeneous activity in full-scale landfills (PhD)
4. Integrated modeling and up-scaling of landfill processes and heterogeneity (Post-Doc)

4.1 Modelling of preferential flow in landfill bodies

This sub-project is being carried out by a PhD-student (4 years) and is focussed on developing methods for describing preferential flow of water, solutes and gas through the landfill body. Experiments will be carried out at different scales to develop a (conceptual) model that can be parameterized at the landfill scale. Close collaboration with the two other PhD-students is foreseen, both in sharing data as well as in developing ideas and experiments. Much attention will be paid to concepts based on tracer experiments and stochastic flow processes.

The characteristics of the waste, the scale of the problem both in space and in time, make understanding and especially quantification of the water and gas flow a challenging task. We will approach the problem in two ways. In the first we consider the landfill to be a black box for which we will use a transfer function approach to quantify input output relations. This approach has been used in the past by [Rosqvist & Bendz 1999; Rosqvist & Destouni 2000; Zacharof & Butler 2004a,b] amongst many others. The main advantage of this approach is that we can quantify the behavior of the landfill using tracer experiments and that the scale of interpretation can be at the scale of the landfill. The disadvantage is that it is very difficult to quantify the processes occurring locally in the landfill body.

The second approach is based on understanding the local driving forces (gradients) and from this understanding, develop an upscaling approach. Important examples of these approaches are those where modelling has been attempted using flow models based on Richard's equation which is Darcy's equation under unsaturated conditions [White et al. 2003; White et al. 2004; Lobo & Tejero 2007; McDougall 2007]. [Johnson et al. 2001] compare different process based models applied to theire data from a landfill. Preferential flow plays a very significant role and the process based models they used at the time were not able to capture the fundamental behavior of the landfill. Investigating this issue will be an important part of our project.

Adopting these different approaches requires a large amount of experimental data. Besides collecting our own data on the different pilot projects and small scale experiments, we will try to obtain data from other sources as well.

The main research questions which will be addressed in this project are:

- How can (conceptual) models be parameterized by using a range of different geo-physcial techniques and experiments?
- What is the essential scale on which we should collect data for quantification of landfill biodegradation processes?
- What is the essential scale for estimating long term emission potential?
- To what extent is natural heterogeneity an important factor for estimating biodegradation and long term emission potential?
- What are the best modelling approaches to estimate biodegradation and/or long term emission potential?

4.2 Integration of high resolution geophysical measurements with 3D process-based modeling to obtain 3D-time lapse images of processes in the landfill body

This sub-project will be carried out by a PhD student and will be focused on developing methods for measuring and modeling the physical heterogeneity (mapping of stiffness) and leachate flow within large landfills. In addition, other physical parameters will be measured, such as settlement, water content, temperature etc. serving as inputs to the process-based modeling An important part of the research will be the combined application of high resolution seismic, electrical resistivity tomography (ERT), induced potential (IP) and self-potential (SP) methods [Ghose et al. 1998; Dahlin 2001; Dahlin et al. 2002a,b; Dahlin & Zhou 2004; Ghose & Goudswaard 2004; Ghose & Slob 2006; Grellier et al. 2006; Grellier et al. 2007; Grellier et al. 2008]. The seismic technology has recently been further developed within the Department of Geotechnology of TU Delft by incorporation of dedicated, high-frequency, shallow seismic vibrator technology into innovative processing algorithms.

The first part of this sub-project we develop conceptual images of the heterogeneity in the two landfills and develop time-lapse approaches suitable for landfill monitoring. This has not been attempted before. The main challenge in applying geophysical techniques in this project will be the interpretation (inverse modeling and image reconstruction). We propose to combine the different images from all geophysical techniques in a qualitative sense. These qualitative 3D-images form the basis for installing local infrastructure for acquiring important bio-geochemical data which will give detailed information on degradation processes and the physical structure of the landfill.

The next step will be to obtain a quantitative probabilistic interpretation of landfill heterogeneity from the geophysical measurements by applying models of occurring processes to obtain additional constraints for inverting the geo-physical measurements. The measurements will pick up the effect of the manipulations that we carry out in the landfill. Adding prior information about how the manipulation changes the situation in the landfill should improve the data interpretation and image reconstruction [Lambot et al. 2006a,b; Lambot et al. 2008] . This will be carried out in close collaboration with the post-doc. Application of the ERT, IP and SP measurements in a time-lapse monitoring mode will give images which indicate the effects of leachate movement throughout the landfill, especially if contrasts in salinity are used (tracer tests). The ERT, IP and SP measurements will not only be carried out from the surface of the landfill but also in so-called well-to-well configurations. We shall explore the option of installing electrodes in the drains present at the bottom of the landfill. The main research questions which will be addressed in this sub-project are:

- How can we visualize the spatial and temporal variation in stiffness in a landfill?
- How can we visualize the spatial and temporal variation in moisture content in a landfill?
- How can we visualize leachate flow in the landfill?
- How does preferential flow change with time?
- What causes the change in preferential flow?
- How can we interpret the geophysical results in the context of enhanced landfill stabilization (leachate infiltration, recirculation and aeration)?
- What are the quantifiable driving forces for the multiphase flow processes in the landfill?
- How does spatial heterogeneity influence the physical processes in the landfill?

4.3 Quantification of heterogeneous bio-geochemical activity in full-scale landfills

This sub-project will be carried out by a PhD student and focuses on development and application of methods for measuring and modeling the heterogeneity in bio-geochemical conditions within large landfills. Using the information from the geophysical images obtained in the project of PhD student 1, samples will be taken from different locations within the landfill. Biological activity will be measured on these samples and changes in the quality in the recirculated leachate and extracted landfill gas will be monitored.

In order to obtain high quality data for model verification, column lysimeter experiments with waste will be carried out within this sub-project. These columns (0.8 m diameter and 2 m height) will be filled with waste representative for the two demonstration sites. A series of recirculation and aeration experiments will be performed while leachate, gas and settlement is monitored in detail. The lysimeters will be equipped with electrodes so that high-resolution ERT and IP measurements can be made. At the end of each experiment, the residue will be analyzed to quantify the remaining emission potential in relation to the heterogeneity present in the lysimeters. Experiments with this setup provide important data on bio-geochemical process-kinetics and the aspects controlling biological degradation in full-scale landfills. The bio-geochemical model concepts will be integrated (together with the post-doc) into a 3D multi-physics model.

An important deliverable of this project will be modeling and measurement approaches which will provide an indication of the heterogeneity in the development of biological degradation processes on a large scale landfill. These approaches provide information on the magnitude and variation of important parameters for the probabilistic exploration of the long-term behavior of the two landfills. The main research questions which will be addressed in this sub-project are:

- What gradients in the landfill have an effect on the bio-degradation?
- How can we visualize the variation in bio-degradation activity?
- How is the visualized physical variation related to the variation in bio-degradation?
- How does preferential flow influence the bio-degradation rates?
- What are the quantifiable driving forces for bio-degradation?
- Can we reliably predict the future behavior of the important chemical species for biological activity (Nitrogen, Carbon etc.)?

4.4 Integrated modeling and up-scaling of landfill processes and heterogeneity (Post-doc)

This sub-project will be carried out by a Post-doc researcher (3 years) and is focused on developing and applying methods for integrating the information obtained over the different scales in a landfill into a modeling and data management framework. This modeling framework is meant to be used for improving landfill emission reduction technology and quantification of the long term emission potential of landfills.

Many different models have been developed that describe one or more processes occurring in landfills e.g. [Barlaz et al. 1989; El-Fadel 1999; McCreanor & Reinhart 1999; Haarstrick et al. 2001; Brun & Engesgaard 2002; Brun et al. 2002; Mora-Naranjo et al. 2003; van Breukelen & Griffioen 2004; van Breukelen et al. 2004; Haarstrick et al. 2004; Mora-Naranjo et al. 2004; McDougall 2007; Reichel et al. 2007]. The post-doc will focus on the more mechanistic approaches and will develop a multi-physics concept integrating water and gas flow, bio-geochemical reactions, reactive transport and settlement on the landfill body. A close collaboration with ECN is foreseen. Van der Sloot and co-workers have developed the expert system LeachXS (www.leaching.org), which couples the geochemical equilibrium modeling framework Orchestra based on standard thermodynamical databases to a large set of leaching data from samples from a wide range of different substances including waste from a large amount of different landfills. The aim is to use the modeling and data management of LeachXS expert system to analyze the data and integrate Orchestra in the multi-physics modeling framework of this project. The research group will also develop a close collaboration with other research groups on this topic throughout Europe.

In order to adequately handle the large heterogeneity within landfills we need to understand how processes occurring at a very small scale (microbial degradation of organic matter) couple to processes that occur at much larger scales (landfill settlement and landfill gas emissions) and how to simplify the description in order to obtain a usable modeling concept. Integrating the multi-physics modeling approach with the LeachXS/Orchestra database is very innovative, and this will allow us to identify general trends in landfill bodies. These trends will assist in extrapolating data obtained from the two demonstration landfills.

We are aware of the complicated nature of multi-scale physics models and that major simplifications will be required before these models can be applied on a day-to-day basis in landfill management. The main research questions to be addressed in this sub-project are:

- What approach should be chosen for integrating all the different landfill processes in a multi-physics modeling and data management framework?
- What approach should be chosen to up-scale the relevant processes to a manageable scale for landfill management?
- How should the multi-physics process models be integrated with the data in the modeling and data-management framework?
- How should the multi-physics models be simplified so that it becomes feasible to perform probabilistic long-term simulations for exploring the future emission potential of landfills?

5. CONCLUSIONS

Currently we are starting up a research program, partly subsidized by the Dutch Technology foundation STW, aimed towards developing a frame work which allows for a quantitative assessment of the long-term emission potential of a landfill. We are in the process of finding 2 PhD researchers and 1 Post-doc. The research program is closely connected to a number of demonstration-projects which will be carried out by the Dutch landfill operators Afvalzorg and Attero. These pilots aim to reduce the long-term emission potential by a combination of leachate recirculation and landfill aeration.

The main hypothesis underlying this project is that heterogeneity in degradation in landfill bodies is due to a lack of mobile water in the non-degraded zones. Quantification of emission potential should be based on an understanding of landfill heterogeneity, water and gas flow patterns through the landfill and how these flow patterns influence the local bio-geochemical processes. In order to achieve this we require methods with which we can link measurement data to the processes occurring so that we can make statements at the scale of a full-scale landfill cell.

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