PROCEEDINGS, TOUGH Symposium 2006
Lawrence Berkeley National Laboratory, Berkeley, California, May 15–17, 2006

MULTIPHASE MODELING AND INVERSION METHODS FOR CONTROLLING A LANDFILL BIOREACTOR

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ABSTRACT

In this study multiphase modeling and inversion methods implemented with the TOUGH2 and iTOUGH2 models are applied for controlling a landfill bioreactor. During a two year (2003-2004) leachate recirculation experiment at Ämmässuo, Finland, data were collected and a modeling approach developed for predicting the effects of leachate recirculation. During the construction of the full-scale bioreactor, modeling will support the planning of the monitoring system. An initial simulation model has been created for the whole landfill area. The model will be updated with all the new data from the area, and the approach will be further developed in order to be able to control the final bioreactor after the closing of the landfill in 2007.

INTRODUCTION

Bioreactor landfills are operated and controlled to rapidly accelerate the biological stabilization of the landfilled waste. The basic process used for waste treatment is leachate recirculation. Laboratory and pilot–scale studies have clearly demonstrated that leachate recirculation accelerates waste degradation, provides in situ treatment of the leachate, enhances the gas production rates, and promotes rapid settlement (Reinhart and Townsend, 1998). A number of full-scale demonstration projects with intensive data acquisition have been carried out or still going on (Reinhart, 1996; Yazdani, 1997), but the technology is still relatively new and under development.

Leachate is that portion of rainfall which comes into contact with the waste. To minimize the risk of leaks from the basal liner, conservative limits have been set on the maximum depth of water allowed to pond on the liner at the base of the landfill. These limits necessitate leachate collection systems for managing the amount of leachate that ponds on the liner. During the operational phase of a landfill, a considerable volume of leachate will be collected. Recirculation results in a decrease in the total volume of leachate that needs to be treated or disposed of, and a reduction in the degradable components of the leachate (Maloney 1986). Leachate recirculation is an attractive option also because it decreases the liabilities associated with the closure of a landfill. Degradation of the organic fraction of the waste will occur during the early phases of the landfill's life while the liner is still new and in its best possible condition (McCreanor, 1998).

The in situ storage of leachate is possible because the water content of the waste is generally below the residual saturation of the waste (McCreanor, 1998). The residual saturation of the waste is reported to be 20 – 35 % by volume (Oweiss et al., 1990; Korfiatis, 1984; Noble and Arnold, 1991). Numerous studies on the effects of leachate recirculation have shown increased biological activity (methanogenesis) and decomposition along with increased moisture content (Barlaz et al., 1990). Gurijala and Sulfita (1993) reported that a moisture content in the range of 50 to 60 % was the best for methanogenesis.

The hydraulic conductivity of the waste has been investigated by a number of researchers (McCreanor, 1998; McCreanor and Reinhart, 2000). Oweis et al. (1990) determined saturated hydraulic conductivities for municipal solid waste (MSW) on the basis of a series of constant rate pumping tests. The study identified a range of saturated hydraulic conductivities for MSW of 10^{-3} - 10^{-5} cm/s. They also concluded that the laws governing the movement of moisture in soils can be applied on a macroscale to MSW. In laboratory measurements, the hydraulic conductivities have been in the range of 10^{-2} - 10^{-7} cm/s (Korfiatis et al, 1984; Bleiker et al, 1993). As can be inferred from these results, the most problematic aspect of predicting and controlling leachate flow through MSW is the heterogeneous nature of the waste mass itself; the measured waste hydraulic conductivity varies over many orders of magnitude. The variety and magnitude of the hydraulic conductivities encountered within the waste mass is as much a function of waste disposal operations (daily cover) as the character and age of the waste itself (McCreanor and Reinhart, 2000).

Zeiss and Major (1992) studied the density, porosity, field capacity, hydraulic conductivity and flow channeling of MSW as a function of compaction. They reported that compaction resulted in very little changes in leachate arrival times, field capacity, and the unsaturated hydraulic conductivity. The reported MSW density values were 165.6 - 304.5 kg/m3 and the porosity values 47.7 - 58.2 % for low and high compaction, respectively.

A number of models have been developed to address the concerns associated with moisture movement within a landfill: hydrological water balances, saturated flow models, unsaturated flow models and biochemical-hydrodynamic models (McCreanor, 1998). Hannoura et al. (1994) suggested that a multiphase model would be the best for modeling leachate movement within a landfill. According to McCreanor (1998), future waste permeability studies should focus on determining the variation in waste permeability, as well as the mean permeabilities. The predominant effects of a heterogeneous waste mass appear to be the movement of leachate around low hydraulic conductivity areas, changes in the shape of the wetting front, and the early arrival of leachate (McCreanor and Reinhart, 2000).

THE ÄMMÄSSUO BIOREACTOR

The Ämmässuo landfill (Figure 1) near Helsinki, Finland, has been operating since 1987. Special attention is continuously paid to environmental issues: for example, extensive water collection systems have been built to drain the water from the landfill area to a municipal waste water treatment plant. The quality of surface waters and groundwater is subject to comprehensive monitoring in accordance with the permit requirements, as well as self-supervision. Methane emissions from the landfill have been monitored systematically since 1988. Landfill gas is gathered using gas-collection systems. A considerable proportion of the landfill gas generated at Ämmässuo is utilized in the production of distinct heating.

Figure 1. The landfill area (50 ha).

The landfill will be closed by the earliest at the end of 2007. After closing the landfill a top cover will prevent rainfall infiltration, as well as isolate the refuse mass from the atmosphere. Because the use of a top cover generally results in conditions that are too dry for optimal anaerobic biodegradation, a leachate recirculation system will be installed throughout the whole area.

In order to gain experience about building and operating a leachate recirculation system, a two-year (2003-2004) leachate recirculation experiment (Figure 2) was carried out in the oldest part of the landfill. At the time of the experiment the age of the MSW in the experiment area was about 3-15 years.

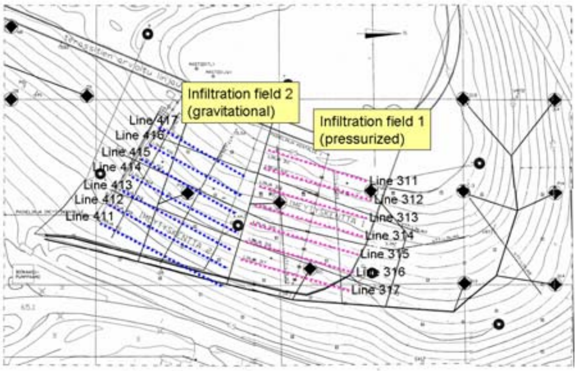


Figure 2. Leachate recirculation experiment (area 2 ha) at the Ämmässuo landfill.

Horizontal infiltration trenches (perforated pipes surrounded by gravel) were used to apply leachate to the landfill. The trenches were operated either by gravity or under pressure. Injection was applied during four months in summer 2003 and summer 2004, and the total amounts of leachate were 2200 m^3 and 3027 m^3, respectively.

Leachate infiltration was monitored by electrical resistivity tomography (ERT) at selected cross-sections (Figure 3). The ERT method allows leachate diffusion to be followed through the waste mass, and the influence zone of the leachate recirculation system to be determined (Robain et al., 2004). Movement of the leachate around low hydraulic conductivity areas was visible in the cross sections. Although, according to McCreanor and Reinhart (2000), the channeled flow is the major leachate movement mechanism, the time-lapse electrical resistivity at this site showed dominant Darcy flow in the cross-sections. After two-year's infiltration, 80% of the waste mass had been moisturized.

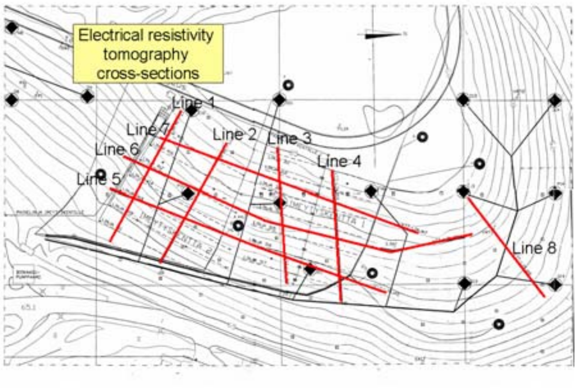


Figure 3. Electrical resistivity tomography cross-sections.

Tracer tests with lithium chloride were also carried out. The highest flow rates calculated from the tracer tests were 1.e-4 and 2.e-5 m/s and a few horizontal channeled flow routes were found. The vertical gas production wells in some cases also caused vertical short-circuiting of the flow.

Other parameters that were monitored during the experiment were: the water level on the bottom liner, leachate injection and production, leachate quality, gas production and quality, gas emissions to the atmosphere, and the amount of settling.

Fiber optics was tested as a method for measuring the temperature in the waste mass. Fiber optics is a relatively new but promising technology that can also be used for measuring moisture changes in porous media (Weiss, 2003; Ettala et al., 2003). In the full-scale bioreactor, the moisture intrusion into the waste mass will be monitored both with electrical resistivity tomography and using fiber optics and the moisture measurements will be calibrated using pointwise TDR moisture sensors.

The main problem in the full-scale application of leachate recirculation is the inability to uniformly apply leachate to the waste mass (McCreanor and Reinhart, 2000). Extensive monitoring is required in order to be able to control the moisture conditions in the extremely heterogeneous waste mass. Different kinds of data will be combined in a model for controlling the water balance and providing a comprehensive idea of the situation throughout the whole area.

MODELING APPROACH

Modeling was started with preliminary modeling of leachate infiltration through different synthetic permeability structures. The simulations were made with the multiphase model TOUGH2 (Pruess et al., 1999). Modules eos3 (water, air) or eos7 (water, brine, air) were used depending on whether the salinity was taken into account in the simulations. The TOUGH2 bioreactor model T2LBM (Oldenburg, 2001) was also tested but, at the present time the focus is on the hydrological modeling.

TOUGH2 is linked with an inversion model iTOUGH2 (Finsterle, 1999) that can be used for calibration, optimization and sensitivity analysis for TOUGH2 simulations. Inversion techniques were used for sensitivity analysis of the model parameters and to obtain the infiltration to get the desired liquid saturation in the preliminary simulations.

The leachate recirculation experiment was first modeled 2-dimensionally in vertical cross-sections across the infiltration trenches. Next, the infiltration field 1 was modeled 3-dimensionally and finally the whole experiment area was modeled. The stepwise approach is presented in figure 4.

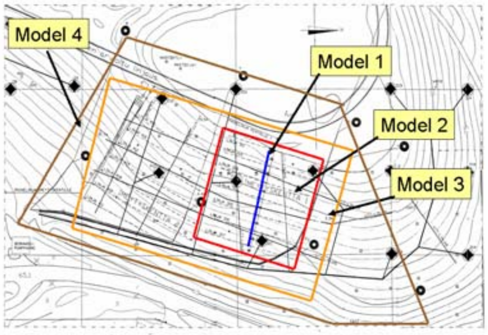


Figure 4. Step-by-step modeling of the leachate recirculation area.

A 3D model was built of the leachate recirculation experiment area using GMS (Groundwater Modeling System), and a TOUGH2 simulation model using pre/post processor Petrasim (Swenson et al., 2003). (Figure 5). Petrasim is a useful tool when building a model interactively, and it can also run TOUGH2 simulations and present the results. A practical approach was to first run the simulations and look at the results with Petrasim, and when the "final" results were obtained to transfer them to the GMS. Using GSM it is possible to look at the data and the simulation results 3-dimensionally in the same coordinate system.

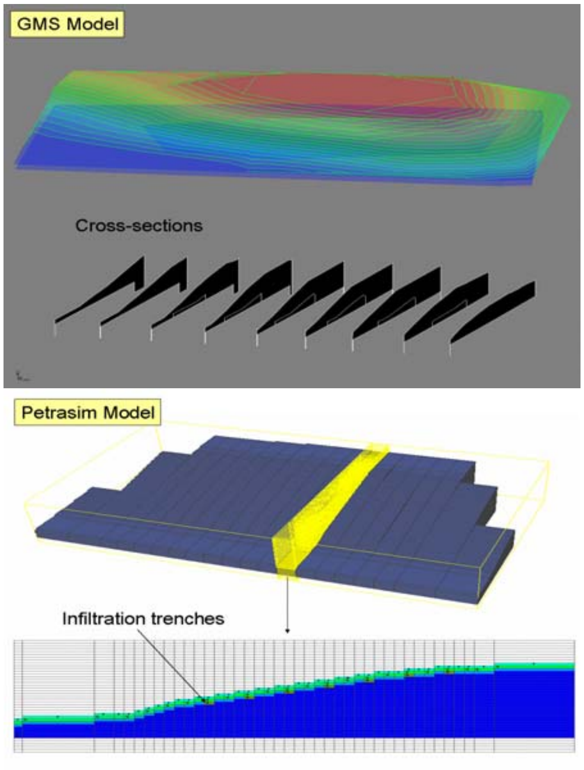


Figure 5. The principle of building a model with GMS and Petrasim.

The same approach was used when creating the full-scale model. The modeling was started with a coarse grid with most of the monitoring wells located in the grid centers (Figure 6). Using Petrasim features can easily be added to the model later: new gridlines or new elements can be added when needed (the maximum size of the Petrasim grid in the vertical direction was defined to be large enough with part of the elements disabled in the beginning). The initial model has 7820 elements. The initial model parameters are presented in the Table 1. The leachate collection system was modeled by defining higher permeability elements on the bottom of the model.

The current model is initial; the landfill is still in use and waste will be piled up until the closing of the landfill, after which the cover and the leachate recirculation system will be installed. The model will be continuously updated with all the new data from the area, and the approach will be further developed so as to be able to control the final bioreactor after the closing of the landfill. During the construction of the bioreactor, modeling will support the planning of the monitoring system.

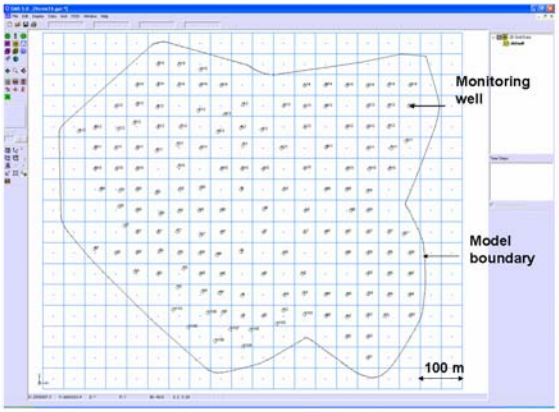


Figure 6. The initial horizontal grid spacing in the full-scale model. The landfill gas production wells that are also used to monitor the water level on the bottom liner can be seen in the figure.

Table 1. The initial parameter values for MSW.

Parameter	Value
Density	594 kg/m^3
Porosity	0.55
Permeability	1.0e-12m^2
Relative Permeability	van Genuchten-Mualem-Model: $\lambda = 0.59$, $S_{lr} = 0.21$, $S_{ls} = 1.0$, $S_{gr} = 0.005$
Capillary Pressure	van Genuchten –Model: $\lambda = 0.59$, $S_{lr} = 0.20$, $S_{ls} = 1.0$, $\alpha/\rho g = 8.4$ e-4 Pa^{-1}, $P_{max} = 1.0e5$ Pa
Wet Heat Conductivity	2.1 w/m°C
Specific Heat	132 J/kg°C

MODELING RESULTS

Several preliminary simulations were made to study the infiltration patterns through different kinds of permeability structure. One of the simulation series is presented in the Figure 7. 100 kg of brine was injected into box-like models with different permeability structures. Brine was used instead of water in order to be able to follow the percolation of the injected water. The brine mass fraction was followed at one monitoring point in the middle of the model. In the first case, the medium was homogeneous with a steady-state moisture distribution corresponding to the situation with 300 mm of annual infiltration (half of the precipitation). The groundwater level was located at the lower boundary of the model. In the second case, the medium had the same average permeability but a stochastically heterogeneous permeability structure. The third case was the same as the second, except that there was a denser layer at three meters depth. The results are presented in the Figure 8. The stochastic permeability structure induces dispersion of the pulse, but only a slightly longer breakthrough time. The dense layer causes perched water behavior: the maximum of the brine mass fraction remains above the dense layer, from where the saline water gradually percolates down through the layer. Both the dispersion and the perched water behavior can be considered advantageous for the leachate recirculation: dispersion promotes the spreading of the leachate over a broader volume, while the perched water behavior promotes the wetting of lower permeability areas under the pond. In all of these cases the breakthrough is rather slow, owing to the low relative permeability in the unsaturated zone and the fact that the injection was relatively small. The breakthrough time would be faster in the case of continuous injection.

Next we studied continuous injection into a homogeneous medium with $k=1e\text{-}11 m^2$ and a porosity 0.35. Injection of 3000 mm/year was applied to an area of 4 m^2. Liquid saturation was monitored under the injection area at a point where the initial steady state liquid saturation was 0.335. The simulation result is presented in Figure 9. Liquid saturation rises at the monitoring point to a new steady-state value of 0.420 in about two months.

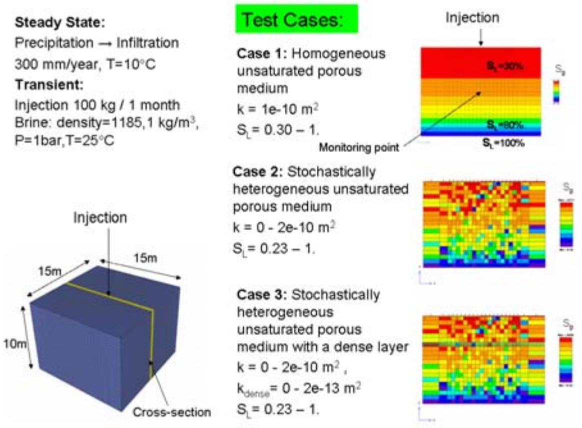


Figure 7. Injection of leachate (brine) through different synthetic permeability structures: conceptual models.

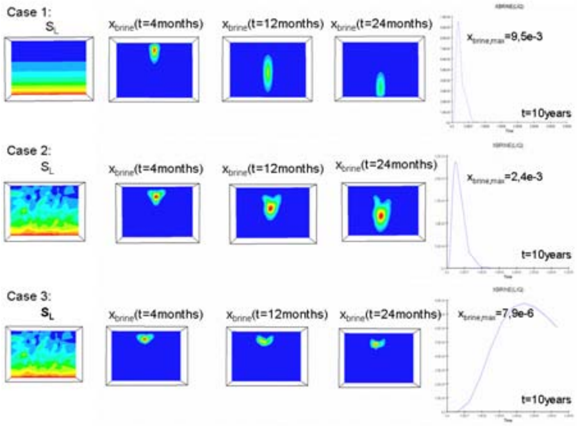


Figure 8. Injection of leachate (brine) through different synthetic permeability structures: simulation results.

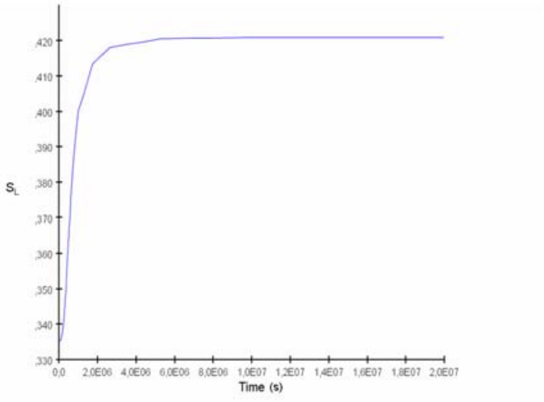


Figure 9. Continuous injection of 3000 mm/year into a homogeneous medium: simulation result.

iTOUGH2 was used to estimate, what the injection amount should be, if we wanted to increase the liquid saturation to a value of 0.4 or 0.5. Synthetic data were created with a steady state liquid saturation of 0.4 or 0.5 after six months. With the selected parameter values only about half of the original injection would be needed to reach the level of 0.4 but about 4.5 times the original amount would be needed to reach the value of 0.5. A Monte Carlo study was carried out for 100 TOUGH2 simulations with a porosity varying in the range 0.3 - 0.5 and a permeability in the range 1.e-10 - 1.e-13 m^2. It can be seen from the results (Figure 10) that, for a specific combination of parameters, the injection has hardly any influence on the steady state liquid saturation, but for a favorable parameter combination the influence is significant.

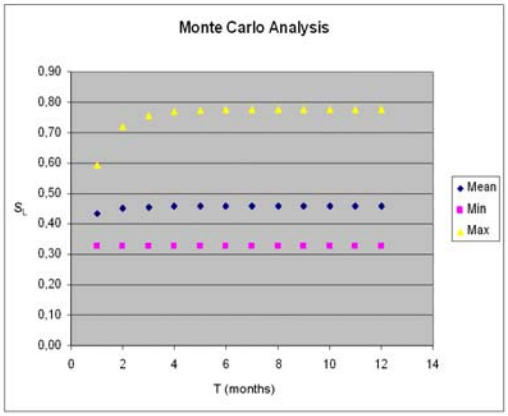
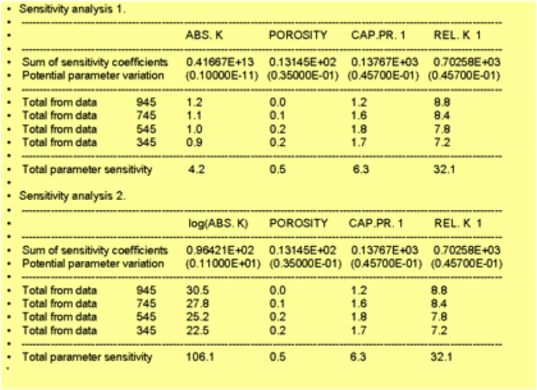


Figure 10. Monte Carlo analysis for the continuous injection of 3000 mm/year into a homogeneous medium.

Sensitivity analysis was carried out with iTOUGH2 for the parameters porosity, permeability and the van Genuchten λ in the relative permeability and capillary pressure functions. The results (Figure 11) showed that the relative and absolute permeabilities are the key parameters, and that the nearest points to the injection area are the most sensitive monitoring points when trying to estimate the parameters from the response of system to the injection.



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•  Sensitivity analysis 1.
•  ------------------------------------------------------------------------------
•                                 ABS. K         POROSITY       CAP.PR. 1      REL. K 1
•  ------------------------------------------------------------------------------
•  Sum of sensitivity coefficients  0.41667E+13    0.13145E+02    0.13767E+03    0.70258E+03
•  Potential parameter variation    (0.10000E-11)  (0.35000E-01)  (0.45700E-01)  (0.45700E-01)
•  ------------------------------------------------------------------------------
•  Total from data        945     1.2            0.0            1.2            8.8
•  Total from data        745     1.1            0.1            1.6            8.4
•  Total from data        545     1.0            0.2            1.8            7.8
•  Total from data        345     0.9            0.2            1.7            7.2
•  ------------------------------------------------------------------------------
•  Total parameter sensitivity     4.2            0.5            6.3            32.1
•
•  Sensitivity analysis 2.
•  ------------------------------------------------------------------------------
•                                 log(ABS. K)    POROSITY       CAP.PR. 1      REL. K 1
•  ------------------------------------------------------------------------------
•  Sum of sensitivity coefficients  0.96421E+02    0.13145E+02    0.13767E+03    0.70258E+03
•  Potential parameter variation    (0.11000E+01)  (0.35000E-01)  (0.45700E-01)  (0.45700E-01)
•  ------------------------------------------------------------------------------
•  Total from data        945     30.5           0.0            1.2            8.8
•  Total from data        745     27.8           0.1            1.6            8.4
•  Total from data        545     25.2           0.2            1.8            7.8
•  Total from data        345     22.5           0.2            1.7            7.2
•  ------------------------------------------------------------------------------
•  Total parameter sensitivity     106.1          0.5            6.3            32.1
•
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Figure 11. Sensitivity analysis for the continuous injection of 3000 mm/year into a homogeneous medium. The monitoring points 945, 745, 545 and 345 were situated at depths of 1.5 m, 3.5 m, 5.4 m and 7.5 m, respectively.

The parameter set presented in Table 1 was chosen as a base case for modeling the leachate recirculation experiment. Infiltration field 1 of the leachate recirculation experiment was first modeled with homogeneous and layered models. As can be seen from the results (Figure 11), the influence of injection is clearly evident in the homogeneous case, but the influence is more difficult to trace in the layered model because the initial steady-state liquid saturation arising from continuous infiltration from precipitation is also much higher in the layered formation. The situation is even more complicated if the permeability structure in the model is stochastically distributed.

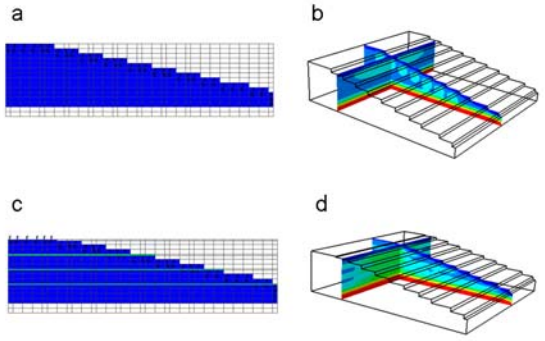

Figure 11. Homogeneous and layered models (a, c) for the leachate recirculation experiment (infiltration field 1) and the corresponding simulation results (liquid saturation; b, d).

When modeling the whole leachate recirculation experiment area, the water level on the bottom liner in the steady state simulations corresponding to a yearly infiltration of 300 mm was substantially calibrated to the measured values 62 - 65 m. With a homogeneous permeability of k = 1.e-12m^2 the match was relatively good. A slightly lower permeability of 0.5e-12 m^2 produced a 1 m higher water level in the simulations. The monthly mean values of the leachate infiltration amounts during the first year (Table 2) were used in the simulations.

The simulation results for the first year (2003) are presented in Figure 12. The simulated infiltration patterns were compared with the time-lapse electrical resistivity measurements (Figure 13). In the lower parts of the cross-sections the simulations and the measurements after one year still showed higher liquid saturations than in the beginning of the period. The influence of injection seems to disperse more in the measurements than in the homogeneous simulations. Simulations were also made using stochastically heterogeneous permeability fields, but this did not solve the problem. The infiltration patterns could not clearly be seen in stochastically heterogeneous material. The homogeneous simulations gave better agreement with the measurements. The zonation approach (Finsterle, 2003) could be used when trying to construct the permeability structure of the waste material at a large scale, but a denser grid of electrical resistivity measurements would be needed to be able to depict the situation in 3 dimensions. An electrical conductivity calculation procedure was created for TOUGH2 in order to be able to use the electrical resistivity measurements for the model calibration in the future. The measurement procedure itself is being further developed in order to make 3D interpretation of the electrical resistivity measurements possible (Figure 14). Pointwise measurements of the absolute moisture content would be needed to calibrate the liquid saturation locally in the unsaturated zone.

Table 2. The actual leachate recirculation during the first year (2003). Injection was applied during a 4 month period.

Line	The amount of leachate that was infiltrated during summer 2003
311	250 m^3 / 4 months
312	180 m^3/ 4 months
313	170 m^3/ 4 months
314	160 m^3/ 4 months
315	210 m^3/ 4 months
316	180 m^3/ 4 months
317	170 m^3/ 4 months
411	100 m^3/ 4 months
412	80 m^3/ 4 months
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414	70 m^3/ 4 months
415	90 m^3/ 4 months
416	80 m^3/ 4 months
417	80 m^3/ 4 months

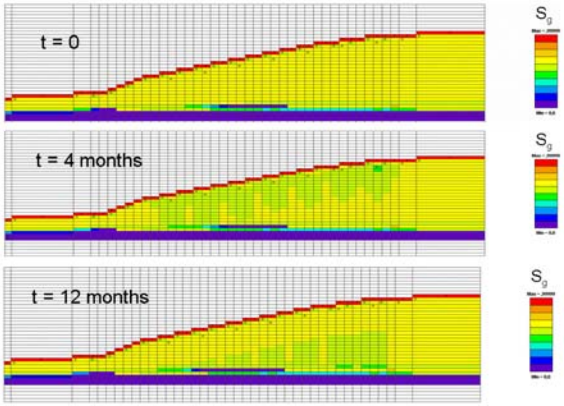

Figure 12. Simulation of the leachate recirculation experiment. Results are presented in cross-sections across the infiltration lines (infiltration field 2). Injection period lasted 4 months.

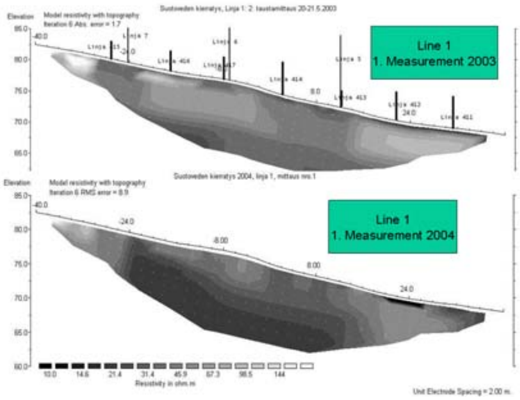

Figure 13. Electrical resistivity tomography measurements of infiltration field 2, line 1. The results are presented in cross-sections across the infiltration lines before the injection period in 2003 and one year later.

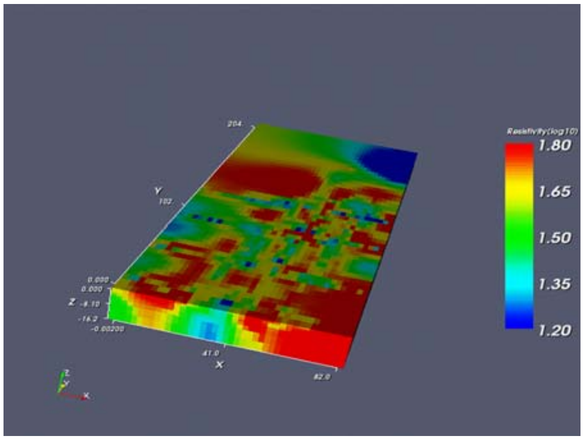

Figure 14. 3D electrical resistivity tomography interpretation.

An initial simulation model has been created for the whole landfill area (Figure 1; Figure 6). iTOUGH2 is being used for the model calibration.

CONCLUSIONS

The most problematic aspect in predicting and controlling leachate flow through MSW is the heterogeneous nature of the waste mass: the measured waste hydraulic conductivity varies over many orders of magnitude depending on the scale. Waste permeability studies should focus on determining the variation in waste permeability as well as the mean permeabilities. The zonation approach could be used in the simulations when trying to construct the permeability structure of the landfill at a large spatial and temporal scale. The ERT method allows leachate diffusion to be followed through the waste mass and determination of the influence zone of the leachate recirculation. However, a denser monitoring grid than that used in the leachate recirculation experiment would be needed to depict the situation in 3 dimensions. The water level on the bottom liner can be used for large scale calibration of the water balance, but pointwise measurements of the absolute moisture content are needed in order to be able to calibrate the liquid saturation locally in the unsaturated zone. A combination of optical fiber measurements, electrical resistivity tomography, saturated water level monitoring and pointwise TDR measurements in the unsaturated zone, combined with multiphase modeling with TOUGH2 and iTOUGH2, appear to be a promising method for modeling and controlling the full-scale leachate recirculation system.

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