Water Balance and Effectiveness of Mineral Landfill Covers – Results of Large Lysimeter Test-Fields

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Summary. Landfills are provided with cover systems in order to separate the waste from the environment and in order to prevent percolation of precipitation and recharge of leachate. The layers of a landfill cover system (restoration profile, drainage layer, compacted clay liner – CCL) have to be specifically designed for long-lasting effectiveness. Special care has to be taken to prevent the CCL from desiccation-cracking due to high matric suction. On a landfill in Northern Bavaria, test fields of some 260 m^2 each were installed with different profiles: The test fields were built according to the recent German landfill ordinance, but with a thicker restoration profile (2.0 m and 1.5 m thick restoration layer, respectively). Water content and matric suction of the soil profiles was measured by FDR-probes and tensiometers. In test field 1 reduction of soil water content during summer was detected down to 1.8 m depth. In test field 2 (1.5 m thick restoration layer) decreasing water content was measured in the CCL, whereas in test field 1 (2.0 m thick restoration layer) the CCL was not affected by loss of water. In conclusion, at the given landfill site only the 2.0 m thick restoration profile is able to effectively shield the CCL from desiccation effects.

Key words: landfill cover, compacted clay liner, lysimeter test field, percolation, matric suction, soil water content

Introduction

Upon completion solid waste landfills are provided with a final cover in order to prevent the migration of contaminants. The cover has to meet two basic requirements: It should be at least as tight as the lining system at the base of the landfill and its ability to minimize percolation should not deteriorate with time.

Landfill covers are exposed to highly variable hydraulic conditions due to seasonally changing weather conditions and influences of vegetation. The upper meters of the pedosphere are dominated by unsaturated conditions. Key element of a landfill cover system is the sealing layer. Most commonly compacted clay liners are used as sealing layers in Germany, either in combination with a geomembrane or as the only sealing element. Since mineral liners are quite common in landfill cover systems and their proper functioning has to be relied upon for long term use, the problem of preventing desiccation and shrinkage cracks of clayey mineral liners has been paid much attention. The physical phenomena which lead to shrinkage cracks have been studied by laboratory experiments on different soils. Theoretical approaches have been developed, and evidence of desiccation or of the successful prevention of desiccation has been obtained by a number of field trials (Ramke et al. 2002, Witt and Zeh 2004).

This paper presents a field testing program, and intermediate results of ongoing research aimed at a better understanding of the performance of the restoration profile and at specifying its properties required for the prevention of desiccation of the compacted clay liner within the cover system of a sanitary landfill under site specific conditions.

Materials and Methods

Field Site

The field site for this study is situated near the village of Aurach in Northern Bavaria, some 60 km southwest of the city of Nuremberg in a gently hilly region at an elevation of 500 m above sea level. Average annual precipitation at the site is 750 mm, mean annual potential evapotranspiration amounts to 550 mm. Average annual temperature is 9°C. The lysimeter test fields were erected on the slope of a municipal waste landfill, inclined at 14°, exposed towards the south. Vegetation at the site is mainly grass.

Profiles of the Lysimeter Test-Fields

The test fields were placed inside large lysimeters (13×20 m) made of PEHD-geomembranes and drainage composites, allowing collection of surface runoff, lateral drainage and percolation.

The test fields consist of a three-component cover system including a soil cover, a drainage layer and a compacted clay liner. The soil cover consists of locally available sandy loam, but instead of compacting it, care was taken to construct it with little compaction. Thus the soil cover should act as water storage layer. The two profiles of test-field 1 and 2 differ in the thickness of the subsoil layer of the restoration profile, which is 1.8 m in field 1 (thickness of the entire restoration profile of 2.0 m), and 1.3 m in field 2 (thickness of the entire restoration profile of 1.5 m). The drainage layer with a thickness of 0.3 m is made of gravel. The compacted clay liner consists of silt loam (25% clay/50% silt/25% sand; plasticity index 21%). It was constructed in two lifts of 0.25 m each, compacted to $> 98\%$ Proctor-density at water content 1–2% below optimum.

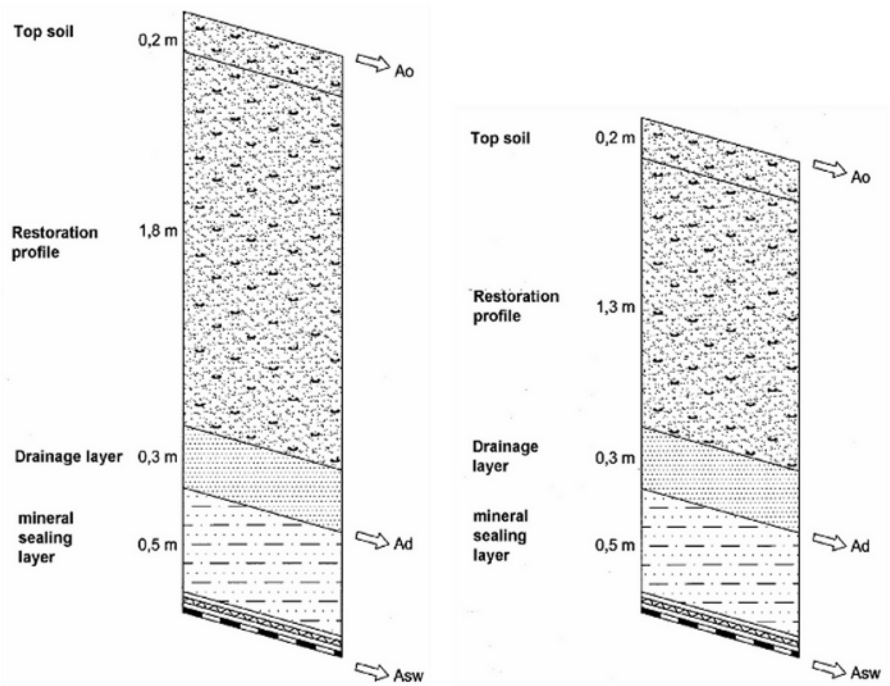

Fig. 1. Profiles of the lysimeter test fields (*left*: field 1; *right*: field 2) at Aurach landfill

Table 1. Properties of soil layers of the test fields

Layer	Thickness	Material	Saturated hydraulic conductivity	Plastic limit; Liquid limit
Top soil and storage layer	2.0 m (#1) 1.5 m (#2)	sandy loam	10^{-6} to 10^{-7} m/s	
Drainage layer	0.3 m	coarse grave	$> 10^{-2}$ m/s	
Compacted clay barrier	0.5 m	silt loam	5×10^{-10} to 2×10^{-9} m/s	20%; 41%

Data Collection

Both lysimeter test fields are equipped with tipping buckets to measure

- Surface Runoff,
- Drainage flow in the drainage layer above the compacted clay liner,
- Percolation through the compacted clay liner.

Matric suction of soil at different depths is measured by tensiometers (pressure transducer tensiometer, type "T 6" by UMS, Munich). Volumetric water content of soil at different depths is measured by FDR-probes (type "Theta Probe ML2" by Delta-T devices, Cambridge). Temperature of soil at different depths is recorded by thermocoupes. Precipitation and air temperature are recorded at the test field site. Readings of all measuring devices are taken automatically. The data are stored locally on PC and are transferred to the office by GSM.

Results and Discussion

Precipitation and Flow Measurements from Lysimeter

Data from lysimeter 1 for the time period from May 2002 until December 2005 are plotted in Fig. 2. Note that the scale of precipitation on the left side is four times the scale of flows on the right side of the plot. In Central Europe, commonly the precipitation is distributed rather evenly over the year, so the cumulative curve of precipitation (thin black line) shows an almost linear increase.

Surface run-off (dashed line) is generally low. In the long run it plays no important role. Among the measured flows, the discharge from the drainage layer (thick grey curve) has the greatest share. Drainage occurs mainly during winter months from November to April. During summer, the precipitation is

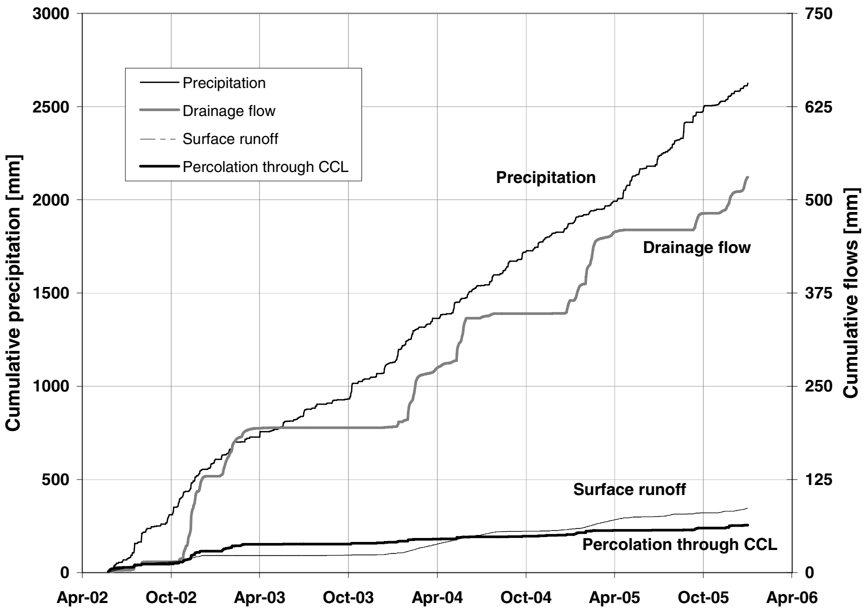

Fig. 2. Precipitation and measured flows at lysimeter test-field 1

partly consumed by evapotranspiration directly and partly stored in the soil layers of the restoration profile for later evapotranspiration, so that there is no drainage flow for a period of several months every year.

Percolation through the compacted clay liner (bold solid curve) occurs simultaneously with lateral drainage. It amounts to about one tenth of the drainage flow. In the water balance of the landfill cover percolation through the CCL amounts to 3% of the total precipitation.

In some other test fields where desiccation of the CCL or GCL took place, the amount of seepage increased and the efficiency of the seals decreased with time (e.g. Melchior 2002). Therefore it is important to take a closer look at the processes which are going on within the layers of unsaturated soil, of which the landfill cover system is composed.

Moisture Content and Matric Suction

Measurements of matric suction (tensiometer measurements) and volumetric moisture content FDR-probe measurements) at different depths within the soil profile are shown in Fig. 3 (for test field 1) and Fig. 4 (for test field 2). The bold lines in both plots represent the probes, which are installed within the CCL (at 2.4 m and 2.6 m in test field 1 and 1.9 m and 2.1 m in test field 2, respectively). The thin lines represent the probes within the storage layer.

During winter season the moisture content of the entire soil profile is generally high ($\theta = 0.35$ to 0.4 in the storage layer and 0.4 to 0.45 in the CCL) and at the same time matric suction is low (generally below 100 hPa). During summer evapotranspiration is usually higher than precipitation and the vegetation extracts water from the soil. The plots show the different response of the soil to the relatively wet summer of 2002 in contrast to the dry summer of 2003:

In 2002 only the tensiometer at 1.0 m depth recorded rapidly increasing matric suction; at greater depths matric suction remained below 100 hPa during summer and fall of 2002. Volumetric moisture content decreased in the upper meter of the soil; below that it almost remained constant. In the dry summer of 2003 the FDR-probes recorded a strong decline in soil water content even at 1.4 and 1.8 m depth. At the same time the tensiometers even at the base of the storage layer recorded an increase of matric suction beyond the measurement range of 700 hPa.

The bold lines represent the measurements within the CCL. In 2002 matric suction and water content showed almost no change at all. During summer of 2003 there was a slight increase in matric suction up to 150–200 hPa and a 1% drop in water content. In comparison with the measurements in the storage layer the diagram shows, that there is an effective hydraulic decoupling between storage layer and CCL.

Figure 4 shows the progress lines of matric suction in the CCL of test field 2 (upper plot) and volumetric water content in the storage layer and in the CCL (lower plot). Again, no critical decrease in water content/increase in

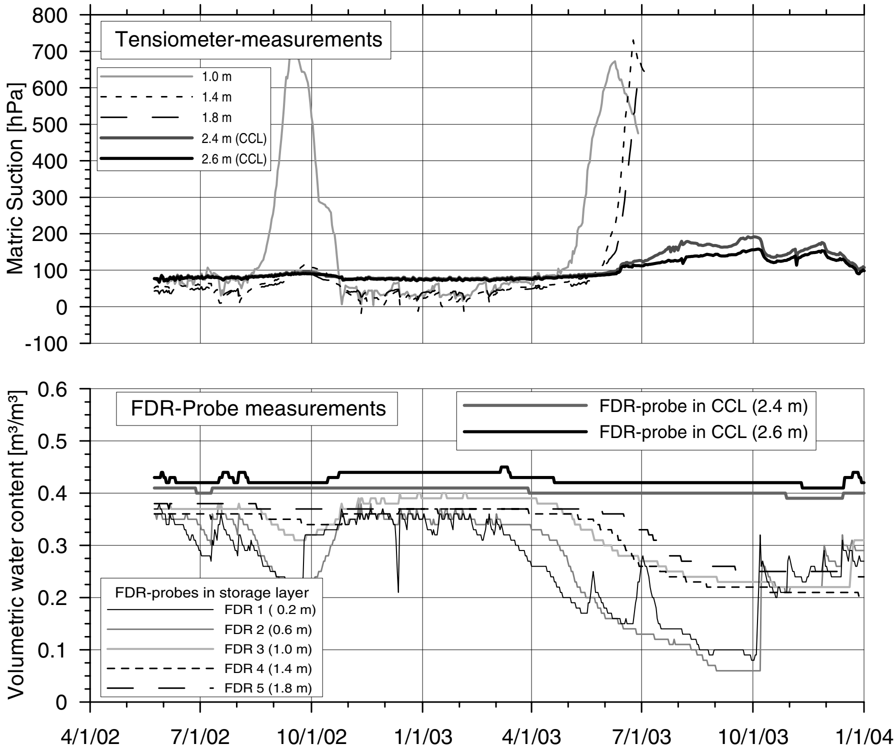

Fig. 3. Results of tensiometer measurements (*upper plot*) and FDR-probe measurements (*lower plot*) at lysimeter test-field 1 for the years 2002 to 2003

matric suction occurred in 2002. But in summer of 2003 water content of the CCL dropped below $0.4\,m^3/m^3$ and at the same time matric suction increased to about 500 hPa.

According to Witt and Zeh (2004) values of matric suction above 250 to 500 hPa are critical with respect to the formation of desiccation cracks in CCLs. The mainly silty material with low to medium plasticity used in this study is less susceptible to cracking than high plasticity clays. The ongoing measurements have not shown any increases of percolation in lysimeter 2 compared to test field 1.

Conclusions

Landfill cover profiles commonly consist of a series of unsaturated soil layers, which are exposed to the dynamics of weather and vegetation. Regulations of EU and Germany recommend a compacted clay layer as sealing component within the design of a landfill cover. In temperate humid climate like in Germany there are periods (generally during winter months) where precipitation

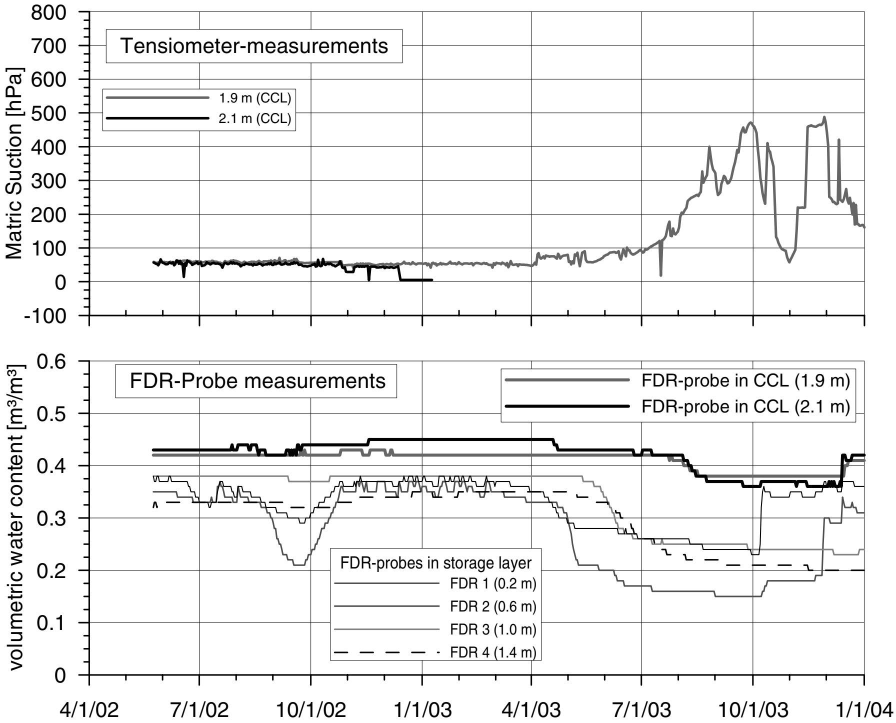

Fig. 4. Results of tensiometer measurements (*upper plot*) and FDR-probe measurements (*lower plot*) at lysimeter test-field 2 for the years 2002 to 2003

exceeds evapotranspiration. In these times low hydraulic conductivity of the CCL is the determining factor for low percolation rates.

In contrast, there are periods during summer and fall, where evapotranspiration exceeds precipitation. The lysimeter measurements show that the periods without drainage flow may last up to nine months. During these periods of time the CCL has to be protected against critical loss of water. This task has to be fulfilled by the top soil or water storage layer. The in-situ-measurements in the soil profiles show an increase in matric suction and at the same time a decrease in water content of the storage layer down to its base at 2.0 m and 1.5 m, respectively. The drainage layer acts as a barrier, which inhibits the capillary rise of water from the CCL to the top soil. In test field 2 with a 1.5 m thick storage layer a reduction of water content of the CCL was detected, which can be attributed to vapour transport through the drainage layer. The temporary reduction of water content did not yet have an adverse effect on the sealing effectiveness of the CCL.

The thickness of the top soil cover should be "> 1 m" according to German and EU regulations. In many cases the actual thickness of the top soil cover is even lower. The results reported here emphasize the importance of a well designed landfill cover including a thick water storage layer in order to protect the CCL against desiccation.

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