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Landfill final cover pilot for hydrogeotechnical and environmental assessment: lessons learned from construction and 3-year monitoring

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ABSTRACT: This paper describes the construction and instrumentation of an ongoing final cover pilot on a landfill for hazardous and non-hazardous waste in southern Norway. The final cover consists of a protection layer of crushed rock above a hydraulic barrier constructed with three different clayey materials received as waste from construction projects. The primary objective of the pilot was to compare the percolation rates from each of the distinctive sections of the barrier and study the development of performance with time. A secondary objective was to quantify their leaching potential as part of an environmental assessment of the use of the different materials in barriers in landfill covers. A lysimeter system with a drainage trench, tipping bucket and a 20-litre bucket placed below allowed automatic and manual quantification of the percolated water as well as sampling the water for geochemical analyses. The barrier and the protection layer were also instrumented with sensors at different depths to measure the temperature, volumetric water content, electrical conductivity and matric suction/water potential. The monitoring data was automatically imported to NGI Live, an online visualization platform, offering quick access to real-time data. This proved useful especially for discussion on data interpretation in meetings and fast detection of sensor errors and limiting downtime. Detailed planning and coordination among the parties involved, and involvement of all parties during the construction phase, were considered important for the success of the project. The pilot set-up efficiently measured percolation for comparison of performance of the barriers and monitoring them over time, as well as collecting valuable data for the environmental assessment. Larger lysimeters and collection of drainage would enable better control of the flow patterns and water balance.

KEYWORDS: Landfill final cover, pilot, construction, instrumentation, percolation, water sampling.

1 INTRODUCTION

Pilot landfill covers and large-scale field experiments provide useful information to validate landfill cover designs and study their long-term performance. For such pilots, percolation measurements are the most critical for performance assessment. Lysimeters, sometimes called underdrains, are typically constructed below the planned barrier to collect and guide the water to a basin where the percolated volume is measured, for example, with a pressure transducer or a tipping bucket. They are often constructed as trenches, lined with an impermeable geomembrane and filled with a drainage material (sand or gravel, or a geocomposite). Due to contrasts in unsaturated hydraulic properties of the barrier material and the materials below, lateral flow in the barrier may occur and lead to some of the flow going on the outside of the lysimeter boundaries. The smaller the lysimeter area and the thicker the barrier is, the greater the potential for lateral flow. Based on numerical and experimental efforts to investigate this issue, Chiu & Shackelford (2000) recommended that the lysimeter width to barrier thickness ratio should be greater than 5. The width is orthogonal to the slope in cases where the lysimeter is inclined.

Most regulations define the barrier performance criteria primarily as a saturated hydraulic conductivity, for example that the saturated hydraulic conductivity must be less than 1×10^{-9} m/s. However, in the field, the barrier is only partially saturated. In addition, and partly as a result, the hydraulic gradient over the barrier is difficult to determine accurately, and the gradient will also typically change over the year. Therefore, it is generally not possible to determine the saturated hydraulic conductivity with monitoring of final cover pilots. However, estimates may be provided given simplistic assumptions. For example, if one assumes steady state flow and no ponding on the barrier surface, the gradient across the barrier will be 1. By dividing the drained volume by the lysimeter area over time, the hydraulic conductivity may be determined. Albright et al. (2006) termed this the effective field hydraulic conductivity and used it to compare with saturated hydraulic conductivities measured in the laboratory on intact samples taken from the compacted barrier.

In addition to percolation, secondary data such as the soil temperature, volumetric water content and water potential or matric suction may also provide valuable context for interpreting percolation data or evaluating changes in cover material properties and behavior. A few documented final cover pilots are also known to have performed an environmental assessment of the cover materials alongside the hydro-geotechnical assessment. For example, Travar et al. (2015) performed geochemical analyses on drainage water, i.e. runoff on the barrier surface, from covers built with various secondary construction materials in the layers above the barrier. Also, Mácsik et al. (2005) performed geochemical analyses on the water percolated from the base of a barrier consisting of fly-ash stabilized sludge.

This paper concerns a landfill final cover pilot constructed at a landfill site in southern Norway in the fall of 2022 and monitored since then. The pilot was set up primarily to quantify the field performance of covers with hydraulic barriers constructed with three different clayey materials considered as surplus/waste from construction projects. The field performance of the cover is in this context referring to (1) the seasonal and annual percolation (outflow) through the barriers, and (2) the effectiveness of the protection layer in isolating the hydraulic barrier. The project also aimed to quantify the leaching of heavy metals from the barrier materials. The pilot was therefore designed to allow for sampling of the percolated water in addition to monitoring the percolation from the barriers and the temperature at different depths in the cover.

The aim of the paper is to share knowledge and experience that can be valuable to other consultants, researchers and practitioners who are planning the construction of field pilot experiments with similar objectives. A detailed interpretation of the field data is beyond the scope of this paper, but a brief discussion of the validity and accuracy of the percolation measurements is provided.

2 PROJECT BACKGROUND & COVER MATERIALS

The materials investigated as barrier materials are soil-washing press-filter residue (filter cake), excavated cement-stabilized clay, and marine dry crust clay. Dry crust clay is typically used in the cover barrier, but because of limited availability, other material types are investigated as part of a circular economy approach. A prior field-testing campaign with laboratory tests, presented in detail by Ritter et al. (2023), showed promising results regarding the suitability of the press-filter residue. The excavated cement-stabilized clay showed a large scatter in hydraulic conductivities and other geotechnical properties. The motivation behind the final cover pilot was to assess the field-performance of a barrier using a more representative volume of the selected materials. The evolution of the cover performance (including a 1.8 m protection layer of crushed limestone) over time was also investigated and field-samples of the barrier materials were collected for testing the effect of freeze-thaw and drying-wetting cycles on the structure and hydraulic conductivity. Previous geotechnical lab and field characterizations were described by Kim et al. (2024) and Ritter et al. (2023), and preliminary percolation results from the pilot were presented by Ånes et al. (2024).

3 PILOT DESIGN AND CONSTRUCTION

3.1 *Location and climate*

The pilot was constructed in the fall of 2022 on the outskirts of a landfill for hazardous and non-hazardous waste in southern Norway. The area is characterized by relatively mild winters, although periods of subzero temperatures can occur in the winter. Based on frost modelling with different climate scenarios, a 1.8 m thick protection layer of crushed rock was constructed above the compacted clay barrier. The annual precipitation in the area is around 1000 mm.

3.2 *Pilot design*

The final cover pilot was constructed as a miniature final cover (Figure 1) on top of a pile of gravelly material. The cover consisted of a (frost) protection layer of crushed limestone and the compacted clay barrier. The barrier itself consisted of four distinctive parts or cells but acting as one continuous barrier. Each of the three materials were used in three different cells, whereas the fourth cell consists of one lift of the press filter residue and two of the excavated cement-stabilized clay. The barrier was around 8 m wide with the surface inclined slightly (~1:15) to each side from the center. The lysimeter trenches were between 11.5 m^2 and 14.5 m^2 (3-4 m × 3-4 m). With a representative barrier thickness of 0.7 m, the width / depth ratio was between 4.3 and 5.7. A vegetation layer was not included as the vegetation around the landfill site is scarce and was expected to take years to develop. Not including one was slightly conservative but more realistic than having vegetation covering the entire surface.

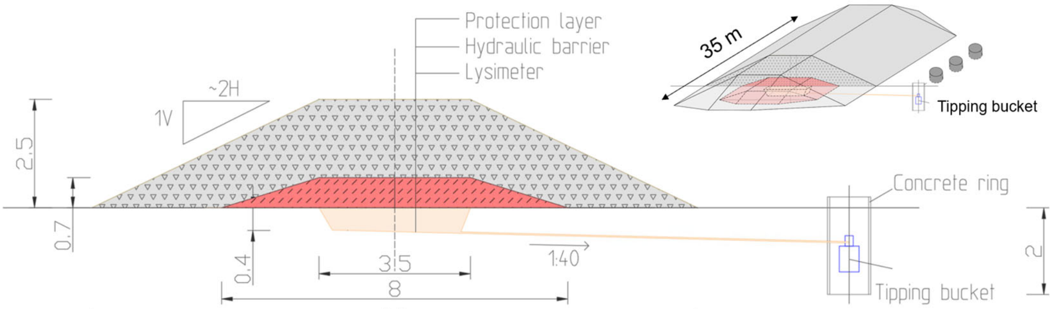


Figure 1. Final cover pilot design. All dimensions are in meters.

3.3 *Timeline*

The construction of the 4 m high foundation and the lysimeter trenches started in October 2023, followed by the construction of the compacted clay hydraulic barriers over two days at the end of October, and the instrumentation and start of protection layer construction in November. The protection layer was completed in early December. During the instrumentation period, there were a few nights with subzero temperatures, but frost was not encountered in the ground. As soon as the barriers were instrumented, the protection layer construction started which quickly increased its thickness to isolate the barrier. There was no indication of damage to the barrier.

3.4 *Lysimeter*

Each cell contained its own lysimeter system collecting and measuring the percolated water (Figure 2). The lysimeters consisted of a 40 cm deep trench covered with a 1.5 mm high-density polyethylene (HDPE) geomembrane and filled with fluvial gravel acting as a drainage material for the percolated water. The membrane was initially stiff and difficult to handle but was shaped into the trench using a heat gun. It should be mentioned that other researchers (e.g. Benson et al., 2001) recommend using a linear low-density polyethylene (LLDPE) membrane as it is more flexible and puncture resistant. However, an HDPE membrane was used in our case as it was already available at the landfill site and experience with it indicated it would work for our purpose.

Bathroom/shower drains were used to drain the water from the trench to the pipe guiding the water to the concrete ring with the tipping bucket. Installation was relatively simple and leakage tests conducted before placing the gravel confirmed the system was watertight.

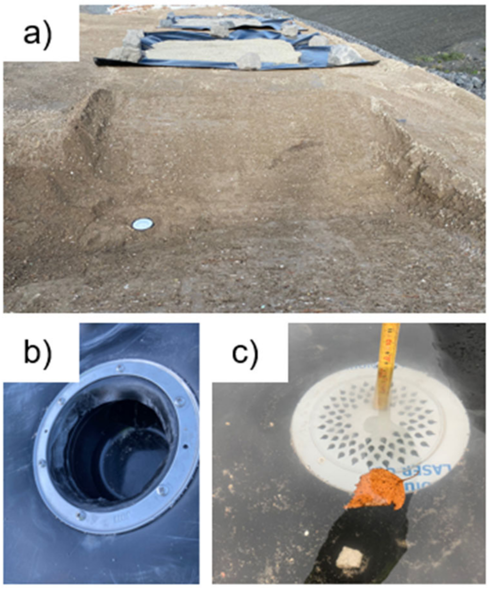


Figure 2. Construction of lysimeters. a) lysimeter during construction, b) installation of shower drain in the geomembrane, and c) leakage test after fully installing the drain and the membrane into the trench. Photos from Kjeldaas.

3.5 *Hydraulic barrier (compacted clays)*

The barrier of each cell was compacted at the same time (Figure 3). Three lifts were compacted using a Cat D6T LGP bulldozer with tracks (23.9 tons and a ground pressure of 36 kPa), making 6 passes per lift. Each lift was 20-25 cm thick after compaction (35 cm loose). The third and final lift was subsequently compacted further with 4 turns with a BOMAG BW 213 D-5 rolling machine, weighing 15 tons. A Troxler nuclear gauge was used to determine the density and water content at several points of the first and third lift. After the third lift had been compacted with the roller, 72 mm tube samples were collected using Shelby steel cylinders pushed 50 cm into the barrier using the back of an excavator bucket. In general, only the upper lift was kept within the cylinder, possibly because the upper two lifts were not completely bonded. The cylinders were weighed after extraction, and the holes were backfilled with an equal amount of loose material and compacted with a tamping rod.

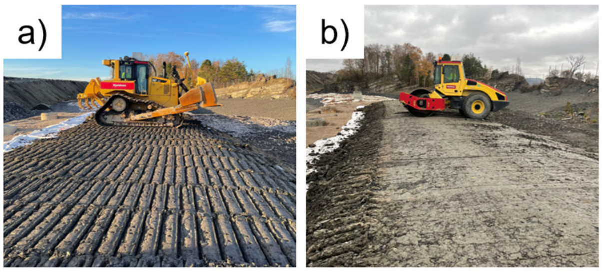


Figure 3. (a) The three lifts were compacted using a bulldozer, and (b) the third lift was further compacted with a rolling machine.

3.6 *Protection layer*

After the compacted hydraulic barrier was constructed, filter cloths were placed over the barrier to reduce particle migration. Crushed rock was then placed with an excavator (Figure 4).

Figure 4. Construction of the protection layer with crushed limestone. a) during construction, and b) after completion. Photos from NOAH and NGI.

4 INSTRUMENTATION AND MONITORING

The pilot was instrumented with fifteen volumetric water content sensors Teros 12 and twelve suction probes Teros 21 (METER group), in addition to seven PT100 temperature sensors.

Sensor placement is shown in Figure 5. The temperature was measured at all levels. Volumetric water content (VWC) and electrical conductivity (EC) were measured in the top of the protection layer, 5 cm above the barrier surface, and 20 and 40 cm above the barrier-lysimeter interface. The suction was monitored directly above the barrier surface, and at the same depth in the barrier as the VWC and EC.

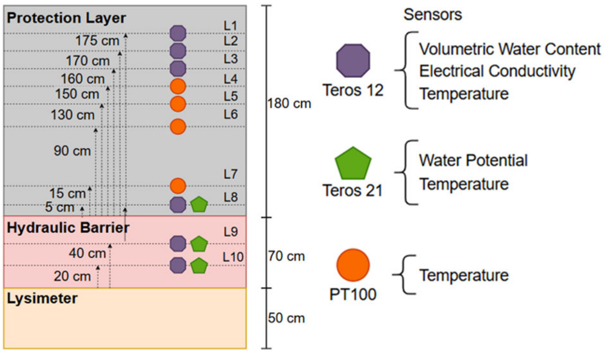


Figure 5. Instrumentation profile. Levels (L) 1-6 were only installed in one of the cells, and all cells have sensors in L10-L7.

Sensors in the hydraulic barrier and the protection layer were installed in November 2022, following the hydraulic barrier compaction. Five full days of field work were required to install all sensors and connect them to logging cabinets.

4.1 *Tipping bucket (lysimeter) and water collection*

In all four cells, the pipe from the lysimeter pan led the water to a Vaisala RG-13 pulse-based tipping bucket (Figure 6). The buckets were configured to tip after collecting 0.008 liters of water. The precision of all buckets was verified in the field before installation by filling two deciliters of water slowly and counting the tips. The percolation data was automatically uploaded to an online dashboard (section 4.5). The first months, the tipping bucket measurements were dominated by signal noise that arose when earthing, making these measurements unreliable. The problem was fixed by installing an optocoupler in the signal circuit of the tipping bucket to physically separate the tipping signal from the rest of the electronics. The tipping buckets have operated since April 2023 with very few issues and need for maintenance. After more than two years of operation, one of the buckets suddenly stopped providing data. The reason was that the bucket had come in contact with another part, causing the tipping mechanism to stop (Figure 6.b). It required some troubleshooting as the parts were small and tipped easily when moving it manually with the hand, but once the problem was detected it was quickly solved by adjusting the position of the bucket fastened on a metal rod.

Leachate was collected in a 20-litre bucket placed directly below the tipping bucket (not shown in pictures). Water was emptied every month, and every third month analyzed for pH, electrical conductivity and heavy metal concentrations.

The concrete rings where the tipping buckets were placed were covered with an isolated lid to protect the system from frost and to avoid debris and dust from getting in. The tipping buckets were also covered with cloth to further prevent external objects from clogging the filter in the funnel.

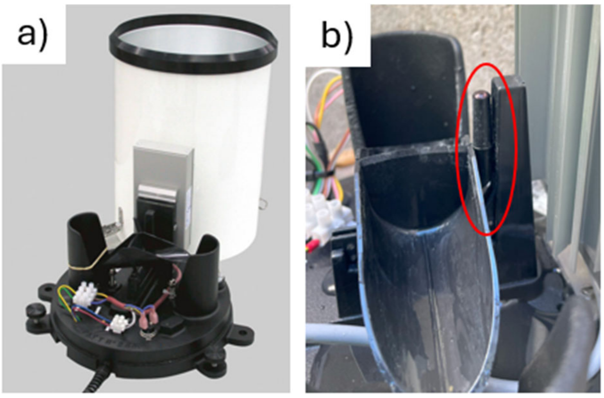


Figure 6. Tipping bucket system. a) © Vaisala. b) contact between the bucket and the side led to downtime for one of the buckets after about two years of operation.

4.2 *Installation of sensors*

For the compacted clay barriers, a hole was made approximately in the middle of each lysimeter area, using a Shelby tube and shovel (Figure 7a). The suction sensors were first packed with moist material (using the barrier materials of the different cells) around the porous disc, before placing it at the bottom of the hole. This was to ensure contact between the material and the disc. The water content sensors were installed by pushing the needles into the sidewall of the hole. The hole was then filled with clay and compacted with a tamping rod up to the next level (L9, Figure 5), before following the same procedure for sensor installation.

Concrete rings were placed on top of the compacted clay, directly above the instrumentation profile in each cell (Figure 8). Cables from the sensors were routed along the rings. The instrumentation of sensors in the protection layer and filling with crushed rock was performed sequentially. The cables were guided through metal rods isolated with plastic tubes to protect them from tear and impact from rocks. The cables were connected to logging cabinets at the top of the rings.

The installation of sensors in both layers with the described procedure was performed without notable issues.

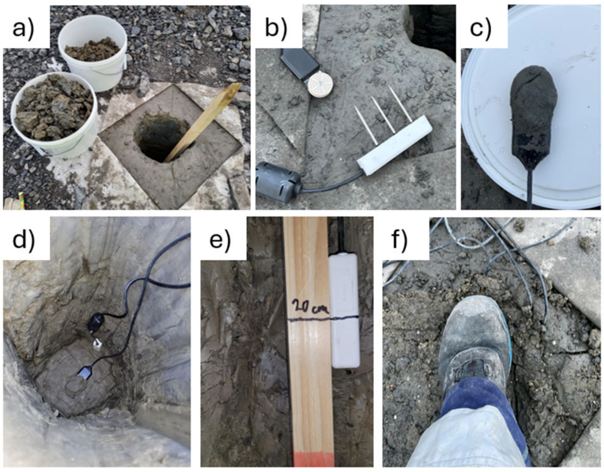


Figure 7. Installation of Teros 12 and 21 in the compacted clays. a) preparation of a hole for installation, b) Teros 21 (left, suction) and Teros 12 (right, water content), c) Teros 21 after being packed with clay, d) installing the sensors at the lowest level (20 cm above the lysimeter/barrier interface), e) installing Teros 12 into the wall, and f) after filling the hole and compacting.

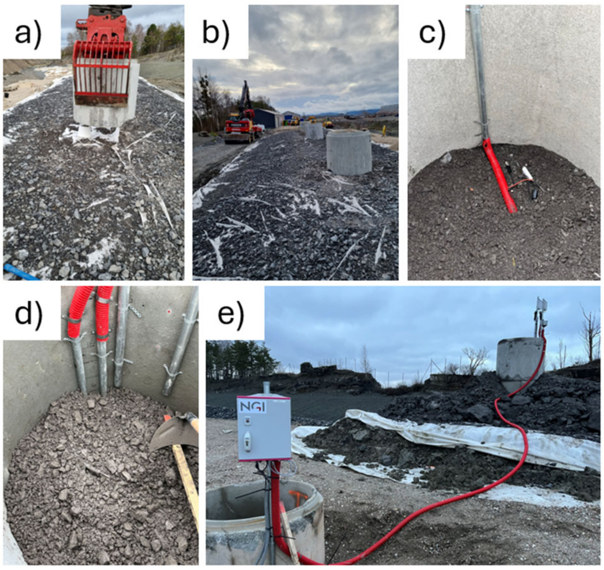


Figure 8. Installation of Teros 12 (water content), Teros 21 (suction) sensors, and PT100 (temperature) in the protection layer. a) and b) placement of concrete rings on top of the compacted clay, c) and d) placement of sensors and sequentially filling of crushed limestone, e) NGI logger cabinet for tipping bucket data, and METER ZL6 Pro on top of the protection layer for logging of installed sensors.

4.3 *Weather station*

A tipping bucket and a temperature sensor were placed at the top of the cover to measure the precipitation and air temperature. Wind speed, wind direction, relative humidity and solar radiation were measured by the weather station installed on the landfill, a few hundred meters from the pilot.

4.4 *Automatic logging*

All data from the pilot were uploaded automatically to NGI Live, a platform for visualization of monitoring data (Figure 9). Battery for some of the loggers had to be changed with time, but other than that, the set-up required little maintenance. The data was logged every hour or 15 minutes. In this project, it was annual and seasonal variations that were of main interest, so for the most part, daily measurements would have sufficed. However, for studying the response of the cover to heavy precipitation events, hourly measurements or even 15-minute measurements have been useful.

4.5 *Automatic data monitoring*

The NGI Live dashboard allowed to compare monitoring data real-time. It gave quick access to the monitoring data and enabled tailoring of what sensor data the charts should depict and for what time periods. In this project, it served well for investigating the data in discussion meetings and allowed sharing data quickly with research and industry partners. In addition, it proved useful in following up on the status of the sensors and detect when a sensor was no longer working and either a battery had to be changed or maintenance was needed. The dashboard also allowed exporting the data to .csv files for further use and interpretation.

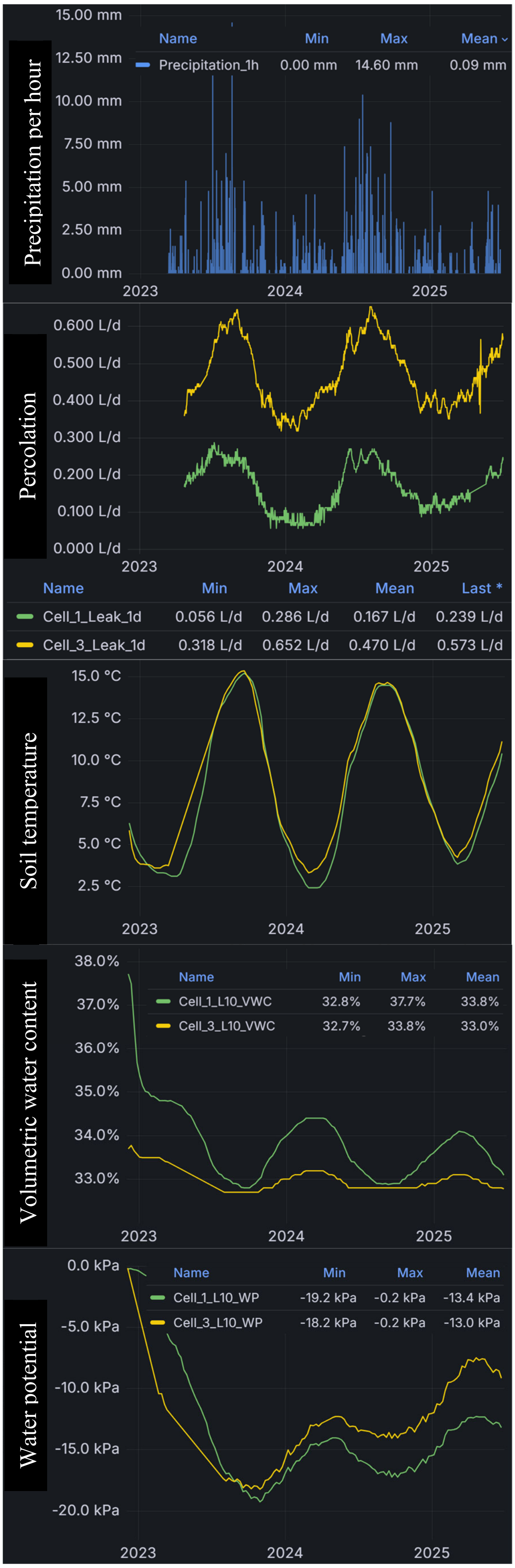
4.6 *Automated measurements vs. manual measurements*

Tipping buckets can be prone to errors and uncertainties. It is therefore useful to have one or more additional methods to determine the percolation. In this project, 20-litre buckets collecting all the water below the tipping bucket were emptied every month and the total cumulated volume of collected water was measured and compared to automated measurements (Figure 10). Tipping bucket measurements generally underpredicted manual measurements. Over the period July 2023 to July 2024, differences in the total volumes varied from 7% to 16% for the various cells, with the largest percentage-wise difference for cell 2, and the lowest for cell 1. The deviance is notable and much higher than the accuracy reported by the manufacturer (2%). Nevertheless, it is not considered to affect the assessment of the barrier performance.

Regarding the reliability of the percolation measurements overall, it may be mentioned that Ånes et al. (2024) in general found a good agreement between laboratory saturated hydraulic conductivities on intact samples from the barriers and the efficient field hydraulic conductivity estimated using the same approach as Albright et al. (2006).

5 LESSONS LEARNED AND PRACTICAL IMPLICATIONS

Construction and instrumentation work: Due to good planning and co-operation between the parties involved, the construction and instrumentation work were efficient and went without notable problems or time delays. It is emphasized that despite excellent planning, questions and unforeseen issues will inevitably arise during the construction phase. It is therefore important for all parties to be present during these days to facilitate efficient discussions and implementation of solutions.



Name	Min	Max	Mean
Precipitation_1h	0.00 mm	14.60 mm	0.09 mm

Name	Min	Max	Mean	Last *
Cell_1_Leak_1d	0.056 L/d	0.286 L/d	0.167 L/d	0.239 L/d
Cell_3_Leak_1d	0.318 L/d	0.652 L/d	0.470 L/d	0.573 L/d

Name	Min	Max	Mean
Cell_1_L10_VWC	32.8%	37.7%	33.8%
Cell_3_L10_VWC	32.7%	33.8%	33.0%

Name	Min	Max	Mean
Cell_1_L10_WP	-19.2 kPa	-0.2 kPa	-13.4 kPa
Cell_3_L10_WP	-18.2 kPa	-0.2 kPa	-13.0 kPa

Figure 9. Monitoring data for cells 1 and 3. Measurements of soil temperature, volumetric water content and water potential were performed 20 cm into the hydraulic barrier from the base.

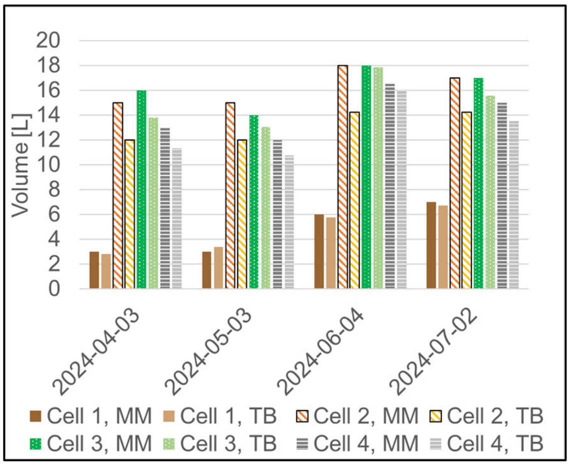


Figure 10. Comparison between manual measurements (MM) and cumulative tipping bucket (TB) measurements for the same periods.

Lateral run-off: Diversion and collection of the drainage water from the barrier surface would have been useful to have better control of the water balance of the cover overall. Thereby it would also be useful for assessing the reliability of the other measurements and for numerical modelling efforts. In addition, collecting drainage water would have been useful for the environmental assessment of the different barrier materials, as one would then also have been able to assess the surface leaching in the field. However, the current design with close to horizontal barrier surface would have needed notable modifications to route and collect all drainage water. This would likely mean both longer time for construction and greater material costs.

Lysimeter size: Disregarding the effect on material representativity, the relatively small lysimeter size increases the uncertainty of the percolation measurements, as lateral flow around the lysimeters may be present. However, the ratios between the width of the lysimeters and the thickness of the barrier is around 5, where an increase in the width has been shown (for one set of materials, Chiu & Shackelford, 2000) to not give appreciable lower error in percolation. Currently, the hydraulic material properties and field conditions have not been studied to assess whether lateral flow may in fact occur, but the continuous downward gradient conditions present in the barriers were expected to reduce potential lateral flow. A larger lysimeter would reduce the uncertainty of percolation measurements but would also mean a greater cost in addition to occupying more space.

Suction measurements: The porous disc in Teros 21 has a lower air entry value than the compacted clays (9 kPa vs. ~20-60 kPa) and requires the influx of air in order to measure values on the dry side of this. The air entry values of the clays had not been surpassed, and therefore the Teros 21 did not provide reliable suction measurements. Other methods for suction monitoring could have been used, such as tensiometers or thermal dissipation sensors, but measurements with these are also subject to error (Benson et al., 2001), and reliable suction measurements in clays seems indeed to be difficult.

Geochemical analyses of percolated water: If performing environmental assessments as part of such field experiments, we emphasize the importance of having an overview of potential sources of heavy metals or other contaminants from the materials that the percolated water is in contact with other than the barrier materials. Comparison with results from laboratory testing (e.g. total content, shaking tests, column tests) will indicate additional contamination, but it will not help in explaining the reason or identifying the external source.

6 SUMMARY

This paper describes the construction and instrumentation of a field-scale final cover pilot at a hazardous and non-hazardous waste landfill site in southern Norway. The hydraulic barrier was divided into four cells, where three different types of clayey materials generated as surplus or waste from construction projects were used. Percolation from each of the four cells was collected by a lysimeter and measured automatically by a tipping bucket before being collected by a 20-litre bucket installed below for monthly measurements and sampling for geochemical analyses. Percolation values from the tipping buckets had the required accuracy for the use in this project, where annual values and seasonal variations from year to year were of primary interest. The pilot set-up was considered to provide reliable measurements of the percolation for comparison of performance of the barriers and their development over time. In addition, it collected valuable data for an environmental assessment of the use of the clayey waste materials in the hydraulic barrier.

7 ACKNOWLEDGEMENTS

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