Sustainable Landfill Design by Monitoring and Managing Cap Infiltration

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EXECUTIVE SUMMARY

Victorian Landfill Guidelines follow a dry-tomb strategy for managing putrescible landfills by effectively requiring the use of geomembrane layers in the basal liner and capping systems. However, based on the climatic setting of Melbourne, Australia, it was hypothesised that effectively all of the rainfall that infiltrates into a landfill cap constructed from local soils could subsequently be evapotranspired out of the landfill cap. Elimination of infiltration into the landfilled waste would preclude generation of rainfall-derived leachate. Hence, a dry-tomb landfill could be constructed without geomembranes provided there is sufficient storage of soil moisture in the cap profile to retain incident rainfall. A corollary to this hypothesis would be that long-term moisture infiltration through the final landfill cap can be regulated (such as for a flushing or bioreactor landfill) by designing an appropriate cap constructed from native soils and vegetated with local plants.

To test this hypothesis, two landfill test caps were constructed on top of a closed landfill cell at a site near Melbourne, Australia. Each cap consists of 300 mm of topsoil and mulch overlying a 1,200-mm-thick barrier layer. The test caps were constructed to evaluate the relative performance of two barrier materials. The barrier layer of one test cap was constructed from site clay; while the barrier layer of the other test cap was constructed from a quarry product comprised of clayey non-descript crushed rock (NDCR).

A soil-moisture-monitoring network was established on each test cap. The performance of each test cap has been evaluated by comparing relative (rather than absolute) changes in soil moisture due to the movement of water through each test cap. To date, changes in soil moisture of each test cap have been similar. Figure 1 shows how soil moisture has varied in each test cap over time at each sensor depth. The soil moisture of the topsoil/mulch layer of each test cap has increased the most in response to both natural and artificial rainfall, then subsequently dried out as most of the stored moisture

evaporated. Moisture levels in the upper portions of each barrier layer (less than 400 mm) strongly mimicked (although with lower amplitude) the wetting and drying cycles exhibited by the topsoil/mulch layer. In each test pad, the sensor located at 700 mm depth has weakly mimicked the response of the topsoil/mulch sensor (at 100 mm depth). Since October 2002, moisture levels in the deeper portions (1,000 mm and deeper) of each barrier layer has varied less than 2 mm. This change corresponds to about 0.5% of the total water applied (about 355 mm as natural and simulated rainfall), which is less than the long-term cap-leakage rate (3.5% of rainfall) predicted by preliminary HELP modelling.

Direct measurement of soil moisture within each test cap provides an improved basis for landfill design and management and fills a serious gap in current monitoring. The monitoring network has recorded the movement of wetting fronts predominantly through the topsoil/mulch layer of each test cap. It is concluded that the similar lag times and responses for sensors in either barrier layer indicate that the two barrier layers perform comparably and that the use of a clay barrier devoid of rock components cannot be justified.

INTRODUCTION

The specification for landfill caps to meet regulations has become ever more prescriptive over the years. This reflects the regulatory goal of providing ever greater protection for the environment from leachate excursions through basal liners, which are driven by hydrostatic head resultant from rainfall infiltration through the cap. Cap specifications also seek to improve gas-harvesting potential.

Current Victorian Guidelines (so called Best Practice) specify the use of geomembrane layers in the cap as well as in the basal liner as well as a series of layers of different layers each with specific purposes. All of this is very expensive and questionable in effectiveness. Recent data compiled by Bonaparte and others (2002) for the US EPA show that even with multiple geomembrane layers in the basal liner, leachate leaks through the upper geomembrane barrier layer. Average leakage rates ranged between:

- 5 and 440 l/ha-day during initial landfill operation (a few lifts with only daily cover).
- 1 and 360 l/ha-day during the active period of landfill operation (intermediate cover)
- 2 and 60 l/ha-day after closure of the landfill cell.

In addition, landfill operators are looking at up to 30 years of post closure management and the provision of very significant financial assurances which must be maintained over this time to provide for any failures in the engineered systems that may occur in that period. These aspects add to the cost of the period at a time when there is no income from the site.

The need for prescriptive specification is the perception that infiltration does occur through the landfill cap and that in time it will drive leachate out of the site and that this will be bad for the environment. Simple water balance models mostly don't support such a "Black Armband" view of landfills in the post-closure period. However, the accepted conservative models (such as HELP) do indicate that there will be a consequence of infiltration and this leads to the situation we have today which is notably not underpinned by any hard data.

For a number of years soil moisture-monitoring equipment has been available for scientists working in irrigation and plant propagation optimisation field. These include gypsum block moisture monitoring indicators and neutron probe moisture meters. These approaches were however difficult to use and to interpret and, in the latter case, quite expensive.

Some work on landfill moisture profiles has been done using neutron probes (Yuen and others, 1999, Joseph and others, 2001 and Aylward, 1997), but the scope was limited by the expense and the time required for the monitoring. Recently the development of new technology has opened up the opportunity to continuously monitor rainfall infiltration through landfill caps.

Sentek Pty Ltd has developed the EnviroSCAN system, which continuously monitors soil moisture conditions. The EnviroSCAN system consists of several access tubes. Each access tube contains a network of capacitance sensors used to measure soil moisture. After calibrating and positioning the sensors at the desired depths in the access tube, data is collected continuously and stored in a central data logger, which can be downloaded directly in the field or via telemetry. EnviroSCAN systems have been used to optimise irrigation for many types of crops (including stone fruit, cotton and potatoes) and to manage disposal of waste water via pasture irrigation.

The Boral Western Landfill operated by Boral Landfill & Waste is located approximately 22km west of the Melbourne CBD. This major Melbourne landfill has seen the first application of the Sentek EnviroSCAN soil moisture monitoring probe arrays at a landfill. The installation monitors moisture variations at two caps (constructed as trial final caps) to compare the performance of two types of materials that could be used for the cap barrier layer.

The climatic setting of the site results in little recharge through the natural soil, which are derived from weathering of Quaternary-aged basalts. Evaporation (about 1,700 mm/year) exceeds the median rainfall (about 540 mm/year). Therefore, recharge through a landfill cap constructed from clayey local materials (such as the site clay soil or NDCR material) can be reduced to effectively zero. This is attained by temporarily storing rainfall-derived moisture in the winter months within the cap, then subsequently removing the soil moisture by evaporation or transpiration (once the cap is vegetated).

The site clay material had fulfilled regulations with regard to hydraulic conductivity (that is, less than 1e-7 cm/s); while the NDCR conductivity had tested slightly higher (about 5e-6 cm/s). However, we hypothesised that either barrier material could store sufficient rainfall-derived moisture, which could be subsequently evapotranspired out of the landfill cap. To provide sufficient storage, each barrier layer is 1,200 mm thick and overlain by approximately 300 mm of compost and topsoil, which has recently been vegetated. Each barrier layer was constructed in lifts (about 200-mm thick). Each lift was moisture conditioned and compacted. Field density tests indicated near optimum moisture contents (within 2%) and standard Hilf density ratios between 98% and 103%.

Four access tubes were installed in each test cap. Each access tube contains sensors that monitor soil moisture at various levels between 100 and 1500mm. In each access tube, one sensor is located at a depth within the topsoil (about 100 mm deep). The next sensor is placed at the depth of the contact between the topsoil and the clay barrier layer (about 300 mm deep). The remaining sensors are located at depths within the clay barrier layer (about 400, 700, 1,000, 1,200, 1,400 and 1,500 mm deep).

RESULTS

Figure 1 shows how soil moisture has varied in each test cap over time at each sensor depth. Output from the array shows downward infiltration of natural and artificial rain events through the cap topsoil and into the upper portion of each barrier layer (to a total depth of about 700 mm) followed by drying as evaporation removed soil moisture from the cap topsoil and upper portion of the barrier layer.

Soil moisture in the topsoil/mulch layers has varied up to 25 mm for the clay test cap and about 15 mm for the NDCR test cap. Typically, the topsoil layer for the clay test cap has a higher moisture content than most of the barrier layer. In contrast, the NDCR topsoil layer has usually been wetter than the NDCR barrier layer (due to the rock fragments in the NDCR barrier layer, which results in lower moisture contents).

Moisture content for individual sensors in the barrier layer of each test cap has varied less than about 2 mm over an overall range for all sensors of about 5 mm. In each test cap, the shallower sensors (300-mm and 400-mm depths) quickly mimicked changes in the topsoil moisture contents (typically within a day of rainfall or water-application events). But the event amplitudes are less than 0.2 mm.

Sensors at greater depths respond with a lag of a few weeks (70-cm sensor) to several months (1,000-mm and 1,200-mm sensors) and amplitudes of individual events of less than 0.1 mm. Initially, moisture contents at the base of each barrier layer (1,500 mm) were higher than moisture contents at 1,400 mm. This presumably reflected the initial moisture contents at these depths.

Initial moisture contents for the NDCR barrier layer were 26.1% at an equivalent depth of about 1,300 mm and 28.4% at an equivalent depth of about 1,500 mm. Corresponding moisture contents for the clay barrier layer were 41.4% (1,300 mm) and 46.5% (1,500 mm). In the NDCR barrier layer, the moisture content at 1,500 mm exceeded the moisture content at 1,400 mm that by mid-December. In the clay barrier layer, the moisture content at 1,500 mm was consistently higher than at 1,400 mm. This may reflect the condensation of saturated landfill gases flowing upward from the closed cell underlying the test caps. Regardless of the mechanism, the net effect is to maintain the moisture content of the lower portion of each barrier layer while allowing temporary storage of moisture in the upper portion of each barrier layer.

CONCLUSIONS

Regardless of the potential vapour-transport process, the cumulative change has been an overall increase in soil moisture in the deeper portions of each barrier layer of about 2 mm since November 2002. This change corresponds to about 0.5% of the total water applied (about 355 mm as natural and simulated rainfall). The monitoring network has recorded the movement of wetting fronts predominantly through the topsoil/mulch layer of each test cap. The similar lag times and responses for sensors in either barrier layer indicates that the relative performance of the two barrier layers is comparable.

This data supports our hypothesis that effectively all of the rainfall that infiltrates into a landfill cap constructed from local soils could subsequently be evapotranspired out of the landfill cap. Note that these results are consistent with observations made by Hancock using Aylward's (op cit.) data, which showed rapid re-hydration of deep soil layers after moisture decline during a prolonged drought period. The significance of this counter-intuitive (but entirely understandable) moisture flux cannot be underestimated, since it acts to maintain the deeper clay cap layer hydrated and sustains vegetative evapotranspiration.

A corollary to our hypothesis would be that using a thinner cap constructed from native soils and vegetated with local plants could regulate long-term moisture infiltration through the final landfill cap. In this way, the landfill cap for either a flushing or bioreactor landfill can be designed to allow infiltration rates through the cap, which can vary during post-closure. Higher infiltration rates may be desirable during early post-closure periods to promote waste decomposition during our generation (rather than preserving the waste for several generations, as often occurs in dry-tomb landfills). Once the waste has been stabilised (ideally within the initial 30 years of post-closure), higher infiltration rates could be accommodated, since leachate strength (indicated by parameters such as salinity and chemical oxygen demand) would be reduced to acceptable levels. In this way, the condition of the landfill cap becomes less critical to the environmental performance of the landfill.

The results of these comparisons provide site-specific data as to the excellent performance of different barrier materials. This performance will be especially enhanced as dense, deep-rooted vegetation is established and matures. This NDCR barrier material would not normally be considered desirable for cap applications by conservative regulators but such materials have been used elsewhere with significant success (Swarbrick and Koupai, 1996).

We believe that the application of this new instrumentation can provide an improved basis for landfill design and management and fills a serious gap in current monitoring. If the ongoing results are as expected, the concepts applied with respect to requirements for capping and for extended post closure monitoring periods will be challenged at least for some sites and opportunities for significant cost savings identified while at the same time maintaining high standards of environmental protection.

On-going monitoring of soil moisture in each test cap will be continued to compare the:

- Current performance of each trial final cap.
- Relative performance as vegetation becomes established and matures.
- Relative performance as each trial final cap stabilises over time.

In addition, it is proposed to expand the monitoring to include re-calibration of the soil-moisture probes, along with evaluation of the temperature profile and soil-gas composition. The authors hypothesise that the combination of cooling and methane degradation in the cap represent sources of moisture travelling vertically upward in the cap profile, which act to keep the cap materials fully hydrated (hence less prone to cracking) and of very low permeability. Notably, the HELP program does not simulate these phenomena, hence cap infiltration is not accurately simulated by HELP.

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Figure 1

Soil Moisture (mm) at Indicated Depth