MONITORING AND EVALUATION OF EVAPOTRANSPIRATIVE COVER PERFORMANCE

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SUMMARY: In 1998, the City of Los Angeles, California, U.S.A. was granted conditional approval of an evapotranspirative final cover for the Lopez Canyon Sanitary Landfill as an engineered alternative to the prescriptive barrier layer final cover. The conditions of approval required a minimum of two years of field performance monitoring to validate the unsaturated flow model used to demonstrate that, in accordance with California regulations, the evapotranspirative final cover provided equivalent or superior infiltration control compared to the prescriptive minimum barrier layer cover called for in the regulations. Initial soil properties for UNSAT-H, the computer program for one-dimensional unsaturated flow in soils used to evaluate infiltration through both the prescriptive and alternative cover, were based upon laboratory testing prior to installation of the monitoring instrumentation and correlation with soil type. The soil properties were then modified within limits expected based upon physical considerations to give the best possible prediction of measured soil moisture content over two successive years of monitoring. The calibrated model was then used to compare the infiltration performance of the engineered alternative evapotranspirative final cover to the prescriptive minimum barrier layer final cover. Results of the analysis yielded a percolation into the waste through the evapotranspirative final cover that was less than half that of the prescriptive minimum barrier layer cover. This analysis provided the basis for final regulatory approval of the engineered alternative evapotranspirative final cover at the Lopez Canyon Sanitary Landfill.

1. INTRODUCTION

In arid and semi-arid climates, evapotranspirative (ET) final cover systems can provide an environmentally superior and cost-effective alternative to prescriptive soil barrier layer final covers for solid waste landfills. An ET cover is a cover system that controls percolation into the waste by storage of infiltrating surface water within the cover and release of the stored water to the atmosphere through evaporation and transpiration before it can percolate into the waste. Prescriptive barrier layer covers are sometimes referred to as “resistive” covers as they control percolation with a barrier layer composed of at least 0.3 m of low-permeability soil. ET covers may be described as “capacitive” covers as they control percolation by storing infiltration...
during wet periods in the soil pores by capillary action and releasing it to the atmosphere during dry periods.

ET covers include both “monolithic soil” covers and capillary break covers. Figure 1 shows cross sections of a prescriptive barrier final cover (designed in accordance with California regulations for unlined municipal solid waste landfills) and typical evapotranspirative monolithic soil and capillary break final covers for southern California. The ET covers both include a vegetated upper layer of relatively fine-grained soil capable of retaining moisture and capillary action but also capable of readily releasing the retained moisture to the atmosphere through evaporation and transpiration. Monolithic soil covers are typically 1.2 m to 1.8 m in thickness and may directly overlie the waste or interim cover.

In addition to superior percolation control in arid and semi-arid climates, ET covers offer advantages compared to prescriptive barrier layer covers. ET covers are generally cheaper and easier to construct and maintain than prescriptive covers, though construction cost comparisons are affected by local soil availability. ET covers have an added advantage of superior resistance to cracking due to desiccation and differential settlement compared to low-permeability soil (i.e., clay) barrier layer final covers. With respect to other functions of the final cover (e.g., waste isolation, erosion control), ET covers are generally at least as thick as the prescriptive cover, thereby affording equivalent or superior isolation of the waste, and a vegetated top layer generally provides adequate erosion resistance. ET covers may also be beneficial with respect to landfill gas control, as they are less likely than a barrier layer final cover to induce gas lateral migration due to the higher gas conductivity and diffusivity of ET covers.

2. REGULATORY COMPLIANCE

2.1 US Federal Regulations

US Federal regulations for closure of municipal solid waste landfills are found in Section 258.60 of Title 40 Code of Federal Regulations (CFR) Subpart F - Closure and Post Closure (Subtitle D). These federal regulations contain the following prescriptive requirements for the final cover of a municipal solid waste landfill. The final cover shall:

- Be designed to minimize percolation and erosion;
- Include a infiltration barrier layer with a minimum thickness of 18 in. (457 mm) and a permeability of less than or equal to the permeability of any bottom liner system or natural subsoils present, or a permeability no greater than 1 x 10^-5 cm/s, whichever is less; and
- Include an erosion control layer, a minimum of 6 in. (152 mm) thick, capable of sustaining native plant growth.

The federal regulations allow the director of an approved state (a state whose regulations have been found by the US Environmental Protection Agency (USEPA) to comply, at a minimum, to Subtitle D) to approve an engineered alternative design to the prescriptive final cover design. However, the performance of the infiltration barrier layer and erosion control layer of the alternative cover must be shown to be equivalent or superior to the performance of the prescribed layers with respect to percolation, wind, and water erosion.

2.2 California Regulations

State of California regulations for design and construction of final covers for closure of municipal solid waste landfills are found in Title 27 of the California Code of Regulations (27 CCR). The California prescriptive final cover, described in Section 21090(a) of 27 CCR, called
herein the “Title 27 prescriptive final cover,” exceeds the Subtitle D minimum standards. The Title 27 prescriptive final cover requires a low-permeability soil barrier layer not less than 1 ft (0.3 m) thick with a saturated hydraulic conductivity no greater than $1 \times 10^{-6}$ cm/s. This barrier layer must be overlain by either a vegetative layer containing no waste or leachate not less than 1 ft (0.3 m) thick and of greater thickness than the rooting depth of any vegetation planted on the cover or a “mechanically-resistant” erosion control layer. California regulations allow for engineered alternative final covers provided the design will function with minimum maintenance and provide waste containment to protect public health and safety by controlling at a minimum, vectors, fire, odor, liter and landfill gas migration. The California requirements for approval of engineered alternatives to the Title 27 prescriptive final cover include demonstrations that:

- The prescriptive standard is not feasible because either it is unreasonable and unnecessarily burdensome and will cost substantially more than alternatives which meet final cover performance criteria or that it is impractical and will not promote attainment of applicable performance standards; and
- There is a specific engineered alternative that is consistent with the performance goal of the prescriptive standard and affords equivalent protection against water quality impairment.

California regulations provide no specific procedures for making the required demonstrations. What constitutes an appropriate demonstration is left to the discretion of the Regional Water Quality Control Board, the Integrated Waste Management Board, and the local enforcement agency and thus may vary across the state.

3. WATER BALANCE ANALYSES

3.1 Mass Balance Equation

Water balance analysis is the key component in ET cover design. A water balance analysis is essentially a mass balance approach to evaluating the flux of water across the bottom of the landfill cover system. The water balance equation may be written as follows:

$$PRC = P - OF - \Delta S - (E + T)$$

where PRC is percolation through the bottom of the cover; P the precipitation; OF the overland flow (runoff); $\Delta S$ the change in soil moisture storage; E the evaporation; and T the transpiration. Percolation (PRC) is the result of the mass balance calculation. Percolation is defined as the quantity of water that moves into the waste mass through the base of the bottom layer of the cover system. Transpiration and evaporation both work to remove soil water from storage, creating upward suction gradients and acting to dry out the soil profile. This drying action restores the soil storage capacity for future rain events. These processes are enhanced by prolonged periods of dry, warm, and sunny weather.

3.2 Input Parameters

Input parameters to water balance analyses include climate data, vegetation properties, and soil properties. Climate data required for the analyses include temperature, wind speed, precipitation, solar radiation, barometric pressure and dew point. Vegetation data includes the rooting depth and root distribution, wilting point, the leaf area index (the ratio of leaf surface area to ground surface area), and the parameters for Ritchie’s equation [Ritchie, 1972]. Ritchie’s equation gives the ratio of potential evaporation to potential transpiration as a function of leaf index.
The key soil properties necessary for a water balance analysis are the unsaturated hydraulic conductivity of the soil and its volumetric moisture content. Both of these parameters are functionally related to the matric suction (negative pore pressure) in an unsaturated soil. The van Genuchten soil-water retention function [van Genuchten, 1980] and the van Genuchten-Mualem unsaturated hydraulic conductivity equation [van Genuchten, 1980; Mualem, 1976] are among the most common means by which to express these relationships.

Figure 1 shows typical moisture content-matric suction curves for four soil types. The shapes of these curves explain their relative suitability for use in an ET cover. The clean gravel has inadequate moisture retention characteristics: it will release the water in its pores when subjected to even minimal gravity gradients, i.e., it yields stored water too readily. The clay soil does not yield stored water readily enough: even at very high matric suction clay soil retains a significant amount of moisture in its pores and thus has minimal storage capacity even at the end of a hot, dry summer. The high matric suction can also lead to cracking of the clay. Sandy silt and silty sand are optimal soils for ET covers, as they do not yield water to gravity forces, but do give up most of the water in their pores when subjected to high-matric suction.

3.3 Numerical Analysis

The water balance equation and its constituents are generally solved numerically using finite difference or finite element methods. LEACHM [Hutson and Wagenet, 1992] and UNSAT-H [Fayer and Jones, 1990; Fayer, 2000] are two numerical models that have been shown to give reliable results when properly employed. Model results can be sensitive to both the physical properties and climate data input to the model and numerical parameters used to set up the model (e.g., element size, time step, numerical integration parameters). However, when properly employed, these numerical models can be powerful tools for designing ET cover systems and demonstrating regulatory compliance.

Figure 1. Representative Moisture Content – Matric Suction Curves
4. CASE HISTORY

The Lopez Canyon Sanitary Landfill is an inactive California Class III municipal solid waste landfill owned and operated by the City of Los Angeles (the City) Bureau of Sanitation (BOS). The Lopez Canyon Sanitary Landfill received waste from the mid-1970’s until 1 July 1996. The Lopez Canyon Sanitary Landfill is located in the Lake View Terrace section of the City.

It was originally planned to construct a prescriptive final cover specified in Title 27 of the California Code of Regulations (the Title 27 prescriptive cover) for unlined portions of the landfill. However, an engineering evaluation indicated that an alternative monolithic soil cover final cover in these areas would offer better performance and be more cost effective than the Title 27 prescriptive cover. Thus, BOS decided to proceed with construction of a monolithic soil cover over the unlined areas and engaged in the course of action necessary to obtain regulatory approval for this alternative final cover.

The requirement for final approval by the RWQCB of the monolithic soil cover is the monitoring and evaluation of infiltration performance of the cover over a two year period at three test sections. The objective of this performance monitoring and evaluation program is to validate the theoretical water balance analyses used to demonstrate superior performance of the monolithic soil cover compared to the Title 27 prescriptive cover. The program developed for infiltration performance monitoring includes:

- installation of three moisture monitoring stations (MMS)
- collection of data from the MMS for a two-year period; and
- preparation and submission to the RWQCB of an installation report; a model calibration report; and a performance evaluation report.

At time of writing, two MMS’s have been installed, one at Disposal Area A and one at Disposal Area AB+ in May and November 1999 respectively. The monitoring system at each MMS consists of Time Domain Reflectometry (TDR) probes for soil moisture monitoring and a site weather station to gather accompanying weather.

4.1 Weather Data

The weather data is collected through five sensors. Given the proximity of the two monitoring stations, only one weather station was installed to collect weather data for the site. Sensors were installed to measure solar radiation, wind speed and direction, soil temperature, rain quantity, and relative humidity and temperature.

The five sensors were selected to collect the necessary weather input parameters for use in modeling the hydraulic performance of the covers. Hourly weather data have been collected since 18 May 1999 from the weather station. The hourly precipitation data collected were reduced to daily totals and are shown on Figure 2 for the period from May 1999 to August 2002.

4.2 Cover Soil Moisture Content

The TDR probes used for performance monitoring provide the average volumetric moisture content from several depth intervals. Hourly TDR moisture content data were collected from May 1999 to November 2000 at MMS A and from November 1999 to November 2000 at MMS AB+. The hourly TDR moisture content data are stored electronically by the datalogger and downloaded periodically for permanent storage and interpretation. The hourly TDR moisture content data are then converted into daily values for analyses and input into the water balance model.
4.2 Vegetation Data

The vegetation on slope A consists of native annual established species. The vegetation on the slope of Disposal Area AB+ was established by hydroteering in the fall of 1999. A new green growth of vegetation was observed late in the winter of 2000, indicating that the pioneering species of the cover vegetation have become established.

4.3 Calibrated Model Simulations

Water balance simulations at stations MMS A and AB+ were performed with the UNSAT-H v3.0 computer code. For each monitoring station, the soil moisture initial conditions used for the simulations correspond to the TDR volumetric water content measurements for the first day of the simulation. Simulations were performed for a 12-month period. The weather data collected at the weather station and vegetation parameters derived from the field observation of the vegetation were used as input parameters to UNSAT-H.

The value of the saturated volumetric moisture content, $\theta_s$, was obtained by setting the maximum peak volumetric moisture content computed in the UNSAT-H analyses to the peak volumetric moisture content measured in the shallowest TDR probe at each monitoring station. The value of the residual volumetric moisture content $\theta_r$ was obtained by matching the minimum TDR volumetric water content measured in any stack at each station. The value of the van Genuchten filtering parameter $n$ which is one of the parameters defining the shape of the moisture content-matric suction curve (Figure 1) was then adjusted to match the observed reduction in soil moisture at the surface during the dry period (i.e., summer).

The initial value of saturated hydraulic conductivity for the bottom soil layer was chosen as the geometric average value of the soil hydraulic conductivities measured on soil samples collected during installation of MMS AB on the slopes of Disposal Area AB and from the literature for the soil in place on the slopes of Disposal Area A. When performing parametric study on the saturated hydraulic conductivity, the aim was to match the propagation speed of the wetting front from the top to the bottom of the cover between observed and simulated moisture.
content. To take into account the effect of surficial soil disturbance (i.e., plant roots, soil unloading, erosion) the saturated hydraulic conductivity of the topsoil layer is computed by multiplying the bottom layer hydraulic conductivity value by a site-specific factor. The site-specific factor (e.g., 2 for MMS AB+) is determined by the parametric study such that the best match between computed and measured TDR volumetric water content is achieved. The results of the UNSAT-H model calibration are reported in Figures 3 and 4 through 3-6 for MMS A at depths of 0.15m and 0.3m respectively. The figures show the moisture contents predicted by UNSAT-H following model calibration and the moisture content measured by the TDR probes.

In general, there is good agreement between simulated and measured moisture content trends. The model and the TDR probe data both show large moisture content fluctuations at the surface in response to rain events. The simulated and measured moisture responses generally decrease in intensity for segments located deeper within the cover.

6. FINAL PERFORMANCE EVALUATION OF THE COVER

6.1 General

The goal of the performance monitoring program was to provide the data necessary to calibrate the water balance model and to use the calibrated model to simulate and compare the performance of the evapotranspirative soil cover and the Title 27 prescriptive minimum cover over the 10-year weather data selected in the initial analyses described in the engineering evaluation [GeoSyntec 1998a]. The soil properties and program parameters derived by matching the measured volumetric soil moisture content to those predicted by UNSAT-H and the vegetation data used in the calibration analyses are used in this final performance evaluation.

Figure 3. TDR measured and UNSAT-H predicted moisture content at 0.15m
6.2 10-Year Modeling of the Cover Performance

Rainfall for the 10-year period 1951 to 1962 from the Sunland Weather Station (selected as the local station that best approximates Lopez Canyon conditions) was used in the engineering evaluation.

Water balance analyses were performed for the 10-year period using the weather data from the Sunland Station and the soil properties, vegetation parameters, and program parameters identified for each cover.

Cumulative percolation predicted by UNSAT-H for the Title 27 prescriptive minimum cover, the evapotranspirative cover on the slope of Disposal Area A, and the evapotranspirative cover on the slope of Disposal Area AB+ are shown in Figure 5. Annual percolation predicted by UNSAT-H for the Title 27 prescriptive minimum cover, the evapotranspirative cover on the slope of Disposal Area A, and the evapotranspirative cover on the slope of Disposal Area AB+ are shown in Figure 6.

The water balance simulation performed using the UNSAT-H model indicates that the predicted percolation through the evapotranspirative covers installed on the slopes of Disposal Areas A and AB+ is less than that through the Title 27 prescriptive minimum cover. Therefore, based on the field monitoring program and the modeling results, the infiltration control performance of the evapotranspirative covers exceed the performance of the Title 27 prescriptive cover.

7. CONCLUSION

Evapotranspirative (ET) final covers offer environmentally superior, cost effective alternatives to prescriptive barrier layer final covers for municipal solid waste landfills in arid and semi-arid
climates. Water balance analyses demonstrate that a properly configured ET cover can provide superior resistance to percolation of surface water into the waste compared to prescriptive barrier layer covers. An ET cover is also more resistant to cracking due to differential settlement and desiccation and less likely to induce gas migration problems than a prescriptive cover.

![Figure 5. Cumulative percolation through covers on sideslope AB+](image1)

![Figure 6. Yearly percolation through covers on sideslope AB+](image2)
ET covers can be designed using water balance analyses. Water balance analyses can be used to evaluate alternative final cover performance standards based on the percolation through prescriptive or existing soil covers. Water balance analyses can also be used to evaluate the necessary thickness of on-site soil or the desired properties of imported soil to meet the established performance standard. Soil moisture measurements demonstrate that the water balance analyses can reliably model unsaturated flow in soil covers for landfills.

This paper present moisture monitoring data and weather data collected at two moisture monitoring stations at the Lopez Canyon Landfill. A comparison of TDR moisture content with laboratory moisture content indicate that the installed TDR probes installed at the Lopez Canyon Landfill are functioning properly. The moisture content and weather data collected at the site were used to calibrate the numerical water balance model used to evaluate alternative final cover performance. The model calibration analyses show good agreement between the simulated and measured moisture content trends. The model and the TDR probes both indicate large moisture content fluctuations at the surface in response to rain events. The simulated and measured moisture responses are generally decreasing in intensity for segments located deeper within the cover. Evaluation of the measured moisture contents show that, generally, there is less than 5 percent change in the relative volumetric moisture content near the bottom of the evapotranspirative soil cover compared to nearly 90 percent near the surface, suggesting that most of the water infiltrating into the cover is removed by evaporation and transpiration and does not percolate through the cover into the waste.

REFERENCES


