Design of Monocovers for Landfills in Arid Locations

JORGE G. ZORNBERG
GeoSyntec Consultants, Huntington Beach, California, USA

JACK A. CALDWELL
GeoSyntec Consultants, Huntington Beach, California, USA

ABSTRACT: This paper presents the results of an unsaturated flow analysis performed to identify and quantify the parameters that govern the design of monocover closure systems for landfills in arid locations. Infiltration control in a monocover system relies on the storage of moisture within the cover soil during the rainy season, and on the subsequent release by evapotranspiration of the stored moisture during the dry season. The study described here provides a rational basis for selection of parameters that govern the design of monocover systems, such as the thickness of the soil cover layer and the rooting depth of the vegetation. An evaluation of the components of the water balance is performed using unsaturated flow modeling of a generic monocover system for weather conditions typical of southern California. Next, an evaluation of the sensitivity of parameters that govern the percolation through the cover system is described. The parametric evaluation indicates that a monocover with a thickness as small as 600 mm in the semi-arid climate of southern California satisfies stringent percolation design criteria.

1 INTRODUCTION

This paper presents the results of unsaturated flow modeling undertaken to identify and quantify the parameters that govern the design of monocover closure systems for landfills in arid areas. Federal and state-mandated cover systems for municipal and hazardous waste landfills in the United States generally consist of "resistive barrier" systems. Infiltration control by these resistive barriers is typically achieved by including a clay layer with a low (typically 10^{-7} cm/s or less) saturated hydraulic conductivity. Although the performance of resistive barriers is generally satisfactory in wet climates, desiccation cracking of the clay layer leads to inadequate performance in arid areas. However, monocovers have shown good performance as alternative cover systems in arid climates. Infiltration control in monocover systems relies on the storage of moisture within the cover soil (generally a silty soil) during the rainy season, and on the subsequent removal by evapotranspiration of the stored moisture during the dry season. However, a consistent methodology for their design has not been developed yet. The study presented herein provides a rational basis for selection of the parameters governing the design of monocover systems.

Two key parameters that govern the design of a monocover are the vegetation rooting depth and the cover soil thickness. This paper presents a sensitivity evaluation of these parameters on the unsaturated flow percolation through the monocover. The analyses consider a silty soil for which the moisture retention properties are known and weather typical of southern California, which is characterized by an average precipitation of 380 mm/year and by an average evapotranspiration of 1015 mm/year.

2 THE MONOCOVER CONCEPT

The final cover system for a hazardous or municipal solid waste landfill should:

- reduce liquid migration into the waste;
- promote drainage while controlling erosion;
- reduce maintenance requirements; and
- accommodate differential settlements.

Monocover systems have been observed to perform successfully the functions above in arid and semi-arid climates. Monocovers are also referred to by other names in the technical literature such as monolithic soil cover, evapotranspirative (or ET) cover, and soil-plant cover (Hakonson, 1997). A typical monocover consists of a single layer of soil varying from 900 to 1800 mm thick (Figure 1). The monocover is usually vegetated with native plants that survive on the natural precipitation.

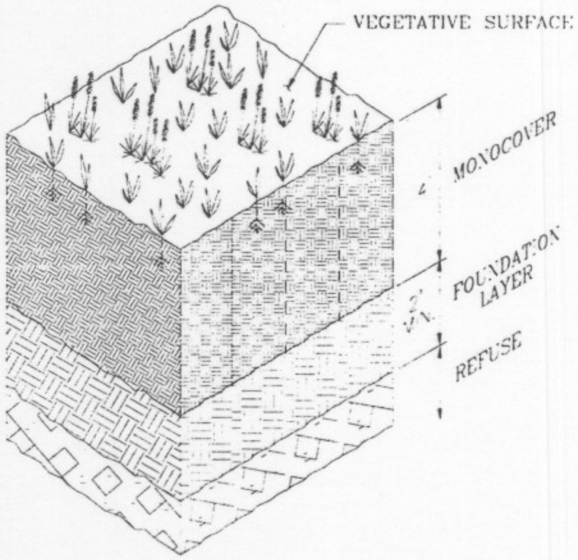

Figure 1. Schematic view of a Monocover System.

While percolation control in a "resistive barrier" is achieved by maximizing surface water runoff (Figure 2a), percolation control in a monocover is achieved by storing the infiltrating liquids in the soil cover during the rainy season and by removing the stored moisture by evapotranspiration during the entire year (Figure 2b).

Since the flow in the cover soil is unsaturated, hydraulic performance evaluation of the system requires a model that incorporates the hydraulic gradients and hydraulic conductivity values as a function of the soil moisture. Although for saturated conditions the hydraulic conductivity of a silty soil, typical of a monocover fill, is higher than the hydraulic conductivity of a clay; for unsaturated conditions the hydraulic conductivity of a silty soil is less than that of a clay. The superior performance in arid climates of monocovers relative to conventional resistive covers can then be attributed to the lower unsaturated hydraulic conductivity of the silty monocover soil, as compared to the saturated flow through a clay barrier.

An additional advantage of a monocover over a barrier system of clayey material is that a monocover constructed with silty material is less susceptible to desiccation and cracking.

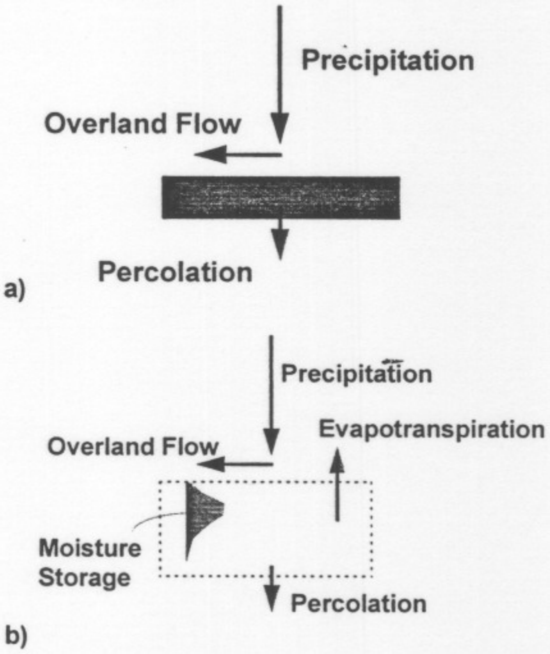

Figure 2. Main components in the water balance. (a) in a conventional resistive barrier. (b) in a monocover system.

3 METHODOLOGY

Comprehensive unsaturated flow modeling was undertaken to provide a design basis for monocovers at landfills in southern California. Unsaturated flow modeling was performed using the computer program LEACHM (Hutson and Wagenet, 1992). The investigation included the following phases:

- evaluation of the hydraulic performance of a generic monocover (Baseline Case), including quantification of percolation and the moisture profiles;
- sensitivity evaluation of key parameters governing the hydraulic performance of the monocover in terms of percolation rate; and
- equivalence demonstration of the cover system by comparing the estimated percolation through the monocover to the percolation

through federal- or state-mandated (prescriptive) covers.

The first phase provides an understanding of the general mechanisms of water transfer within a monocover system. The second phase identifies and quantifies the design parameters that govern the design of a monocover. Finally, the third phase assesses the conservatism and demonstrates regulatory compliance of the monocover design. This paper presents some of the results obtained for the two initial phases of that investigation.

The model LEACHM was selected for this investigation because (i) it was found suitable for design purposes, as it is particularly appropriate for parametric evaluations; (ii) it has an evapotranspiration routine which is better adapted to arid climate than other models; and (iii) it has received approval by local regulatory agencies for projects in California.

4 BASELINE MONOCOVER CONFIGURATION AND MODELING

The Baseline monocover is a 1500 mm thick single soil layer with a saturated hydraulic conductivity of 1 x 10^{-5} cm/sec and moisture retention properties typical of silty soils. Input parameters required for unsaturated flow modeling include soil properties, climatic data, vegetative data, finite difference nodal arrangement, and initial and boundary conditions.

Soil properties input data consist of saturated hydraulic conductivity and fitting parameters for the Campbell's soil-water retention function used in the analyses (Campbell, 1974). Campbell's fitting parameters (constant value *a* and exponent *b*) were obtained using soil-water retention data reported for silty soils by Khire et al. (1997) and Benson et al. (1994). The soil parameters used in this investigation are presented in Table 1.

Weather data for unsaturated flow modeling include daily precipitation and daily minimum and maximum air temperatures. Precipitation information used in the analyses was generated synthetically from the data base provided in US EPA's HELP code (Schroeder, 1994). The precipitation was generated for 30 years using data for southern California. Information on average temperatures was also generated synthetically using the HELP data base. Potential evapotranspiration was calculated by LEACHM as a function of precipitation and air temperature data using the Linacre's equation (Hutson and Wagenet, 1992).

Table 1. Properties used in the Baseline analysis.

	PROPERTY	VALUE
Soil Properties	Campbell parameter *a*	-4.89
	Campbell parameter *b*	4.215
Weather data	Average precipitation	379 mm
	Standard deviation	103 mm
Vegetation data	Rooting depth	25.4 mm
	Wilting point	1500 kPa
	Minimum root potential	3000 kPa
	Max. pot./actual transp. ratio	1.1
	Root resistance ratio	1.05
	Crop cover ratio	0.75
Modeling parameters	Initial volumetric moisture	23%
	Number of nodes	25
	Maximum time step	0.005 day

Vegetation data for the unsaturated flow analysis includes the root depth and root distribution, plant growth options (e.g. constant vegetation or "growing" vegetation), wilting point, minimum root potential, maximum ratio of actual to potential transpiration, root resistance, and germination, emergence, maturity, and harvest dates. The rooting depth of native annual grasses for southern California ranges from 200 to 450 mm. For the purposes of the evaluation of the baseline monocover, an average root depth of 300 mm was used. Additional parameter values listed in Table 1 were selected based on typical values recommended in the LEACHM manual. The crop cover fraction is used to split potential evapotranspiration into potential transpiration and potential evaporation. A crop cover fraction of 0.75 was considered in the analyses.

For the finite difference nodal arrangement, the 1500 mm thick cover profile was divided into 25 segments. Thus, the nodal spacing was 60 mm. The maximum time step was set at 0.05 day. The actual time step was lower, as it is reduced during the computation depending on the rate of precipitation to gain accuracy in the water balance calculations.

The lower boundary condition was modeled as a unit gradient boundary. Initial conditions for the unsaturated flow analysis are specified by assigning an initial water content to each node in the finite-difference nodal grid. The volumetric water content that corresponds to optimum conditions, as defined by Standard Proctor compaction tests, was used as initial condition. The initial volumetric moisture content for the baseline monocover case was 23 percent.

Water balance simulations were performed for periods of 10 and 30 years. Total precipitation, evapotranspiration, surface water runoff, percolation, and moisture storage change were calculated. The estimated cumulative percolation at the end of year 10 is only 0.37 percent of the cumulative precipitation. The cumulative values of the components of the water balance at the end of ten years, expressed as a percentage of the total precipitation, are shown in Figure 3.

The different components of the water balance for the baseline monocover on a yearly (instead of cumulative) basis are shown in Figure 4. As can be seen in the figure, the overland flow follows the trend of the precipitation records. For example, a comparatively high precipitation for year 3 results in a comparatively high overland flow for that year. The yearly evapotranspiration also tends to follow the trend of the precipitation. However, evapotranspiration trends do not follow the precipitation trends as closely as the overland flow. The yearly moisture storage change shows a negative value in the first year (i.e. the monocover loses moisture). This is due to the comparatively high initial volumetric moisture at which the cover was placed. Towards the end of the 10-year simulation period, the moisture in the monocover appears to have reached an equilibrium condition and the yearly storage change fluctuates around zero. Finally, the annual percolation shows a clearly decreasing trend with time. The initially higher percolation (particularly for the first year) is due to the comparatively high initial moisture content at which the monocover is assumed to be placed.

The components of the water balance were also evaluated on a daily basis. Figure 5 shows the different components of the water balance (infiltration, evapotranspiration, overland flow, storage change, percolation) for the wettest year of the year simulation. The wettest year corresponds to the third year of the 10-year simulation (see Figure 4). The yearly precipitation for that year is 563 mm.

The infiltration shown in Figure 5 corresponds to the difference between precipitation and surface water runoff. The figure illustrates the mechanics of the hydraulic performance of a monocover in arid regions during a comparatively wet season. Infiltration into the cover exceeds evapotranspiration during the winter, which is the rainy season in southern California. Infiltrated water is stored in the monocover (note the increase in storage change), but essentially no liquids exit the base of the monocover (note the essentially zero percolation). The cumulative moisture storage curve decreases following the significant rain (around mid-February), and shows some smaller peaks during successive rainy events. Eventually, the cumulative evapotranspiration exceeds the cumulative infiltration (by August) and the cumulative storage change becomes negative (i.e. the monocover ends the year at a lower moisture than at the beginning of the year).

This figure shows how the monocover performs by storing moisture during the rainy season and evapotranspiring moisture during the dry season, but without triggering percolation through the base of the monocover. Since the percolation does not follow the precipitation pattern, the moisture increase within the monocover did not reach the bottom of the monocover. A simple explanation is that even though a wetting front may advance from the top of the monocover into the cover during the rainy season, percolation is not triggered as this wetting front does not reach the base of the monocover.

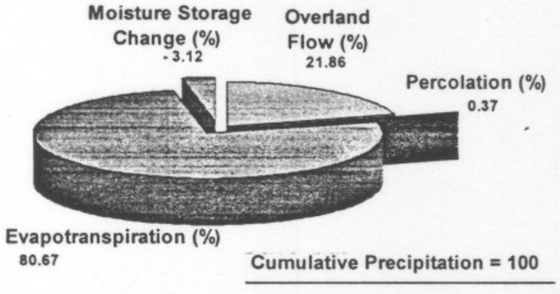

Figure 3. Monocover Water Balance results presented on a cumulative basis at the end of ten years.

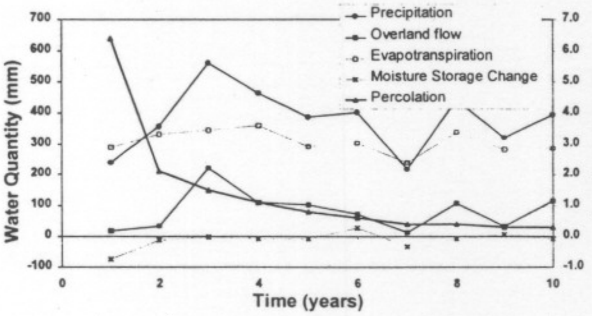

Figure 4. Monocover Water Balance results presented on a yearly basis.

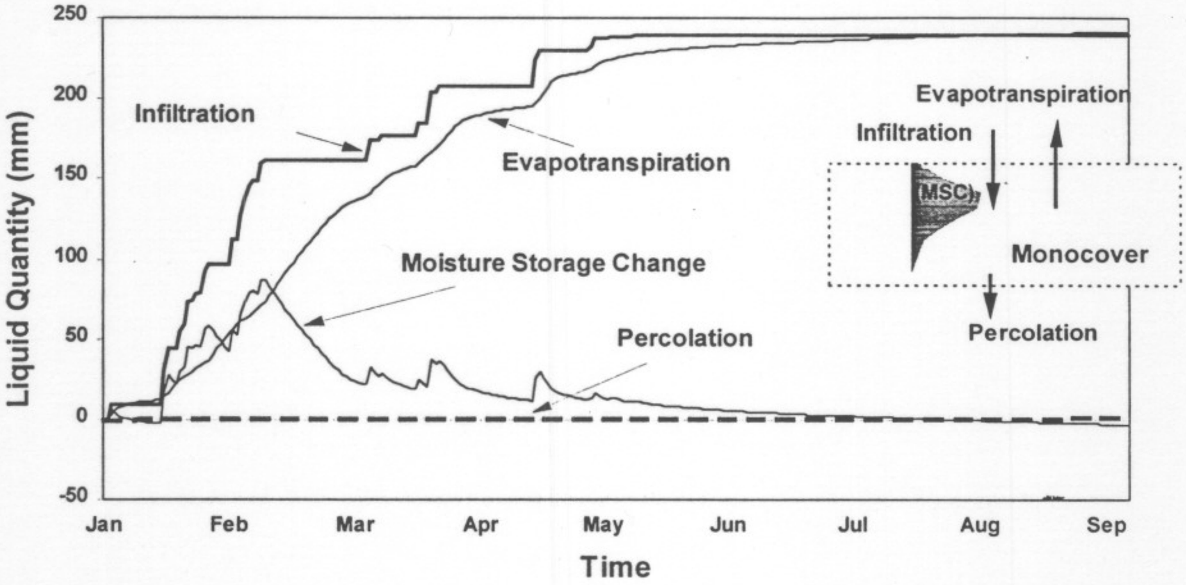

Figure 5. Monocover Water Balance results presented on a daily basis (wettest year of the simulation).

5 PRELIMINARY PARAMETRIC EVALUATIONS

This section describes some of the sensitivity evaluations performed to evaluate the percolation through the monocover. The Baseline Case evaluated in the previous section was used as a the reference case.

The baseline monocover configuration presented in the previous section used a rooting depth of 300 mm. The sensitivity evaluation considers rooting depths ranging from zero (no roots) to 1200 mm. Figure 6 shows that the response of the percolation to increasing rooting depths is highly nonlinear and that no significant decrease of percolation is obtained for rooting depths larger than approximately 300 mm. Although the results for the case of zero rooting depth show a comparatively higher percolation, the percolation is still on the order of magnitude of that estimated for prescriptive covers. In summary, and based on the results of the sensitivity analysis presented herein, it may be concluded that there is a rooting depth value beyond which percolation does not decrease significantly and that, in the absence of vegetation, the estimated percolation is still relatively small.

The baseline monocover was a 1500 mm thick soil layer. Monocover thicknesses from 12 to 1800 mm were used to evaluate the sensitivity of this parameter. The results are presented in Figure 7. The figure shows that the percolation as a function of cover thickness is highly nonlinear. There is a sharp decrease in the estimated percolation for monocover thicknesses less than 300 mm and no further decrease of the estimated percolation for higher cover thicknesses. In summary, ~~it may be~~ concluded that there is a cover thickness beyond which percolation does not decrease significantly.

A percolation design criterion that has been established for the monocover design at some sites is that the percolation rate should not exceed 3 mm/year (i.e. the percolation that would occur through a barrier layer with an hydraulic conductivity of 10^{-8} cm/sec under a unit gradient). For the weather conditions considered in the analyses described here, this percolation rate criterion corresponds to approximately 1 percent of the annual precipitation. Even for this stringent percolation criterion, the sensitivity evaluations in Figures 6 and 7 indicate that a monocover design is feasible for a wide range of conditions. In particular, a 1500 mm-thick silty soil monocover with a minimum rooting depth of 300 mm comfortably exceeds the percolation criterion. In fact, the parametric evaluation indicates that, for the aforementioned rooting depth, a monocover thickness as small as 600 mm in the arid climate of southern California would still satisfy the percolation criterion.

Additional elements that should be evaluated as part of the design of a monocover system are the effect of the moisture retention properties of different cover soils, the initial moisture content to be specified for monocover construction, the potential degradation of the hydraulic properties of the monocover with time, and the irrigation of the cover system. Sensitivity evaluations using unsaturated flow modeling indicated that the placement moisture content significantly impacts the percolation during the initial years of the cover performance. Moreover, analyses showed that potential degradation with time of the monocover soil (e.g. due to root penetration and desiccation cracking) would not increase the percolation rate significantly provided the degradation does not affect the entire thickness of the monocover. Finally, irrigation programs to sustain permanent vegetation in the cover should be discouraged, as modeling results indicate that such irrigation detrimentally affects the monocover performance.

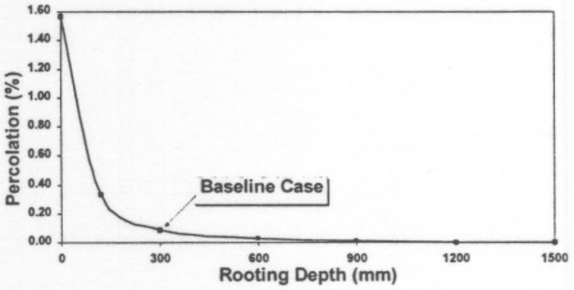

Figure 6. Parametric evaluation considering Rooting Depth.

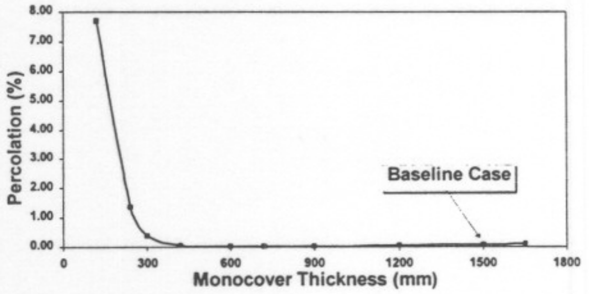

Figure 7. Parametric evaluation considering Monocover Thickness.

6 SUMMARY AND CONCLUSIONS

This paper presents the results of an unsaturated flow modeling effort undertaken to identify and quantify the parameters governing the design of monocover systems for landfills in arid locations. Parameters governing the design of a monocover include the characteristics of the selected soil, the saturated hydraulic conductivity of the cover soil (controlled by the compaction effort at which the selected soil is placed), the weather conditions, the rooting depth of the proposed vegetation, and the thickness of the monocover. An evaluation of the sensitivity of the last two parameters on the estimated percolation through the cover system was presented in this paper. The analyses considered a silty soil for which the moisture retention properties are known and a weather typical of southern California, which is characterized by an average precipitation of 380 mm/year and by an average evapotranspiration of 1015 mm/year.

Considering a stringent percolation design criterion that the percolation rate should not exceed 3 mm/year, the sensitivity evaluation shows that the monocover design is feasible for a wide range of conditions. In particular, ~~a~~ 1500 mm-thick monocover designed with a minimum rooting depth of 300 mm comfortably exceeds the percolation criterion. The parametric evaluation indicates that, in fact, for the aforementioned rooting depth, a monocover thickness as small as 600 m using the selected soil in the arid climate of southern California would still satisfy the established design criteria.

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