Analysis and Design of Evapotranspirative Cover for Hazardous Waste Landfill

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Abstract: A site-specific unsaturated flow investigation was undertaken for the design of an evapotranspirative (ET) cover system at the Operating Industries, Inc. (OII) Superfund landfill in southern California. This cover system constitutes the first ET cover approved by the US Environmental Protection Agency for construction at a Superfund site. Percolation control in an ET cover system relies on the storage of moisture within the cover soils during the rainy season and on the subsequent release of the stored moisture by evapotranspiration during the dry season. The site-specific sensitivity evaluation shows that percolation response to design parameters such as rooting depth, cover thickness, and saturated hydraulic conductivity is highly nonlinear. This facilitated selection of the design parameters in the final cover. The analyses also provide insight into the effect of irrigation, increased natural precipitation, and initial moisture content of the cover soils. Unsaturated flow analyses performed for closure design at the OII site show that an ET cover is feasible for a wide range of conditions. Equivalence demonstration procedures using site-specific weather conditions and soil-specific hydraulic properties were developed to evaluate compliance of the proposed alternative cover with the prescriptive system. A laboratory testing program, implemented to determine the hydraulic characteristics of candidate borrow soils, indicated that placement conditions do not affect significantly the moisture retention properties of the compacted soils.

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Introduction

A numerical study was performed to identify and quantify the parameters that govern the design of evapotranspirative (ET) cover systems for landfills in arid and semiarid regions. The investigation was prompted by the need to quantify the design parameters of an alternative cover system for the former Operating Industries, Inc. (OII) Landfill, now a Superfund site. The analyses documented herein led to the first ET cover system approved by the US Environmental Protection Agency (USEPA) for construction at a Superfund site.

Federal- and state-mandated cover systems for municipal and hazardous waste landfills in the United States (i.e., prescriptive covers) have endorsed the use of resistive barriers. Percolation control in resistive barriers is typically achieved by constructing a compacted clay liner with low saturated hydraulic conductivity. However, the focus of this investigation is on alternative, ET systems constructed using soils with low susceptibility to desiccation cracking (e.g., silts, low-plasticity clays). These systems are expected to result in superior covers for arid climates in spite of the higher saturated hydraulic conductivity of low-plasticity soils. An underlying concept emphasized in this study is that selection of the appropriate cover for each hazardous waste site should carefully account for local weather conditions of the site under investigation.

The approach implemented for cover design at the OII Superfund site involves generic and soil-specific numerical simulations that account for site-specific weather conditions. A general overview of ET cover systems, the OII Superfund site, and the characteristics of the numerical simulations implemented in this study are initially discussed. The results of site-specific numerical simulations are then presented to evaluate the performance of a baseline ET cover and a prescriptive cover. The results of a parametric study, performed to identify and quantify the parameters governing the performance of ET covers, are subsequently presented. Finally, after discussing the final selection of cover design parameters at the site, the paper presents the results of an equivalence demonstration performed using soil-specific hydraulic properties.

Evapotranspirative Cover at OII Superfund Site: Background

Cover systems for waste containment have conventionally been designed using “resistive barriers,” in which leachate generation is reduced by constructing a liner (e.g., a compacted clay layer) with low saturated hydraulic conductivity (typically 10^{-9} m/s or less). Percolation control in this comparatively simple system is achieved by maximizing overland flow. However, designing a truly impermeable barrier (i.e., one leading to zero percolation) should not be within any engineer’s expectations. Instead, the engineer should aim at designing a system that minimizes percolation to environmentally safe values. Quantification of this minimized, though finite, percolation of liquid into the waste poses significant challenges.

Evapotranspiration and moisture storage, two components usually not considered in the design of resistive barriers, become

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significant elements in the performance of this system. The novelty of this approach is the mechanism by which percolation control is achieved: an ET cover acts not as a barrier, but as a sponge or a reservoir that stores moisture during precipitation events, and then releases it back to the atmosphere as evapotranspiration. Although the adequacy of alternative cover systems for arid locations has been acknowledged by field monitoring assessments (e.g., Anderson et al. 1993; Nyhan et al. 1997; Ward and Gee 1997; Dwyer 1998), procedures for quantitative evaluation of the variables governing the performance of this system have not been compiled in the systematic manner required for design at hazardous waste sites.

The hydraulic conductivity of low-plasticity soils typically used in ET covers is higher, under saturated conditions, than the hydraulic conductivity of typical clay barrier materials. However, under unsaturated conditions, the hydraulic conductivity of low-plasticity soils is typically less than that of clays. ET covers have also been referred in the technical literature as monocovers, monolithic, store-and-release, and soil-plant covers. They are usually vegetated with native plants that survive on the natural precipitation. In addition, ET covers are less vulnerable than clay barriers to desiccation and cracking during and after installation, are relatively simple to construct, require low maintenance, and can be constructed with a reasonably broad range of soils. As in the OII Superfund site, ET covers may represent a technically superior alternative than prescriptive covers when the design is governed by stability considerations.

The OII Superfund site is located in the city of Monterey Park, California, approximately 16 km east of downtown Los Angeles. Before implementation of the final closure system at the site, the refuse mass reached over 76 m above grade with slopes as steep as 1.3H:1V. The landfill, a former sand and gravel quarry pit excavated up to 60 m deep in places, was filled with solid and liquid wastes over a 40-year period. There is no evidence indicating that subgrade preparation or installation of a liner system took place prior to the placement of solid waste in the quarry. The maximum vertical thickness of the solid waste in the landfill is approximately 100 m. The landfill received waste until 1984, when an interim soil cover of variable thickness (1–5 m) was placed on top of the landfill. The site has been undergoing final closure under the USEPA Superfund program since 1986.

A variety of site characterization and seismic studies were undertaken as part of predesign analyses for final closure of the site (e.g., Matasovic and Kavazanjian 1998). Selection of the final cover system at the site was driven by stability concerns, which led to the identification of alternative covers such as exposed geomembrane and ET cover systems. One of the reasons for considering alternative covers for final closure was the difficulty in demonstrating adequate stability of conventional covers under static and seismic conditions. Although an exposed geomembrane cover would be stable under both static and seismic conditions, evaluation of the uplift by wind of the geomembrane becomes a key design consideration (Zornberg and Giroud 1997; Bouazza et al. 2002). Finally, an ET cover system was selected because of aesthetic, economical, and technical considerations. Selection of this system allowed the use of geogrid reinforcements on steep portions of the landfill to satisfy static and seismic stability design criteria. The analyses presented in this paper document the procedures that led to the design of the final ET cover system, the construction of which was completed in April 2000.

Evapotranspirative Cover at OII Superfund Site: Phases in Analysis

The analysis and design of the ET cover at the OII Superfund site involved unsaturated flow simulations conducted using the computer program *LEACHM* (Hutson and Wagenet 1992). *LEACHM* is a one-dimensional finite-difference water balance model that uses Richards' equation to simulate unsaturated water flow. The model has algorithms to predict evaporation from the soil surface and transpiration by plants. The soil surface is considered horizontal, and precipitation in excess of the infiltration capacity of the profile is shed as overland flow. The program has fitting routines to compute moisture retention parameters from experimental data. Moisture retention is described by Campbell's equation (Campbell 1974)

$$h = a(\theta/\theta_s)^{-b} \tag{1}$$

where h = pressure head (suction); θ = volumetric moisture content; θ_s = volumetric moisture content at saturation; and a and b = constants. By applying a capillary model to Eq. (1), an unsaturated hydraulic conductivity function can be defined as (Campbell 1974)

$$K(\theta) = K_s(\theta/\theta_s)^{-2b+2+p} \tag{2}$$

where $K(\theta)$ = hydraulic conductivity at a volumetric moisture content θ; K_s = saturated hydraulic conductivity; and p = pore interaction parameter (usually set to 1).

The evapotranspiration subroutines are based upon the methods of Childs and Hanks (1975). Potential evapotranspiration is defined from pan evaporation measurements and a pan factor, or from Linacre's formulation (Linacre 1977). Potential evaporation, potential transpiration, actual evaporation, and actual transpiration are then defined based on a crop cover fraction (fraction of ground surface blanketed by leaves), current pressure head, and unsaturated hydraulic conductivity values. Specifically, the maximum possible evaporative flux density is estimated at the ground surface using the current pressure head and conductivity for the top nodes. Sink terms are used in Richards' equation to represent water uptake by plant roots (Nimah and Hanks 1973). Hutson and Wagenet (1992) provide additional information on the evapotranspiration algorithms.

To simulate flow and redistribution of water in soil using finite difference techniques, the profile is divided into segments and the total time period is divided into intervals. The Crank–Nicolson implicit method is used to solve the nonlinear system. The upper boundary condition can vary between ponded infiltration, nonponded infiltration, upward evaporative flux, and zero flux. The model choices for the lower boundary condition include fixed-depth water table, free draining profile with unit hydraulic gradient at the boundary, and fixed pressure head.

LEACHM was selected for analysis at the OII Superfund site because: (1) the code was particularly suitable for parametric evaluations, which was a significant component of this study; (2) local experience was available involving comparison of measured pan evaporation data with predicted values for the arid climate of southern California; and (3) it had received acceptance by local regulatory agencies for projects in California. *LEACHM* has been used and tested processes in agricultural projects involving comparison between lysimeter measurements and numerical results (Majeed et al. 1994; Hagi-Bishow and Bonell 2000; Sogbedji et al. 2001a,b). However, no comparisons have been made to date between lysimeter data from covers and model predictions. The original version of the *LEACHM* code was modified as part of this investigation to accommodate analyses involving longer periods of time and moisture retention functions other than those implemented in the original version of the code. Other codes, such as *UNSAT-H* (Fayer and Jones 1990), *HYDRUS-2D* (Simunek et al. 1996), and *SoilCover* (Geo2000 1997) have also been used for simulation of ET cover systems (Wilson et al. 1999).

The approach followed for analysis of the cover at the site involved five phases undertaken to define the cover configuration, evaluate its performance, and demonstrate regulatory compliance:

1. Evaluation of the hydraulic performance of a baseline ET cover. This provides understanding of the general mechanisms of water transfer within an ET cover under site-specific weather conditions.
2. Equivalence demonstration of the baseline cover system. This phase evaluates regulatory compliance of the baseline cover by comparing percolations estimated through the ET cover and the regulatory-mandated (prescriptive) cover.
3. Sensitivity evaluation of parameters governing the hydraulic performance of ET covers. This evaluation quantifies the sensitivity of parameters governing the design of an ET cover (e.g., rooting depth, cover thickness) and provides a site-specific basis for the final cover design.
4. Compilation of the ET cover design at the OII Superfund site. This includes final selection of the cover design parameters based on results obtained in the previous three phases using site-specific, though generic, soil information.
5. Equivalence demonstration of the selected cover layout performed using site-specific and soil-specific hydraulic properties measured for each candidate borrow soil. This final phase accounts for the moisture retention properties of the actual soils used for construction.

Baseline Cover Evaluation

A baseline ET cover was initially evaluated as part of this investigation. The selected baseline cover was a 1500-mm-thick single soil layer with a saturated hydraulic conductivity of 10^{-7} m/s and moisture retention characteristics typical of silty soils. Unsaturated flow modeling of the cover requires initial definition of soil retention properties, weather data, vegetation data, finite difference nodal arrangement, initial moisture, and boundary conditions.

The relative merits of the different functions used to represent the suction-volumetric moisture-hydraulic conductivity relations of unsaturated soils have been discussed at length in the technical literature (e.g., Khire et al. 1995; Leong and Rahardjo 1997). In this investigation, the unsaturated characteristics of cover soils were represented using the relations defined by Campbell (1974). The numerical code used in this investigation includes this unsaturated function, which fits well the experimental data obtained for soils used for cover construction. A decision was made early in the design process that baseline cover simulations would be performed using generic soil properties accepted by USEPA reviewers. Accordingly, moisture retention parameters selected for the baseline cover were based on silty soils data reported by Benson et al. (1994). The average fines content reported for these soils is 54% and the Plasticity Index is 5% (USCS designation ranges over CL to ML). Campbell's fitting parameters used for the baseline cover are listed in Table 1.

Weather data needed for the analyses includes daily precipitation and daily minimum and maximum air temperatures. Precipitation and temperature information was generated synthetically from the database provided by USEPA's *HELP* code (Schroeder et al. 1994). Other investigators have also used *HELP*-generated weather information as input for unsaturated flow analyses (Stormont and Morris 1988). Weather conditions generated for 30 years using data for southern California led to an average precipitation of 379 mm/year and an average evapotranspiration of 1015 mm/year. The synthetically generated weather information compared well to records from meteorological stations in the vicinity of the OII Landfill (''Percolation'' 1997). Consequently, the synthetically generated weather information was deemed representative of the conditions at the site for the purposes of the analyses presented in this investigation.

Table 1. Properties Used in Baseline Cover Analysis

	Property	Value
Soil properties	Campbell parameter *a*	-4.89
	Campbell parameter *b*	4.215
Weather data	Yearly average precipitation	379 mm
	Standard deviation	103 mm
Vegetation data	Rooting depth	300 mm
	Wilting point	1500 kPa
	Minimum root potential	3000 kPa
	Maximum potential/actual transpiration ratio	1.1
	Root resistance ratio	1.05
	Crop cover fraction	0.75
Modeling parameters	Initial volumetric moisture	23%
	Number of nodes	25
	Maximum time step	0.05 day

Vegetation data needed for the unsaturated flow analyses include rooting depth and distribution, plant growth options (constant vegetation, ''growing'' vegetation), wilting point, minimum root potential, maximum ratio of potential to actual transpiration, root resistance, and dates for germination, emergence, maturity, and harvest. Since the rooting depth of native annual grasses in southern California ranges from 200 to 450 mm, an average rooting depth of 300 mm was selected for the baseline analysis. Additional parameters, selected based on previous experience and on default *LEACHM* values, are listed in Table 1. A crop cover fraction of 0.75 was considered in the analyses (''Percolation'' 1997).

The 1500-mm-thick cover profile was divided into 25 segments for the finite difference nodal arrangement (uniform nodal spacing of 60 mm). The maximum time step was set at 0.05 day. The actual time step was lower, as it is reduced to gain accuracy during calculations depending on the precipitation rate. The flux boundary condition at the surface of an unsaturated soil is determined by both atmospheric forcing conditions and the hydraulic properties of the surficial soils (Wilson et al. 1994; Choo and Yanful 2000). A unit gradient boundary condition, commonly used in previous unsaturated flow modeling efforts (Fayer et al. 1992; Khire et al. 1999), was adopted in this investigation. Although use of this lower boundary condition was deemed conservative (i.e., flow is always directs downward at the boundary), the appropriate selection for the lower boundary condition is not obvious. It has been recognized, for example, that this boundary condition would not be appropriate if capillary barrier effects occur at the base of the liner system (Shackelford et al. 1994). However, a unit gradient lower boundary condition was selected because the engineered cover under evaluation rests over silty soils (foundation layer) rather than directly over coarser material. Initial conditions for the unsaturated flow analyses were specified by assigning initial moisture content to each node. The volumetric moisture content used as the initial condition corresponds to the

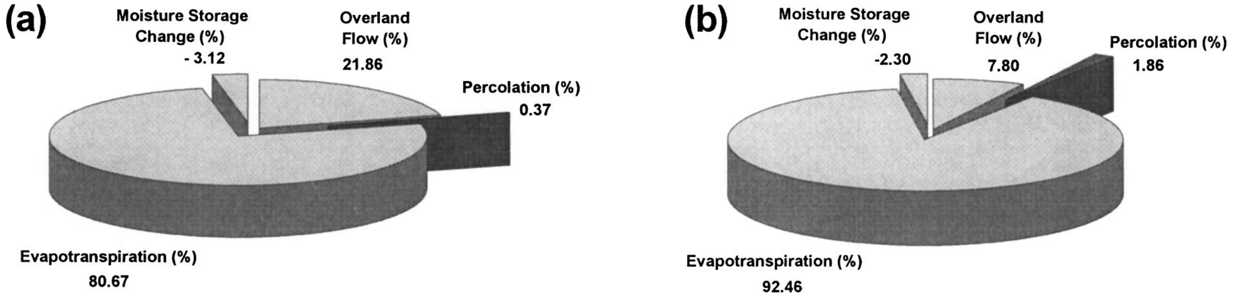

Fig. 1. Results of water balance analyses shown as percentage of cumulative precipitation at end of ten years: (a) baseline evapotranspirative cover; and (b) prescriptive cover.

optimum moisture condition of the cover soils (23%) defined by Standard Proctor compaction tests.

Total precipitation, evapotranspiration, surface water runoff, percolation, and change in moisture storage were computed for periods of 10 and 30 years. Typical water balance error in the analyses did not exceed 0.1 mm/year. Cumulative values of the water balance components at the end of 10 years, expressed as a percentage of the total precipitation, are shown in Fig. 1(a). The estimated cumulative percolation at the end of year 10 was only 0.37% of the cumulative precipitation (1.39 mm/year). The relatively high placement moisture content led to comparatively high percolation during the first year. A percolation value not affected significantly by the first year performance, used in the parametric study, is the average percolation for the last three years of the 10-year simulation (0.09% or 0.33 mm/year). The estimated cumulative percolation at the end of year 30 is only 0.16% of the cumulative precipitation (0.57 mm/year).

The different components of the water balance for the baseline ET cover are shown in Fig. 2(a) on a yearly (rather than cumulative) basis. As can be seen in the figure, the overland flow follows the trend of the precipitation records. For example, the comparatively high precipitation during the third year leads to a comparatively high overland flow for that year. Although not as closely as overland flow, yearly evapotranspiration also follows precipitation trends. The yearly moisture storage change shows negative values during the first year (i.e., the cover loses moisture). This is due to the comparatively high initial volumetric moisture content used to simulate soil placement conditions. Moisture storage in the ET cover appears to have reached an equilibrium condition a few years after construction, as the yearly storage change fluctuates around zero. Finally, 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 used to simulate soil placement conditions.

The water balance components were also evaluated on a daily basis. Fig. 2(b) shows the different components of the water balance (infiltration, evapotranspiration, moisture storage change, percolation) for the wettest year of the 30-year simulation. The wettest year corresponds to the third year of the simulation (yearly precipitation of 563 mm). The difference between precipitation and surface water runoff is shown in the figure as infiltration. The figure illustrates the hydraulic performance of an ET cover in arid regions during a comparatively wet season. Infiltration into the cover exceeds evapotranspiration during the rainy season in southern California (winter). Infiltrating water is stored within the ET cover, but essentially no liquids exit the base of the ET cover. The cumulative moisture storage curve decreases following the significant rains, showing smaller peaks due to successive precipitation events. Eventually, the cumulative evapotranspiration exceeds the cumulative infiltration and leads to a negative cumulative moisture storage change during the summer.

The volumetric moisture regime within the ET cover can be analyzed by evaluating the moisture content profiles as a function of time. Fig. 3(a) shows the profiles of volumetric moisture content within the ET cover during the initial 10 years following construction of the ET cover. The volumetric moisture content towards the base of the ET cover decreases from an initially constant volumetric moisture of 23% to a final moisture content of approximately 16%. Fig. 3(b) shows the profiles of volumetric moisture content during the third year (wettest year) of the simulation. The figure illustrates that the seasonal moisture fluctuations take place within the upper portion of the baseline cover. A simple explanation for the comparatively low percolation obtained in the analysis is that, even though a wetting front advances into the ET cover during the rainy season, percolation is not triggered because the moisture content remained comparatively low towards the base of the cover. Fig. 3(b) also illustrates that moisture increases taking place below the rooting depth (300 mm) during the rainy season can be reverted by upward flux during the dry season. The area between the January 1 and February 8 profiles corresponds to the maximum value of cumulative moisture storage change (87 mm) shown in Fig. 2(b).

Generic Equivalence Demonstration

The design criterion for the cover system at the OII Superfund site required that the percolation through the proposed ET cover be less than through the prescriptive cover. The prescriptive cover at the site was defined by a consent decree as the State of California mandated prescriptive cover. The approach adopted for evaluating equivalence between the proposed ET cover and the prescriptive cover was to compare percolations estimated numerically through both covers when exposed to identical climatic conditions. Comparison of numerically predicted percolations had proven valuable in estimating equivalency of capillary barriers (Morris and Stormont 1997). The prescriptive cover consists of a horizontal, 1200-mm-thick system that includes a 300-mm-thick protection layer, a 300-mm-thick clay layer having a saturated hydraulic conductivity of 10^{-8} m/s, and a 600-mm-thick foundation layer. The protection layer and the foundation layer were both assumed to have a saturated hydraulic conductivity of 10^{-6} m/s. Generic moisture retention properties for the clay layer were based on experimental results reported by Benson et al. (1994) for a typical barrier material used in a liner system. The adopted Campbell's parameters for the clay layer were a

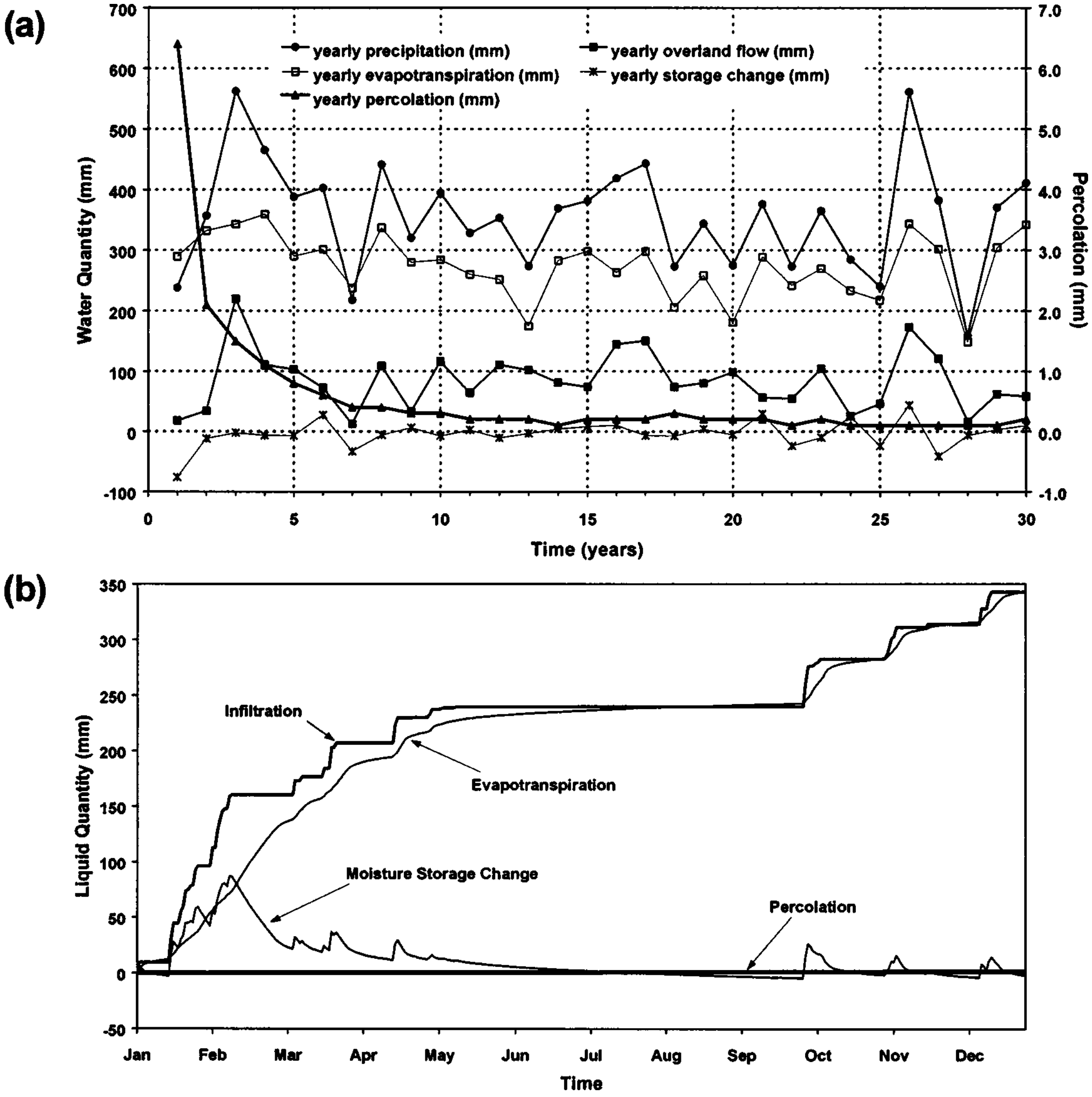

Fig. 2. Results of water balance analyses for baseline evapotranspirative cover: (a) shown on yearly basis; and (b) shown on daily basis (wettest year of simulation).

$=-1.88$ and $b=5.973$, and the adopted initial volumetric moisture content was 30%. Parameters needed for the prescriptive cover simulation that are not explicitly stated in the regulations were agreed upon for the purpose of the equivalence demonstration at the OII Superfund site. For example, it was concurred that the protection layer of the prescriptive cover would have a lower saturated hydraulic conductivity than the baseline ET cover and that it would benefit from evaporation but not from plant transpiration. On the other hand, even though the hydraulic conductivity of the prescriptive clay layer may severely increase with time in semiarid climates, the parties concurred that the equivalence demonstration would conservatively neglect potential desiccation cracking in the prescriptive cover.

The percolation estimated through the prescriptive cover was larger than that estimated for the ET cover. The different components of the water balance in the prescriptive cover at the end of year 10 are shown in Fig. 1(b). The estimated cumulative percolation at the end of year 10 is 1.86% of the cumulative precipitation (7.05 mm/year). The average percolation for the last three years of the 10-year simulation, which is not significantly affected by the first year performance, is 0.75% (2.9 mm/year). To satisfy the equivalence demonstration, the percolation through the ET cover (P_e) should be less than or equal to the percolation through the prescriptive cover (P_p). That is the percolation ratio ($\mathrm{PR}=P_e/P_p$) should be less than or equal to one. The PR values estimated at the end of years 10 and 30 are 0.20 and 0.13, respectively. The PR was also estimated on a yearly basis in order to assess whether the ET cover performs better than the prescriptive cover for each year of the simulation. Fig. 4 shows the estimated yearly PR for the baseline ET cover, which shows ratios less than one for each year of the 30-year simulation. Although the clay layer in the prescriptive cover has a lower hydraulic conductivity than the silt in the baseline cover under saturated conditions, its moisture retention characteristics lead to a comparatively higher conductivity than the silt under unsaturated conditions. Also, the higher hydraulic conductivity of the topsoils in the prescriptive cover led to a comparatively lower overland flow and higher evapotranspiration than in the baseline cover. As mentioned, the input parameters used in this generic cover demonstration were agreed upon by authorities early in the design process. Accordingly, different comparison outcomes may have resulted from different selection of input parameters. Nonetheless, these generic

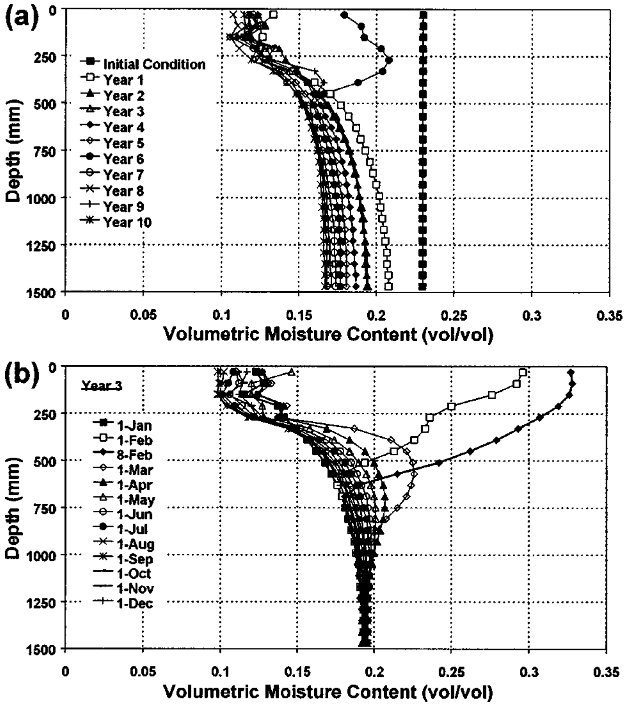

Fig. 3. Moisture content profiles for the baseline evapotranspirative cover placed at optimum moisture content: (a) yearly profiles throughout the 10-year simulation (note: profiles shown for the first day of each year); and (b) monthly profiles throughout year 3 (wettest year of the simulation) [note: profiles shown for the first day of each month and for the day with highest moisture storage (8 February)].

results pointed to the ability of an ET cover to satisfy equivalence requirements at the OII Superfund site.

Parametric Evaluations

An investigation was performed to evaluate the sensitivity of the different parameters governing the percolation through the baseline ET cover under site-specific weather conditions. Preliminary parametric results have been reported by Zornberg and Caldwell (1998). The parametric analyses assess the effect of vegetation rooting depth, soil saturated hydraulic conductivity, soil cover thickness, annual precipitation, irrigation, and placement moisture content of the cover soils.

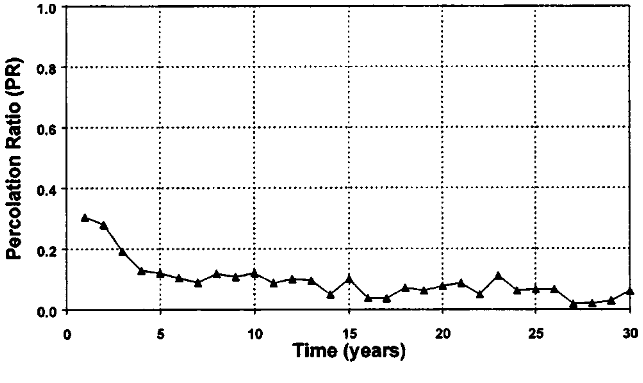

Fig. 4. Percolation ratio estimated for baseline evapotranspirative cover system

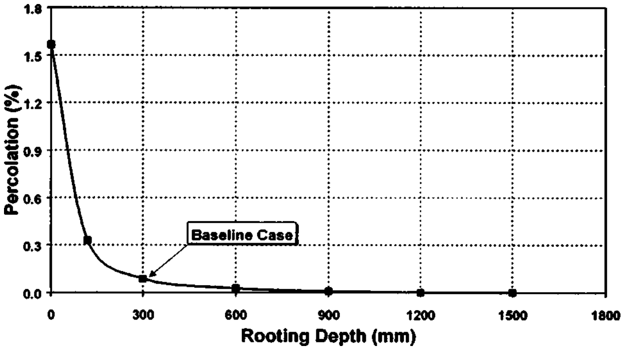

Fig. 5. Parametric evaluation of rooting depth for baseline evapotranspirative cover system

The vegetation rooting depth used in the baseline analysis was 300 mm. Rooting depths ranging from 0 (no roots) to 1200 mm were considered in the sensitivity evaluation. Fig. 5 shows the response of the ET cover to varying rooting depths. Percolation results are shown in the figure as a percentage of the total precipitation and were defined by averaging percolation values for the last 3 years of a 10-year simulation. The 3-year average values were considered representative of long-term percolation rates through the baseline ET cover and are reported for the evaluations discussed in this section. As expected, the estimated percolation decreases with increasing rooting depth because of increasing opportunity for removal of moisture that may have infiltrated into the cover soils. The figure shows that the response of the percolation to increasing rooting depth is highly nonlinear, and that rooting depths larger than approximately 300 mm would result in no significant decrease in percolation. It should be emphasized that these results are site-specific and should not be extrapolated to climates and soil conditions different than those considered in these analyses. Although a zero rooting depth leads to a comparatively higher percolation, the results suggest that percolation would still be relatively small in case of unexpected absence of vegetation. Based on these results, it may be concluded that there is a rooting depth value beyond which percolation does not decrease significantly. This rooting depth value is approximately 300 mm for the baseline cover.

Although the percolation criterion at the OII Superfund site was based on site-specific equivalence analyses, percolation criteria at other hazardous waste sites have required not exceeding an agreed percolation threshold value (e.g., “Agreement” 1998). The comparative character of the design criterion at the OII Superfund site complicated drawing conclusions from sensitivity analyses based only on the response of the ET cover. Consequently, a percolation threshold value of 3 mm/year was also used for preliminary evaluation of the range of parameters that could lead to acceptable cover performance. A percolation rate of 3 mm/year corresponds approximately to the percolation through a barrier layer with a hydraulic conductivity of 10^{-10} m/s under a unit hydraulic gradient. For weather conditions considered in the analyses described herein, a percolation rate of 3 mm/year corresponds to approximately 1% of the annual precipitation. The results shown in Fig. 5 indicate that a rooting depth of 300 mm would not exceed the threshold percolation of 3 mm/year (1% of annual precipitation) assuming the cover layout considered in the baseline case.

The saturated hydraulic conductivity used in the baseline analysis was 10^{-7} m/s. Saturated hydraulic conductivity values ranging from 10^{-5} to 10^{-8} m/s were considered to evaluate the

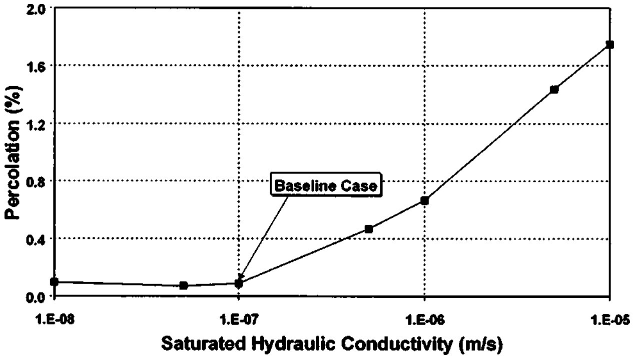

Fig. 6. Parametric evaluation of saturated hydraulic conductivity for baseline evapotranspirative cover system

sensitivity of this parameter. The same Campbell's parameters used in the analysis of the baseline cover, which correspond to silty materials, were used in this evaluation. Experimental results obtained for actual soils used for cover construction suggest that moisture retention properties do not vary significantly with soil placement conditions. However, as discussed later, the effect of moisture retention properties was addressed in this study by conducting soil-specific equivalence demonstrations. Fig. 6 presents the estimated percolations, which show an expected decreasing percolation with decreasing saturated hydraulic conductivity. Similar to the analyses performed to evaluate the effect of rooting depth, the figure shows that the response of the percolation to varying saturated hydraulic conductivity is highly nonlinear. The results indicate no significant decrease of the estimated percolation for saturated hydraulic conductivity values less than 10^{-7} m/s. In particular, a maximum saturated hydraulic conductivity value of 10^{-7} m/s used for the baseline cover does not exceed the threshold percolation of 3 mm/year.

The cover thickness used in the baseline analysis was 1,500 mm. ET cover thickness values ranging from 120 to 1,650 mm were selected to evaluate the sensitivity of this parameter. The results presented in Fig. 7 show that the response of percolation to varying cover thickness values is highly nonlinear. A sharp increase in the estimated percolation can be observed for cover thickness values less than 300 mm and no significant decrease of the estimated percolation is obtained for higher thickness values. A slight increase in the estimated percolation is observed for thick covers, which is caused by drainage of the comparatively high initial moisture content of the cover. This slightly increasing trend does not occur in simulations performed using low initial moisture values. Based on these results, it may be concluded that there is a cover thickness value beyond which percolation does not decrease significantly. Fig. 7 indicates that a cover thickness of 1500 mm, used for the baseline cover, would not exceed the threshold percolation of 3 mm/year. In fact, the parametric evaluation indicates that such threshold percolation would not be exceeded by a cover thickness of 300 mm in the arid climate of southern California.

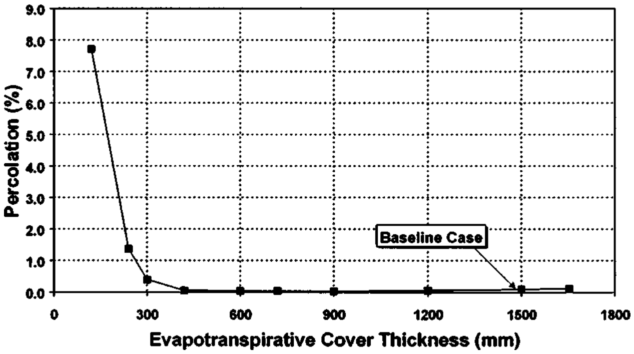

Fig. 7. Parametric evaluation of evapotranspirative cover thickness for baseline evapotranspirative cover system

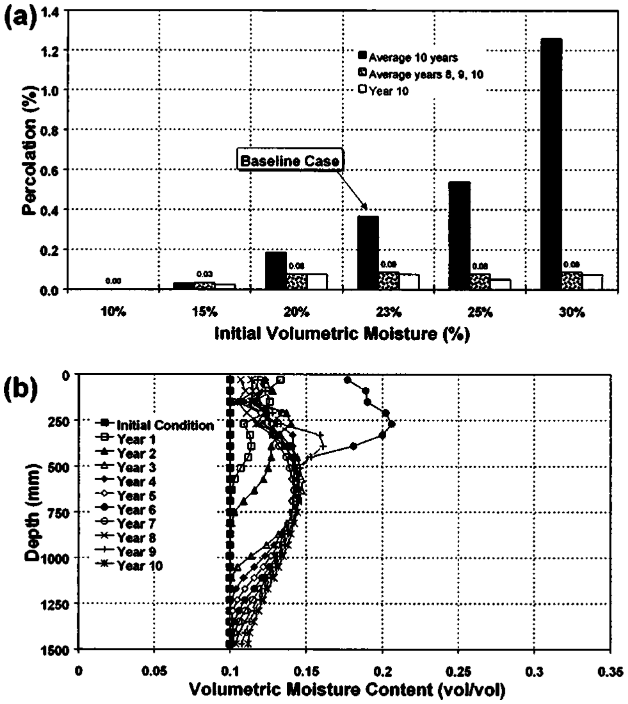

Fig. 8. Initial moisture conditions: (a) parametric evaluation; and (b) moisture content profiles for evapotranspirative cover placed at comparatively low initial moisture content

The initial volumetric moisture content used in the baseline analysis was 23%. Initial volumetric moisture values ranging from 10 to 30% were considered to evaluate the sensitivity of this parameter. Percolation results shown in the previous sensitivity evaluations were defined by averaging percolations for the last 3 years of a 10-year simulation. However, the results of the sensitivity evaluation for initial moisture content are presented in three different ways [Fig. 8(a)]: (1) average percolation for the 10-year simulation; (2) average value for the last 3 years of the 10 year-simulation; and (3) percolation obtained for year 10. The results reported using (2) and (3) above suggest that the long-term performance of the cover is comparatively insensitive to the initial moisture content. However, the results reported using (1) above suggest that the short-term performance of the cover is highly influenced by the initial moisture content. The average percolation results shown in the figure for the 10-year simulation [(1) above] are significantly skewed by the performance of the cover during its first year. Cover soils placed comparatively wet have a relatively higher initial hydraulic conductivity that facilitates migration of excess moisture through the base of the cover, leading to the increasing percolation trend with increasing initial moisture shown in case (1).

The initial moisture content of the ET cover also affects the overall pattern of the moisture content profiles. Fig. 8(b) shows the volumetric moisture content profiles for a case in which the cover soil is placed at comparatively low initial volumetric mois-

Table 2. Reference Irrigation Rates

Month	Irrigation (mm)
January	39.4
February	47.3
March	55.2
April	118.2
May	110.3
June	110.3
July	164.7
August	126.1
September	86.7
October	78.8
November	47.3
December	31.5
Total	1016.0

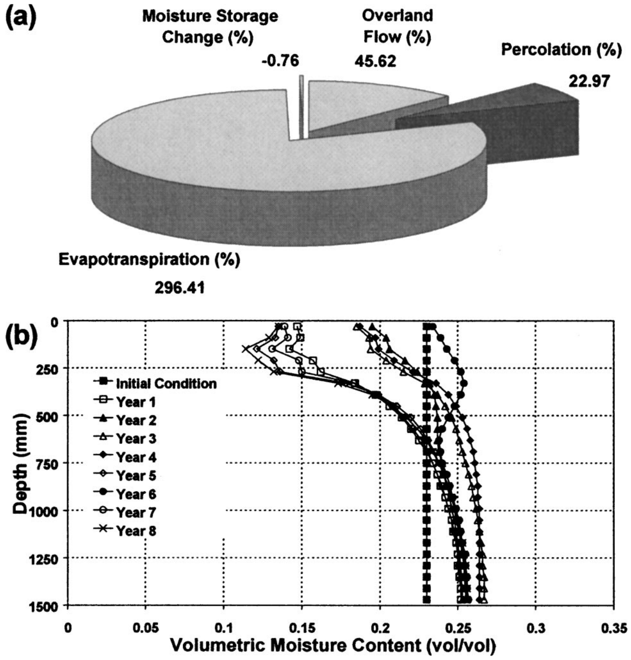

Fig. 9. Effect of a 1000 mm/year irrigation scheme in addition to natural precipitation: (a) water balance; and (b) moisture content profiles. [Note: Percolation in (a) is presented as a percentage of the natural precipitation (379 mm/year).]

ture (10%). Differently than in the baseline ET cover [Fig. 3(a)], where moisture profiles decreased with time from high initial moisture content (23%), moisture profiles in Fig. 8(b) show an increasing trend with time. However, it should be noted that the increasing trend with time does not represent poor cover performance. In fact, as shown in Fig. 8(a), the percolation estimated after 10 years is negligible for an initial moisture of 10%. This is because of the significant impact of initial moisture content during the initial cover performance period. These analyses suggest that there is a certain moisture content value towards the base of the cover to which the soils tend in the long-term (approximately 15% for the soils and weather conditions in this analysis). That is, for sufficiently thick covers, soils placed initially wet will dry out, while soils placed comparatively dry will wet up to a long-term equilibrium moisture content. In summary, the sensitivity evaluations indicate that long-term percolation rates are relatively insensitive to the initial moisture content of the cover soils, but short-term percolation rates are significantly affected by placement moisture conditions. These results also emphasize that the overall cover performance should not be directly inferred from trends in moisture content profiles, at least during monitoring periods immediately after cover construction.

The analyses of the baseline ET cover considered only natural precipitation as the liquid source. The effect of implementing a permanent irrigation scheme at the site was also evaluated. The seasonal irrigation rates for cool season grasses recommended by the Metropolitan Water District of Southern California (MWDSC 1991) were used as reference irrigation in the analysis (Table 2). As shown in Fig. 9(a), the estimated cumulative percolation when irrigation is considered (22.97% of the cumulative natural precipitation) is significantly higher than that obtained in the baseline analysis that considered only natural precipitation. Since the natural yearly precipitation is used as a reference, the summation of the different water balance components in the figure exceeds 100%. It should be emphasized that the interdependence of periodic biological phenomena (e.g., rooting depth) in relation to climatic/irrigation conditions was not explicitly accounted for in these analyses. Fig. 9(b) shows the moisture content profiles obtained in this case. While the baseline cover without irrigation showed a decreasing moisture trend [Fig. 3(a)], moisture content in the irrigated ET cover increases beyond the comparatively high placement moisture content of 23%. The reference irrigation was scaled using the same seasonal distribution in order to assess the sensitivity of the total irrigation amount. In this way, the yearly irrigation was varied from zero (baseline cover) to twice the reference irrigation (over 2,000 mm/year). The results show an increase in the estimated percolation with increasing irrigation rate (Fig. 10). Even irrigation schemes significantly below the reference irrigation would lead to percolation exceeding a threshold value of 3 mm/year. Although irrigation may be useful for initial establishment of vegetation, these results suggest that permanent irrigation schemes should be avoided at the OII site. These conclusions are site-specific and should not be extrapolated to other sites.

Analyses performed using increased precipitation amounts that follow the natural precipitation pattern show significantly smaller impact than irrigation on the estimated percolation. Fig. 11 shows the percolation obtained by proportionally varying the natural precipitation used in the baseline cover analyses (percolation in the figure is still shown as a percentage of the original precipitation). The precipitation factor, F, was varied from 0.1 to 3.0. The results of these analyses show that, if the natural precipitation

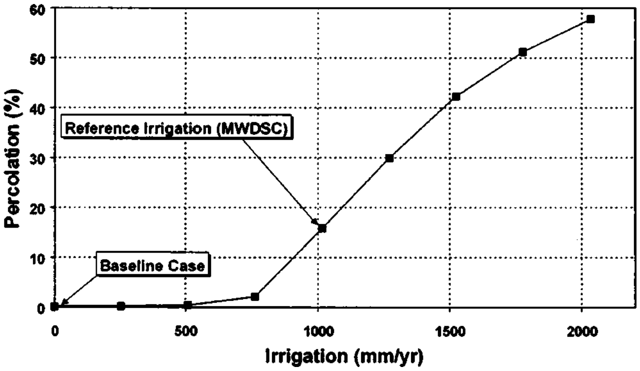

Fig. 10. Parametric evaluation of use of irrigation schemes for baseline evapotranspirative cover system

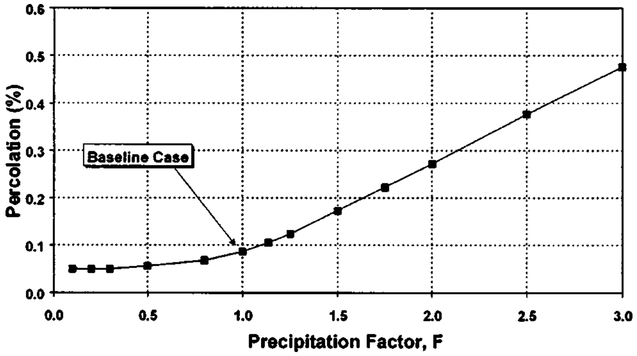

Fig. 11. Parametric evaluation of increased natural precipitation for the baseline evapotranspirative cover system. (Note: Percolation is shown as percentage of the original reference precipitation rather than of the factored precipitation.)

pattern is maintained, increasing values of total precipitation would not affect the calculated percolation nearly as much as irrigation schemes. This is because irrigation compensates low natural precipitation during the dry season, leading to an approximately uniform impingement rate (irrigation plus natural precipitation) throughout the year. The results in Fig. 11 indicate that even a precipitation rate as high as three times the baseline precipitation magnitude would still result in percolations not exceeding a threshold percolation of 3 mm/year.

The individual analysis of specific parameters may mask negative impacts due to potential interdependency of different parameters. Also, the reported results indicate average percolations for typical weather conditions rather than for extreme weather events. Nonetheless, the parametric evaluations provided guidance for design at OII and indicate that an ET cover design is feasible for a wide range of conditions. In particular, the sensitivity evaluations indicate that a cover thickness significantly smaller than that adopted in the baseline cover would satisfy stringent percolation criteria in the OII site.

Selection of Evapotranspirative Cover at OII Superfund Site

The use of site-specific weather conditions for southern California provided a basis for the design of an ET cover at the OII Superfund site. The rationale for selection of the cover design parameters at the site is as follows:

- *Rooting depth*. The analyses indicated that rooting depths larger than that selected for the baseline case (300 mm) would not significantly enhance the performance of the ET cover system (Fig. 5). Consequently, native vegetation, which typically exceeds 300 mm in rooting depth, was selected for the cover.
- *Saturated hydraulic conductivity*. Although the saturated hydraulic conductivity is only one of the parameters governing the hydraulic performance of an unsaturated cover system, it is probably the only hydraulic parameter feasible of being incorporated into construction specifications. Based on the results of parametric evaluations (Fig. 6), the ET cover was specified to have a saturated hydraulic conductivity below 5×10^{-7} m/s. This requirement was usually achieved for identified borrow soils by specifying a minimum density of 90% of the maximum Standard Proctor density and placement moisture ranging from optimum plus or minus 2%. In addition to saturated hydraulic conductivity, moisture retention properties had to be defined for each borrow source for use in soil-specific equivalence demonstrations, as discussed in the next section.
- *Cover thickness*. Based on the evaluation of the performance of the baseline cover system and on the sensitivity of the cover thickness (Fig. 7), a 1,200-mm-thick engineered ET cover was selected for the site. Although the analyses indicated that a thinner ET layer was feasible, erosion and maintenance considerations governed the final selection of the minimum cover thickness. In addition, a 600-mm soil foundation layer was adopted for construction underneath the engineered ET cover layer.
- *Placement moisture content*. Sensitivity analyses indicated no major influence of placement moisture content on long-term percolations [Fig. 8(a)]. Nonetheless, placement moisture content was usually specified as the optimum moisture content plus or minus 2% in order to achieve the target saturated hydraulic conductivity and control the desiccation potential of cover soils.
- *Irrigation*. The analyses suggested that ET cover systems in arid and semiarid climates rely on periods of relative dryness to remove moisture stored in the system during previous precipitation events. Also, parametric evaluations showed that permanent irrigation schemes may lead to unintended results, such as increases in percolation (Fig. 10). Consequently, no permanent irrigation scheme was considered for the cover system at the site.

Although the focus of this paper is on hydraulic evaluation, the design of the final cover system at the OII Superfund site was also constrained by requirements involving shear strength, resistance to erosion, shrinkage potential, and ability to sustain vegetation. Erosion calculations were performed to evaluate both sheet erosion and gully erosion on the landfill slopes. These evaluations led to the use of erosion control products, in addition to vegetation, in steep landfill slopes. Agronomic properties of the soils (salinity, pH, sulfate content, organic content) were also measured in borrow soils in order to design the appropriate seed mix and assess the potential need of soil enhancements to facilitate vegetation growth. Besides specifying the maximum saturated hydraulic conductivity of the cover soils and requiring soil-specific equivalence demonstrations, construction specifications also limited the soil types to be used (CL, ML, SC, and SM), plasticity index (between 8% and 30%), and fines content (more than 35%). The range of moisture retention properties of the cover soils was not explicitly specified because of the difficulty in translating moisture retention properties into construction specifications. Instead, as described in the following section, the suitability of each candidate borrow soil was evaluated by implementing a soil testing program and compiling soil-specific equivalence demonstrations.

Soil-Specific Equivalence Demonstration

Several design variables of the ET cover at the OII Superfund site (cover thickness, rooting depth, saturated hydraulic conductivity, irrigation schemes) were defined based on the parametric analyses performed using generic cover soils and site-specific weather conditions. However, parametric analyses proved impractical for identification of the range of suitable unsaturated soil properties (i.e., ranges for Campbell's parameters) that would meet the design criterion (i.e., PR lower than one). Consequently, evaluation of the suitability of soil types to be used for cover construction

Table 3. Top Deck Stockpile Soils

Series	Dry unit weight, γ_d (kN/m^3)	Gravimetric moisture, w (%)	Volumetric moisture, θ^a (%)	Saturated hydraulic conductivity, $K_s{}^b$ (m/s)	Campbell parameter a	Campbell parameter b
T1	13.9	23.6	33.6	2.8×10^{-8}	-4.89	7.028
T2	12.9	26.3	34.7	1.1×10^{-7}	-4.89	6.328
T3	12.3	25.7	32.1	3.7×10^{-7}	-4.89	5.495
T4	13.1	22.3	29.9	3.3×10^{-8}	-4.89	7.278
T5	13.0	27.1	36.2	1.7×10^{-7}	-4.89	6.463
T6	11.5	27.3	32.0	1.9×10^{-6}	-4.46	6.678

Note: USCS classification = CL (ASTM D2487); LL = 43%; PI = 18% (ASTM D4318); Maximum dry unit weight = 14.8 kN/m^3 (ASTM D 698); Fines content = 66% (ASTM D 1140); $G_s = 2.79$ (ASTM D 854); and $w_{\mathrm{opt}} = 23.0\%$ (ASTM D 698).

[a] $\theta = w(\gamma_d/\gamma_w)$.

[b] ASTM D 5084.

and of their compaction characteristics was achieved by: (1) identifying the candidate borrow soils; (2) determining the unsaturated hydraulic properties of these soils; and (3) performing an equivalence demonstration using the measured properties of the candidate soils. This approach led to analyses conducted using not only site-specific weather conditions, but also soil-specific hydraulic properties.

The laboratory testing program implemented to characterize the candidate borrow soils was performed using soil specimens remolded under different compaction and moisture conditions. The overall experimental program included determination of hydraulic, shear strength, desiccation potential, and agronomic properties. In order to illustrate the soil-specific equivalence demonstration, hydraulic test results are presented herein for one of the candidate borrow soils, namely the Top Deck Stockpile (TDS) soils.

Saturated hydraulic conductivity tests (flexible wall permeameter tests, ASTM D 5084) were conducted using soil specimens remolded to various levels of relative compaction and moisture content. Although the analyses focused on unsaturated hydraulic performance, the saturated hydraulic conductivity is a valuable indicator of the hydraulic performance of candidate soils, as it defines the saturated end of the unsaturated hydraulic conductivity function. Table 3 shows the results of saturated hydraulic conductivity tests on TDS soils, which were performed using specimens remolded to various placement conditions (T1 to T6). Tests were conducted under a confining pressure of 35 kPa, which was considered representative of cover conditions. The TDS soils were eventually used for cover construction over steep (1.5H:1V) landfill slopes located at the south portion of the landfill.

Moisture retention properties (volumetric moisture versus matric suction curves) were obtained for soils remolded to likely ranges of fill placement conditions. Soil placement conditions evaluated as part of the testing program corresponded to relative compaction values ranging from 80 to 95% of maximum density (relative to Standard Proctor ASTM D 698) and moisture content values ranging from optimum minus 2% to optimum plus 2%. Moisture retention curves were developed using hanging columns (Klute 1986) for comparatively low values of suction, pressure plate extractors (ASTM D 2325-68) for medium values of suction, and thermocouple psychrometer tests (Klute 1986) for comparatively high values of suction. Only desorption curves were measured. Fig. 12(a) shows the test results obtained for the TDS soils using specimens compacted under placement conditions indicated in Table 3. As observed in the figure, similar volumetric moisture content versus matric suction curves were obtained using soil specimens remolded under a wide range of molding density and initial moisture conditions. While the saturated hydraulic conductivity was sensitive to soil placement conditions, these results suggest that moisture retention properties were not significantly affected by initial density and moisture content conditions, at least for the soils tested under this experimental program. The moisture retention experimental results were used to define the Campbell's parameters listed in Table 3. Fig. 12(a) shows the Campbell function obtained for specimen T1, prepared at a density of approximately 95% of maximum Standard Proctor value and optimum moisture content.

Unsaturated hydraulic conductivity versus suction relationships, needed for the unsaturated flow modeling analyses, were usually established indirectly in this investigation using the Campbell (1974) parameters obtained from experimental moisture retention data. However, direct measurements of unsaturated hydraulic conductivity were also performed in order to validate the indirect estimates. Direct measurement of unsaturated hydraulic conductivity was conducted using steady-state centrifugation

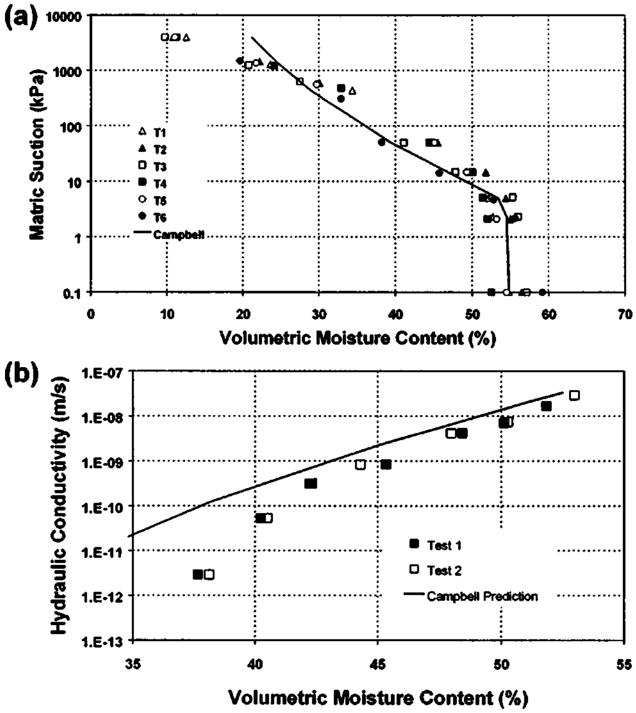

Fig. 12. Top deck stockpile soils: (a) characteristic curves (note Campbell curve is shown for specimen T1); and (b) unsaturated hydraulic conductivity obtained using direct centrifuge measurements

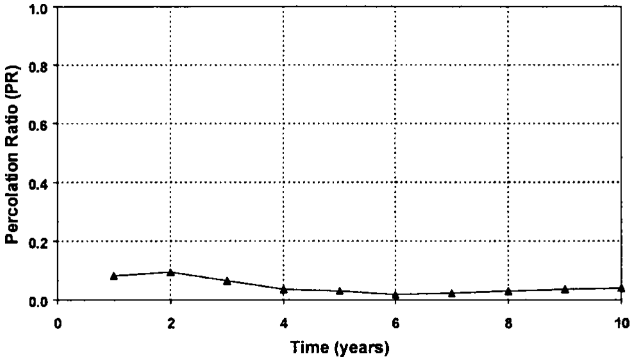

Fig. 13. Percolation ratio estimated for evapotranspirative cover constructed using top deck stockpile soils

methods (ASTM D 6527-00). This test is conducted by inducing specific hydraulic gradients (using centrifuge acceleration) and fluxes (using a constant flow rate pump), and measuring the soil volumetric moisture content after reaching a steady state condition. Fig. 12(b) shows direct measurements of unsaturated hydraulic conductivity obtained using TDS soil specimens prepared at 90% of the maximum density (relative to Standard Proctor) and optimum moisture content. The unsaturated hydraulic conductivity defined using Campbell's parameters obtained from moisture retention data is somewhat higher than the experimental results. The use of Campbell's parameters to indirectly define the unsaturated hydraulic conductivity was deemed conservative, as it would lead to overpredicted percolations in unsaturated flow analyses. Consequently, although moisture retention properties were measured for all borrow soils considered for cover construction, direct measurement of unsaturated hydraulic conductivity was not required for all soils.

Following identification of the candidate borrow soil sources and determination of their hydraulic properties, soil-specific equivalence demonstrations of the proposed ET cover were performed. Soil-specific parameters used in the unsaturated flow analyses include moisture retention data, saturated hydraulic conductivity, and specific gravity. In addition, soil-specific information from compaction tests was used in the analyses to define the initial conditions (initial density and moisture content) of the engineered ET cover. Fig. 13 shows the results, in terms of PR, of the equivalence demonstration performed for an ET cover system constructed using TDS soils placed under compaction conditions defined by series T1 (Table 3). The PR is below 0.1 for each year of the soil-specific, 10-year simulation. Consequently, the engineered ET cover constructed using the TDS soils, and placed under conditions defined by the T1 series, satisfied compliance with the prescriptive cover according to the required demonstration.

Additional analyses were performed using the range of hydraulic properties and placement conditions indicated in Table 3 in order to define the compaction specifications for construction using TDS soils. These analyses, as well as analyses of stability and desiccation cracking susceptibility (not discussed herein), led to construction specifications requiring a minimum relative compaction of 90% and placement moisture defined by the optimum plus or minus 2% (relative to Standard Proctor). As for the case of the TDS soils, laboratory testing programs were performed to evaluate the hydraulic characteristics of the other candidate borrow soils, and equivalence demonstrations were compiled to evaluate their suitability for the ET cover at the OII Superfund site.

Summary and Conclusions

An investigation was undertaken using unsaturated flow modeling to identify and quantify the parameters governing the performance of ET cover systems in arid and semiarid locations. The analyses documented herein provide the basis for the design of an ET cover system for the OII Superfund Landfill. Design criteria involving demonstration that the proposed cover outperforms a regulatory-prescribed cover poses difficulties and potential ambiguities in the design of alternative cover systems. The approach followed in this investigation to overcome such difficulties included the sensitivity evaluation of a generic cover using site-specific weather conditions, the subsequent determination of hydraulic properties of candidate borrow soils, and the final equivalence demonstration using site-specific weather conditions and soil-specific hydraulic properties.

Unsaturated flow analyses were initially performed for a baseline cover considering weather conditions typical of southern California. The analyses also showed that the response of percolation to varying rooting depth, cover thickness, and saturated hydraulic conductivity is highly nonlinear. This nonlinearity facilitates the design process because specific values of minimum rooting depth, minimum cover thickness, and maximum saturated hydraulic conductivity could be defined such that percolation would not decrease significantly for parameters beyond those specific values.

The sensitivity analyses showed that the cover thickness has major impact on percolation and that permanent irrigation programs to sustain vegetation was not suitable for this site. On the other hand, the vegetation rooting depth and the total amount of natural precipitation that follows seasonal patterns showed comparatively smaller impact on the cover performance. Finally, sensitivity evaluations also indicated that placement moisture content of the cover soils may considerably impact short-term percolation rates, but it does not significantly impact the long-term hydraulic performance of the cover.

The ET cover system designed for the OII landfill constitutes the first ET cover approved by the USEPA for construction at a Superfund site. The unsaturated flow analyses showed that an ET cover design at the site is feasible for a wide range of conditions. In particular, a 1,200-mm-thick ET cover designed with a minimum rooting depth of 300 mm in the arid climate of southern California would satisfy stringent design criteria.

A laboratory testing program was implemented to evaluate the suitability of candidate borrow soils, which included determination of saturated hydraulic conductivity, moisture retention properties, and unsaturated hydraulic conductivity for a wide range of soil placement conditions (initial density and moisture conditions). The experimental results suggested that, while soil placement conditions affect the saturated hydraulic conductivity of the candidate soils, moisture retention properties were not significantly affected by placement conditions. Equivalence demonstrations performed using site-specific weather conditions and soil-specific hydraulic properties showed compliance of the proposed alternative cover with the prescriptive cover system. Overall, the design approach proposed in this investigation addressed needs for understanding the expected performance of alternative cover systems, satisfying regulatory compliance, and compiling construction specifications.

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