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Decision Analysis for Design of Evapotranspirative Landfill Covers

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Abstract

A decision framework was developed to identify the optimal cover thickness, soil type, and soil density for an evapotranspirative landfill cover. A simplified model was used to consider the hydraulic performance of several cover alternatives during a design precipitation event, neglecting effects of interflow, surface water runoff, and moisture removal due to evapotranspiration. Monte Carlo simulation was used to estimate the probability of failure of each alternative given a selected failure criterion. Expected costs for each alternative were calculated using the probability of failure and the costs associated with implementation, compaction effort, and failure. The optimal alternative was identified as having the lowest expected cost.

Introduction

The management of waste generated by a growing population is an important topic for regulators and engineers. The current trend in waste management is the isolation of waste in protected containment facilities to minimize human and environmental contact. Accordingly, one of the key engineered components in municipal and hazardous waste containment systems is the cover system. The objective of a cover system is to prevent infiltration of water into the waste, which is often translated as a design that minimizes basal percolation. If water reaches the waste, it may mobilize contaminants that may eventually reach the groundwater.

One particular cover type, the evapotranspirative (ET) cover, is gaining popularity in arid climates (Dwyer 1998; Zornberg *et al.* 2003). Conceptually, an ET cover is a simple system that involves a monolithic soil layer with a vegetative cover. Evapotranspiration and moisture storage play significant roles in the performance of this system. An ET cover acts not as a barrier, but as a reservoir that stores moisture during precipitation events and subsequently returns it to the atmosphere as evapotranspiration. ET covers are generally constructed using low plasticity silts and clays placed at different relative compactions to satisfy design values of moisture storage, saturated hydraulic conductivity, desiccation cracking potential, and ability to support vegetation. ET covers are relatively simple to construct, require low long-term maintenance, and may provide significant cost savings (Zornberg *et al.* 2003). As ET covers function with a reasonably broad range of soils, much of the cost savings result from constructing these covers using local soils.

A decision analysis is presented in this paper using experimental data obtained as part of the design process of a multi-acre ET landfill cover (Zornberg and McCartney 2003). A significant testing program was conducted for this site to characterize soil hydraulic properties for identification of appropriate borrow sources, and to characterize the site meteorology. Further, a field monitoring program was conducted at the site to evaluate the actual performance of several prototype covers with different soil types and cover thicknesses. For simplicity, this study focuses on cover design using the information available from the laboratory testing program (*i.e.*, a prior analysis), while the field monitoring results will be used in a future study to refine the design process (*i.e.*, a Bayesian posterior analysis). A decision framework is presented to objectively consider the optimal cover thickness, soil type, and soil-placement conditions given a design precipitation event (intensity and duration). A simple performance model for ET covers is used to evaluate the suitability of the framework for cover design. An example with a hypothetical set of construction and failure costs is used to evaluate different cover alternatives on a minimal cost basis.

Design of Evapotranspirative Cover Systems

The goal of an ET cover is to minimize basal percolation over a multi-acre area for the lowest cost possible. There are several tradeoffs between performance and cost that must be considered when selecting appropriate values of the relevant design variables. The primary design variables that must be considered include the cover geometry, soil hydraulic properties, vegetative cover properties, design precipitation event, and initial conditions (*e.g.*, the soil moisture storage at the time of the design precipitation event).

Cover geometry variables include the thickness of the cover T, as well as the cover slope angle β. As the performance of the cover soil depends on its capacity to store liquid, a thicker cover will have a higher moisture storage capacity. The slope of the cover will determine both its stability as well as the amount of surface water runoff during a precipitation event. The slope angle can be considerable in some covers such as the OII landfill in Pomona, California (Zornberg *et al.* 2003).

The soil hydraulic properties relevant to the performance of ET covers include the saturated hydraulic conductivity (K_{sat}), the soil-water retention curve (SWRC), and the K-function. The SWRC is the relationship between soil suction and moisture content, which can be used to determine the moisture storage capacity of the soil. The saturated hydraulic conductivity provides a measure of the minimum impedance to moisture flow through the cover, while the K-function provides a measure of the increased impedance to moisture flow as the soil dries out (decreasing the available pathways for water flow). Determining the required soil hydraulic properties is perhaps the most challenging aspect of ET cover design. Target values of the hydraulic properties are typically selected based on the required cover performance under the expected precipitation conditions at the site. The target values can be obtained using numerical modeling or judgment, and are useful to identify acceptable soil types from local borrow areas. However, even when target values are selected, the methods used to evaluate hydraulic properties in the laboratory are highly sensitive to sample preparation and testing procedures. In particular, the relative compaction of the soil and its compaction moisture content will typically determine the soil's hydraulic properties. Finally, the hydraulic properties determined in the laboratory are often different from those in the field (Daniel *et al.* 1984). In addition to specimen preparation variability, the field hydraulic properties may change with time due to processes such as hysteresis (different behavior during wetting and drying), soil cracking, settlement, plant or animal intrusion, and erosion. Practically, hydraulic properties are typically selected at a site by characterizing soils from different local borrow sources placed at several densities, and comparing the experimental hydraulic properties with target values.

Vegetative cover properties are those that determine the amount of water that can be removed from the cover. Evapotranspirative covers should perform adequately without the assistance of plants for removal of water from the cover. This is especially relevant for locations that may suffer from prolonged droughts. Because this study considers the cover behavior during an infiltration event, this study does not consider the moisture removal properties of a vegetative cover.

As meteorological conditions are highly site specific, they are critical to the selection of the required cover thickness and soil properties. Design typically involves use of numerical models to determine the performance of the cover under the actual precipitation and evapotranspiration recorded at the site (Zornberg and McCartney 2005). For simplicity, this study considers only a design precipitation event and neglects moisture removal processes during this event.

Decision Analysis

Among the decisions to be made in the design of ET covers, the choice of the cover thickness may have the greatest impact on cover performance and cost. A thicker cover can store more water, but will increase costs due to greater soil requirements. This may also have implications on the selection of the particular borrow sources for cover soils. The decision process must also evaluate the tradeoffs between the hydraulic properties of the soils from the available borrow sources, which are often sensitive to the soil-placement conditions (density). Given a design precipitation event, the particular combinations of design variables will lead to cover success or failure. As the hydraulic properties for a given soil type and soil density were obtained from available test results, this study is classified as a prior analysis. A decision tree for an ET cover is shown in Figure 1. More information on the use of decision trees may be obtained from Ang and Tang (1990). In this tree, the squares denote decision nodes, while the circles denote chance nodes. The tree is shown in collapsed form: starting from the left, each open-ended alternative is connected to the next set of branches. In other words, once the thickness is selected, the soil type must be selected, and then the density must be selected. For each combination of alternatives, a likelihood of success or performance can be calculated by assuming a performance model, a failure criterion, and an approach to consider uncertainty. This study uses a Monte Carlo analysis to consider uncertainty.

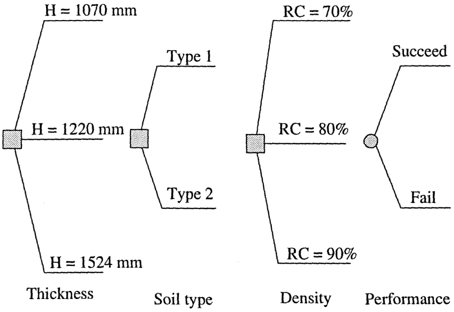


Figure 1: Decision tree for ET cover design

The decision framework can be evaluated on a minimum cost or maximum utility basis. As an example, this study assumes hypothetical values of costs for each alternative (*e.g.*, a cover with a given thickness, soil type, and density) to evaluate the framework on a minimum cost basis. Soil transportation costs of $120,000 and $100,000 per 1-m thickness were selected for soil types 1 and 2, as the borrow source for soil type 1 is further from the site. Soil compaction is assumed to cost $10,000 for 70% relative compaction, $20,000 for 80% relative compaction, and $40,000 for 90% relative compaction. These compaction costs were selected to incorporate construction costs as well as possible costs required to establish plant growth in denser soil. Failure criteria used for ET covers typically do not indicate catastrophic failure (McCartney and Zornberg, 2002). However, excessive percolation may require increased maintenance costs, such as addition of amendments to the soil or improvement of the vegetative cover health. Accordingly, the failure cost is assumed to be related to the probability of failure given from the performance model as $50,000p_f$. In summary, the costs assumed for this example penalize thicker covers, longer soil transportation distances, denser cover soil, and cover soils that are not hydraulically suitable for a design precipitation event. The costs were arbitrarily assigned, and are used only to analyze the features of the decision framework.

Performance Model

Vertical flow of water through a soil layer under unsaturated conditions requires the numerical solution of Richards' equation, given by:

$$\frac{\partial \theta}{\partial \psi}\frac{\partial \psi}{\partial t}=\frac{\partial}{\partial z}\left[K(\psi)\left(1+\frac{\partial \psi}{\partial z}\right)\right] \qquad (1)$$

where z is the depth from the surface of the cover, t is time, θ is the volumetric moisture content, ψ is the soil suction, $\delta\theta/\delta\psi$ is the slope of the SWRC, and $K(\psi)$ is the K-function. To avoid long computation times associated with solving Richards' equation for different hydraulic parameters simulated using Monte Carlo analysis, a simple load-capacity model was developed to estimate the hydraulic response of the landfill cover to a design precipitation event (described by intensity and duration). The field capacity is used as a measure of the moisture storage of the cover. The field capacity can be thought of as the moisture content at which water will drain from the soil under its own weight. In other words, field capacity is reached during an infiltration process when the gravity potential of the water exceeds the pressure head potential of the water. Water will want to flow downward instead of being held within the soil pores. The field capacity is typically calculated as the moisture content corresponding to a suction of 33 kPa, calculated from the SWRC. This rule-of-thumb is generally accepted to be representative of the field capacity in most soil types (sand, silt, clay). The van Genuchten model (van Genuchten 1980) was used to characterize the SWRC for the different soils, given by:

$$\theta_{\mathrm{fc}} = \theta_{\mathrm{r}} + (\theta_{\mathrm{s}} - \theta_{\mathrm{r}})\left[1 + \left(\alpha\psi_{\mathrm{fc}}\right)^{N}\right]^{-\left(1-\frac{1}{N}\right)} \qquad (2)$$

where θ_{fc} is the field capacity moisture content, ψ_{fc} is the suction at field capacity equal to 33 kPa, θ_r is the residual moisture content, θ_s is the saturated moisture content (equal to the porosity), and α and N are shape factors.

The moisture storage capacity (MSC) of the cover can be calculated using the thickness of the cover, the moisture content at field capacity, and the moisture content at the initiation of the design precipitation event θ_i, as follows:

$$\mathrm{MSC} = (\theta_{fc} - \theta_i)T \qquad (3)$$

In this simple model, the amount of moisture that infiltrates into the cover during a design precipitation event is assumed to depend both on the characteristics of the precipitation event and the impedance of the cover to moisture flow. The minimum impedance of the cover to moisture flow is the saturated hydraulic conductivity. For a precipitation event with an infiltration rate I and duration D, it is assumed that the amount of moisture that infiltrates into the cover during the event (M_{in}) is equal to:

$$M_{\mathrm{in}} = \begin{cases} K_{\mathrm{sat}}D \text{ if } I > K_{\mathrm{sat}} \\ I\,D \text{ if } I < K_{\mathrm{sat}} \end{cases} \qquad (4)$$

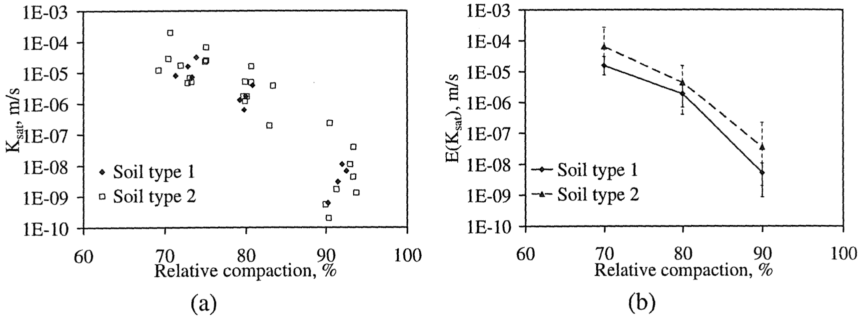
This implies that if the infiltration rate is less than the saturated hydraulic conductivity of the soil, moisture will enter the soil at a rate equal to I. Otherwise moisture will enter at the saturated hydraulic conductivity. Eq. (4) assumes a unit gradient in the total head, representative of gravity-driven flow, and neglects surface ponding. However, water infiltration into the cover will occur at a higher rate due to matric suction gradients greater than unity corresponding to low suction at the soil surface and a higher suction corresponding to the initial moisture content. Accordingly, the assumption of a unit gradient may represent unconservative estimate of the moisture infiltrated into the cover. To account for this in the simplified model, the duration of precipitation was overestimated by 20%.

The failure criterion selected for this study is the event for which the amount of moisture entering the cover exceeds the MSC. Although this criterion indicates failure when percolation initiates, drainage from the soil will continue to occur after failure, resulting in significant percolation. Future research will incorporate different performance criteria proposed in the literature (McCartney and Zornberg 2002) using numerical solutions of Richards' equation for given atmospheric boundary conditions.

Statistical Evaluation of Model Parameters

Soil Properties. The saturated hydraulic conductivity and the van Genuchten parameters governing the shape of the SWRC parameters (α, N, θ_s, θ_r) were considered to be random variables in this analysis. Two soil types were identified at the site for hydraulic characterization, referred to as Soil type 1 and Soil type 2. Both soils have similar mineralogy, and are classified as clays of low plasticity (USCS type CL). Soil type 1 has a fines content ranging from 37 to 40%, while Soil type 2 has a fines content of 53 to 67%. A total of 4 specimens from different borrow sources and depths from the surface were identified as Soil type 1, while a total of 8 specimens from other borrow sources were identified as Soil type 2. K_{sat} and the SWRC were determined for specimens from each soil type placed at optimum water content at relative compactions of 70, 80, and 90% with respect to the maximum dry density obtained using the Standard Proctor compaction energy (for a total of 12 specimens from Soil type 1 and 24 specimens from Soil type 2). Flexible wall permeameter tests were used to define the K_{sat} values for specimens, while a combination of the pressure plate, hanging column, chilled mirror hygrometer, and thermocouple psychrometer were used to determine the drying path of the SWRC. This study uses the drying path SWRC to estimate the field capacity moisture storage during infiltration.

Figure 2(a) shows the variation in hydraulic conductivity with the actual relative compaction of each specimen (*i.e.*, not the target relative compactions). This figure indicates a decrease in saturated hydraulic conductivity of 7 orders of magnitude when RC increased from 65% to 95%. Figure 2(b) shows the variation in the mean hydraulic conductivity $E(K_{sat})$ for the two soil types with increasing relative compaction, with 95% confidence bounds. This figure replicates the increasing trend, and indicates that variability tends to increase with increasing relative compaction.



(a) (b)

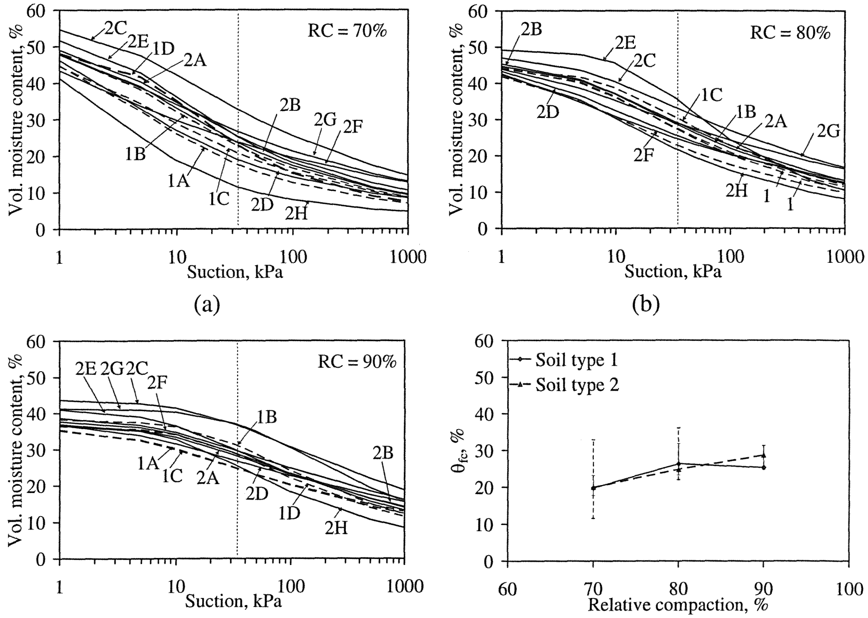
Figure 2: (a) Variation in K_{sat} with relative compaction; (b) $E(K_{sat})$

Table 1 summarizes the statistical descriptors for the saturated hydraulic conductivity values. Despite some scatter, the coefficient of variation (c.o.v.) increases with relative compaction for Soil types 1 and 2. This indicates that variability in hydraulic conductivity increases with increasing relative compaction. This is supported by the wide range in hydraulic conductivity values observed for specimens compacted at high densities in Figure 2(a). The cumulative density functions for the K_{sat} data indicates a lognormal distribution can be used to estimate its probability distribution.

Table 1: Statistical descriptors for the saturated hydraulic conductivity

Descriptor of K_{sat}	Soil type 1			Soil type 2		
	RC = 70%	RC = 80%	RC = 90%	RC = 70%	RC = 80%	RC = 90%
Mean (m/s)	1.56E-05	1.88E-06	5.33E-09	6.41E-05	4.32E-06	3.60E-08
St. dev. (m/s)	9.56E-06	1.23E-06	3.93E-09	9.14E-05	4.72E-06	7.43E-08
c.o.v.	0.61	0.65	0.74	1.43	1.09	2.06
Min. (m/s)	7.2E-06	6.2E-07	6.2E-10	4.7E-06	1.9E-07	2.0E-10
Max. (m/s)	3.1E-05	3.9E-06	1.1E-08	2.8E-04	1.6E-05	2.3E-07

Figures 3(a-c) show the SWRCs for the 12 different soil specimens (labeled 1A to 1D, and 2A to 2G) tested under relative compactions of 70, 80, and 90%. As a reference, the dashed vertical lines in Figures 3(a-c) denote the field capacity suction of 33 kPa. The field capacity varies between 12% and 40% for the soils tested.



(a) (b)

(c) (d)

Figure 3: SWRC results: (a) 70% relative compaction; (b) 80% relative compaction; (c) 90% relative compaction; (d) Moisture content at field capacity

In general, the porosity (θ_s) decreases with increasing relative compaction, and the rate of decrease in moisture content with suction decreases with relative compaction (*i.e.*, the soil will hold more water at higher suctions for denser soils). Figure 3(d) shows the moisture contents at field capacity for the two soil types with increasing relative compaction, along with 95% confidence bounds. In general, the field capacity increases linearly with relative compaction, although the variability is higher at lower relative compactions. Table 2 shows the statistical descriptors of the SWRC parameters. In the Monte Carlo analysis, the SWRC parameters were modeled using lognormal distributions as they are strictly positive for soils, and because of the multiplicative combination of the parameters in the SWRC function [Eq. (2)].

Table 2: Statistical descriptors for the SWRC parameters

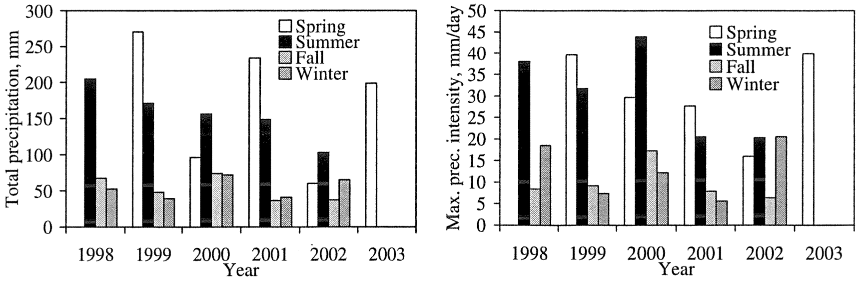
Relative compaction (%)	Descriptor	Soil type 1					Soil type 2				
		α (kPa^{-1})	N	θ_s (%)	θ_r (%)	θ_{fc} (%)	α (kPa^{-1})	N	θ_s (%)	θ_r (%)	θ_{fc} (%)
70	Mean	0.004	1.38	49.59	2.83	39.07	0.007	1.32	52.46	1.99	37.58
	St. dev.	0.002	0.07	0.99	0.75	0.02	0.007	0.11	2.56	1.63	0.06
	c.o.v.	0.385	0.05	0.02	0.26	0.00	0.975	0.08	0.05	0.82	0.00
	Min.	0.002	1.31	48.67	2.06	17.71	0.003	1.18	47.56	0.00	11.53
	Max.	0.005	1.49	51.26	3.78	23.09	0.025	1.55	56.79	4.21	32.86
80	Mean	0.002	1.30	44.70	1.27	40.90	0.003	1.26	46.69	0.77	40.04
	St.dev.	0.001	0.02	0.55	0.26	0.03	0.003	0.10	1.48	1.31	0.05
	c.o.v.	0.502	0.01	0.01	0.21	0.00	0.821	0.08	0.03	1.70	0.00
	Min.	0.001	1.27	43.87	0.94	23.18	0.000	1.17	44.24	0.00	22.01
	Max.	0.003	1.32	45.35	1.67	30.77	0.009	1.52	49.41	4.13	36.10
90	Mean	0.001	1.28	36.67	1.35	34.99	0.001	1.261	39.39	1.16	37.94
	St.dev.	0.001	0.08	0.99	1.38	0.03	0.001	0.079	2.34	1.29	0.04
	c.o.v.	0.634	0.06	0.03	1.02	0.00	0.629	0.063	0.06	1.11	0.00
	Min.	0.000	1.19	35.75	0.00	24.84	0.000	1.163	36.85	0.00	24.84
	Max.	0.002	1.36	38.33	3.12	31.32	0.002	1.391	43.87	3.44	31.32

The correlation coefficients between the soil hydraulic properties calculated for the Soil types 1 and 2 are shown in Table 3. The parameters of the SWRC and K_{sat} have strong interrelationships because the soils have similarly shaped SWRCs, as shown in Figure 3. Further, soils with a smaller porosity have lower saturated hydraulic conductivity, which adds physical significance to the use of correlation coefficients. Accordingly, the correlation coefficients should be considered in the Monte Carlo analysis represent these inter-relationships. The correlation coefficients are used in the Monte Carlo analysis to transform independent standard normal variables to correlated random variables (Ang and Tang 1990).

Table 3: Correlation coefficients for the different soil types

Variable 1	Variable 2	Correlation coefficient $\rho_{1,2}$					
		Soil type 1			Soil type 2		
		RC = 70%	RC = 80%	RC = 90%	RC = 70%	RC = 80%	RC = 90%
K_{sat}	α	0.71	1.00	0.97	0.86	0.87	-0.15
K_{sat}	N	-0.60	-0.79	-0.92	-0.17	-0.29	0.60
K_{sat}	θ_s	-0.59	-0.69	-0.76	0.13	0.11	-0.47
K_{sat}	θ_r	-0.44	-0.27	-0.83	-0.02	-0.30	0.16
α	N	-0.75	-0.79	-0.99	-0.40	-0.56	-0.67
α	θ_s	-0.06	-0.69	-0.72	0.14	-0.08	-0.49
α	θ_r	-0.51	-0.27	-0.94	-0.40	-0.51	-0.52
N	θ_s	-0.30	0.33	0.71	-0.74	0.43	0.07
N	θ_r	0.95	0.79	0.98	0.83	0.97	0.82
θ_s	θ_r	-0.43	-0.05	0.58	-0.56	0.58	0.22

Design Precipitation Event. The precipitation intensity was determined by analyzing the precipitation history for the site for the period from July 1998 to May 2003. The site is located near Denver, Colorado and is in a relatively arid region. Figure 4(a) indicates that the cumulative seasonal precipitation is greatest in the spring or summer, while Figure 4(b) also indicates that the maximum seasonal precipitation intensities occur in the spring and summer. The maximum precipitation in the spring and summer months was modeled with a type I maximum value distribution with a mean of E(I) = 30.5 mm/day and a standard deviation of $\sigma(I)$ = 9.9 mm/day.



(a) (b)

Figure 4: (a) Total seasonal precipitation; (b) Maximum precipitation intensity

To determine the duration of the precipitation event, precipitation records were analyzed to find the maximum number of subsequent days in which precipitation occurred. Table 4 indicates that during the spring months, when the number of precipitation events is the highest, 40% of the days in any period of time had precipitation. Accordingly, 4 sequential days of rain during a 10 day period was assumed as the worst case scenario. To account for the underestimation of the influx in Eq. (4), the duration was increased. The maximum duration was modeled with a type I maximum value distribution with a mean of E(D) = 5 days and a standard deviation of $\sigma(D)$ = 2 days. A correlation coefficient of 0.6 between I and D was used to estimate a scenario in which a longer duration storm has high intensity.

Table 4: Duration analysis

L (days)	D = # of events in a period of L days		
	L = 20	L = 10	L = 5
Spring 1999	7	4	2
Spring 2000	9	5	2
Spring 2001	7	4	2
Spring 2002	6	3	2
Spring 2003	8	4	2
E(D)	7	4	2
σ(D)	1.31	0.65	0.35
E(D)/L	0.37	0.39	0.40

Initial Conditions. Eq. (3) indicates that the capacity of the soil depends on the initial moisture content in the soil. Investigation of the moisture content values in the instrumented ET test covers at the site indicates that the mean volumetric moisture content in the cover is approximately 0.15 (McCartney and Zornberg 2004). After periods of intense precipitation during which significant increases in moisture content were observed, the covers returned to the mean volumetric moisture content after 2 to 3 weeks. Accordingly, the initial moisture content θ_i was modeled using a lognormal distribution with a mean value of 0.15 and a standard deviation of 0.05. To account for the possibility that higher moisture contents are likely during periods of intense precipitation, positive correlation coefficients of 0.75 were assumed between the initial moisture content and the precipitation intensity and duration, respectively.

Monte Carlo Analysis

Monte Carlo analysis was used to simulate the variables in Eqs. (3) and (4) to determine the likelihood that the moisture applied to the soil during a precipitation event is greater than the moisture storage capacity of the soil. 10,000 realizations were used to estimate the probability of failure for each alternative using correlated non-normally random variables (Ang and Tang 1990). Each realization consisted of: (*i*) generating a uniformly distributed random number for each of the variables in the performance model, (*ii*) transforming the random numbers to a standard normal distribution, (*iii*) transforming the independent standard normal random numbers to correlated normal variables using the mean values and correlation coefficients defined from the laboratory testing program, (*iv*) transforming the correlated normal variables to the probability distribution selected for each variable, (*v*) calculating the MSC and moisture infiltrated from Eqs. (3) and (4) using the simulated variables, and (*vi*) checking if failure occurred for the realization. Estimates of the probabilities of failure for covers with different thicknesses constructed using Soil types 1 and 2, given the design precipitation event, are shown in Figures 5(a) and 5(b). The estimated probabilities of failure ranged from $1.4\text{x}10^{-4}$ to 0.8 except for Soil type 1 with RC = 90%, which had a probability of failure less than the precision of the Monte Carlo analysis (*i.e.*, less than 10^{-5}). The relatively high probabilities of failure are consistent with field observations by Zornberg and McCartney (2003), who report that test covers using these soils exceed field capacity approximately every two years.

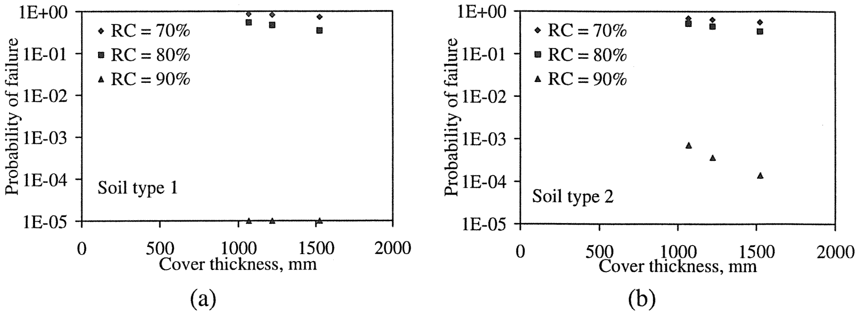


Figure 5: Simulation results: (a) p_f for Soil type 1; (b) p_f for Soil type 2

Results

Using the probability of failure values from the Monte Carlo simulations, the decision analysis was conducted for the example costs. The total alternative cost was calculated as the sum of the construction, densification, and the failure costs. As each alternative has a likelihood of successful or failure and will have different total costs based on the outcome of its performance, the probability of failure is used to calculate the expected cost for the alternative, as follows:

$$\text{Expected Cost} = p_f\left(\text{Cost of failed cover}\right) + (1 - p_f)(\text{Cost of successful cover}) \qquad (5)$$

The expected costs for the different cover alternatives using the example costs given in the introduction are shown in Figure 6. For these example costs, the cover alternative with the minimum expected cost is a 1.067 m-thick cover constructed using Soil type 2 placed at 80% relative compaction. Although this cover had the lowest expected cost, is did not have the lowest cost of success. However, the expected cost allows the likelihood of success and failure to be balanced. Although this approach allows the optimal design alternative to be identified, the approach is undeniably sensitive to the example costs. However, the flexibility of assigning the costs allows a designer to customize the decision analysis to the goals of the parties interested in cover design.

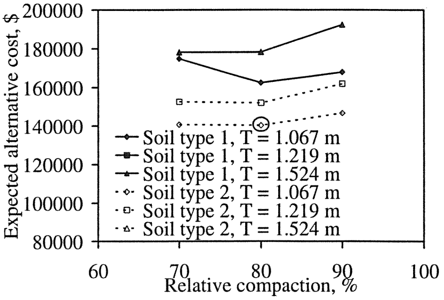


Figure 6: Decision analysis for example costs with optimum alternative circled

Discussion

The decision analysis presented in this paper provides a simple yet objective means to select important design variables that affect the performance of ET covers while considering uncertainty in soil hydraulic properties and design precipitation events. This analysis may be extended by incorporating a rigorous solution of Richards' equation in response to atmospheric boundary conditions into the Monte Carlo analysis routine. Further, it may be extended by including moisture removal from the cover, which is an essential component to cover performance. Incorporating these features into a decision analysis may lead to a better quantification of the expected performance for each cover, but it will significantly increase the computation time. Although the technical features of the flow process may be improved, an appropriate failure criterion and alternative costs are still required to evaluate the analysis results. An important future component of this research will include comparison of the results of the prior decision analysis presented in this paper with the data from the field monitoring program for the ET covers at the site. As mentioned, field monitoring data is available from several prototype test covers, each with different cover thicknesses and soil types. Accordingly, the field data can be used to update the probabilities of failure calculated in this study using Bayesian analysis. This may help determine whether site-specific compliance testing is necessary, or if reliance on laboratory data and simplified analyses is sufficient.

Acknowledgements

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