Design and Performance Criteria for Evapotranspirative Cover Systems

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ABSTRACT: Although evapotranspirative cover systems are becoming acceptable alternatives for use in hazardous or municipal waste landfills located in arid climates, consistent design and performance criteria specifically applicable to these systems are not well established. This paper discusses the rationale of criteria that have been recently used or proposed in the United States for evapotranspirative covers. The performance and design criteria for two prominent hazardous waste sites, the Operational Industries Inc. (OII) landfill site in southern California and the Rocky Mountain Arsenal in Denver, Colorado are introduced as they have either implemented or are planning to implement evapotranspirative cover systems. Development of the criteria adopted at each site involved the use of either numerical simulations or field monitoring. Performance criteria implemented to date involve either a comparison of the performance of an evapotranspirative cover with that of a prescriptive cover (comparative criterion), or definition of a maximum level of acceptable percolation for the evapotranspirative cover (quantitative criterion). Equivalence demonstration when adopting a comparative criterion is straightforward, while its use for design and regulatory compliance calculations is comparatively difficult. On the other hand, equivalence demonstration when adopting a quantitative criterion may be more ambiguous, but its use for design and regulatory compliance assessment is straightforward.

1 INTRODUCTION

The design of final cover systems for new municipal and hazardous waste containment systems in the United States is prescribed by the Resource Recovery and Conservation Act (RCRA) Subtitles D and C, respectively. Federal- and state-mandated cover systems for municipal and hazardous waste landfills have endorsed the use of "resistive barriers". These resistive barriers have also been referred to as "prescriptive" barriers, as their design is based on prescribed dimensions and material properties that have been deemed to lead to acceptable performance. Although satisfactory performance has been reported for these prescriptive systems in humid climates, problems induced by desiccation cracking of clay liners has led to inadequate performance in arid climates (*e.g.* the Western United States). Also, prescriptive covers required at some containment facilities have often resulted in significant material and construction costs.

In order to enhance cover performance and lower construction costs, RCRA regulations allow alternative cover systems if comparative analyses and/or field demonstrations can satisfactorily demonstrate equivalence with prescriptive systems. One such alternative cover system, the evapotranspirative cover, is expected to have adequate long-term performance while mimicking natural systems by using a soil layer placed in natural conditions and a vegetative cover consisting of a diverse native plant community.

Until a decade ago, little research had specifically focused on the behavior of evapotranspirative covers and the aspects governing their design. While there is significant recent effort to expand the knowledge base, assessment of the physical processes governing the moisture flux within evapotranspirative covers has often been fragmented. Further difficulties have been posed by the need to compare the performance of alternative cover systems with that of prescriptive cover systems (*i.e.* equivalency demonstration), by the need to account for phenomena associated with temperature driven moisture flux, and by errors in monitoring equipment (*e.g.* lysimeters and moisture probes). This has led to difficulties in developing suitable design criteria for these cover systems.

Because of the site-specific interactions between an evapotranspirative cover and the local climate and environment, design criteria for evapotranspirative covers cannot be established in a prescriptive manner. Instead, design criteria must specifically account for site-specific conditions. The objective of this paper is to outline different types of performance criteria that have been put forth for evapotranspirative covers. The type of performance criteria will in turn determine the design procedures, as well as the methods of compliance demonstration for an evapotranspirative cover.

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2 PERCOLATION CRITERIA FOR EQUIVALENCE DEMONSTRATION OF EVAPOTRANSPIRATIVE COVER SYSTEMS

One of the key engineered components of municipal and hazardous waste landfills is the cover system. The cover system should be designed to minimize percolation of rainwater into the waste and prevent leachate generation that may lead to environmental contamination of soil and groundwater. A conventional "resistive barrier" type cover system involves a liner (*e.g.*, a compacted clay layer) constructed with a low saturated hydraulic conductivity (typically 10^{-7} cm/s or less) to reduce percolation. Figure 1(a) illustrates the water balance components in this comparatively simple system, in which percolation control 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 be able to design a system that *minimizes* percolation to environmentally safe values. Quantification of this minimized, though finite, percolation of liquid into the waste poses significant challenges.

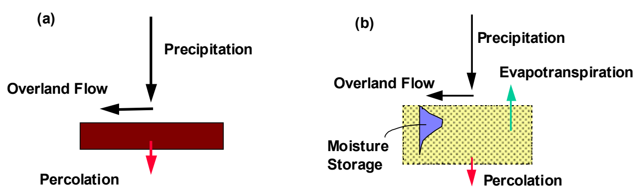

Figure 1: Water Balance Components: (a) in a Resistive Barrier; (b) in an Evapotranspirative Cover System.

Figure 1(b) illustrates schematically the water balance components in an evapotranspirative cover system. Evapotranspiration and moisture storage, two components that do not play a major role in resistive barriers, are significant elements in the performance of this system. The novelty of this approach is the mechanism by which percolation control is achieved: an evapotranspirative 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. The adequacy of alternative cover systems for arid locations has been acknowledged by field experimental assessments (*e.g.*, Anderson *et. al.,* 1993; Dwyer, 1998, Nyhan et. al., 1997), and procedures for quantitative evaluation of the variables governing the performance of this system have been compiled in a systematic manner for final cover design (*e.g.* Zornberg & Caldwell, 1998).

Evapotranspirative covers are vegetated with native plants that survive on the natural precipitation. The superior performance in arid climates of evapotranspirative covers relative to conventional resistive covers can be attributed to the lower unsaturated hydraulic conductivity of the selected cover soils. Additional advantages of evapotranspirative covers over typical clay barrier systems include their invulnerability to desiccation and cracking during and after installation, their relatively simple constructability, and their low maintenance. Also, as evapotranspirative covers can use a reasonably broad range of soils, they are typically constructed using soils from nearby areas.

Performance criteria should address a broad range of factors affecting the behavior an evapotranspirative cover. For instance, criteria may be placed upon particle size gradation of the soil to result in desired unsaturated hydraulic characteristics, upon the thickness of the soil layer to address erosion concerns and prevent animal intrusion, upon the density of the soil layer to enhance vegetation growth, or upon the compaction of the soil to prevent differential settlements, slope instability and surface ponding. However, as a primary objective of a cover system is to limit percolation into the underlying waste, the focus of this paper is restricted to percolation criteria.

As mentioned above, a cover can not conceivably be designed to completely prevent percolation. Instead, designers must consider a non-zero percolation criterion that satisfies equivalence with prescriptive covers. Definition of this percolation criterion has been approached from two different perspectives in past evapotranspirative cover projects in the USA. The first involves defining quantitatively a maximum value of percolation that cannot be exceeded. The second involves a comparative approach aiming at a percolation value smaller than that through a prescriptive cover under the same weather conditions. These two approaches for percolation criteria are discussed in the following sections.

3 QUANTITATIVE PERCOLATION CRITERION

3.1 Definition

A percolation criterion for evapotranspirative covers involves defining the maximum amount of percolation that is allowed for the cover. The quantitative percolation value is considered to satisfy equivalence with a prescriptive cover. This maximum percolation value is typically defined by agreement with regulatory agencies, yet it should be based on actual performance data from prescriptive type covers or on the results of verified numerical models.

The percolation through the evapotranspirative cover (P_e) should be less than the maximum quantitative percolation value (MQPV), deemed to satisfy equivalence, as follows:

$$P_e < MQPV \quad (1)$$

where MQPV has the dimensions of flux rate (mm/year) and P_e is the evapotranspirative cover percolation typically defined from field monitoring and/or from numerical simulations.

3.2 *Case Study*

A project where design is governed by a quantitative percolation criterion is the Rocky Mountain Arsenal (RMA) near Denver, Colorado, USA. Almost 200 acres of RCRA-Equivalent evapotranspirative covers are to be built at this site over contaminated materials. The Record of Decision (ROD) for the site requires an equivalent percolation demonstration before construction of the alternative covers. This involved comparative numerical analyses and a field demonstration (Chadwick *et. al.*, 1999).

Field demonstration plots were constructed at the Rocky Mountain Arsenal and are being evaluated in order to assess the conditions by which a quantitative percolation criterion will be satisfied. A MQPV threshold of 1.3 mm/year was selected at this site (RMARVO, 1997). This value represents the average of eight years of leachate data collected from two landfill covers built to RCRA Subtitle C standards in Hamburg, Germany, according to analysis described by Melchior (1997). This type of criterion was selected for its simplicity, as it sets a benchmark to be used in post-closure monitoring to demonstrate compliance.

The RCRA Subtitle C test covers in Hamburg consist of 75 cm of vegetated topsoil, a geotextile, a 25-cm drainage layer, a 60 mil HDPE geomembrane, a 60-cm compacted clay layer, another geotextile, a 20-cm drainage layer and a lower HDPE geomembrane acting as a lysimeter to capture deep percolation. The two test covers used for development of the percolation criterion (F2 and S2) had slopes of 4% and 20%, but were otherwise equivalent. The leachate rates, defined as the amount of water collected from the drainage layer divided by the area of the covers, were between 0.4 and 3.5 mm/year for cover F2 and between 0.3 and 3.0 mm/year for cover S2. The 8-year average leachate rate for the two covers was reported to be 1.3 mm/year (Melchior, 1997). This percolation value was selected at the Rocky Mountain Arsenal project as it appears to be a conservative, yet representative percolation value for resistive covers.

As part of a field demonstration project at the Rocky Mountain Arsenal, four test covers were designed on the basis that the moisture flux through site-specific soils calculated using numerical modeling under local weather conditions was estimated to be less than the MQPV (Chadwick *et. al.*, 1999).

One of the covers was constructed with silt-loam soils from on-site locations having at least 35% fines content (Cover A), and the other three were constructed using the same soil but having at least 50% fines content (Covers B, C and D). The soil depths and characteristics for these four covers are shown in Table 1 (Chadwick *et. al.*, 1999). Each test cover was constructed at a 3% slope to prevent surface water ponding. The covers were underlain by a 60-mil VFPE geomembrane lysimeter with a geocomposite drain to collect deep percolation. In addition, the covers were equipped with tipping-bucket gauges for measuring precipitation and irrigation, boundary swales for collecting surface water runoff, and time domain reflectrometry (TDR) probes for measuring volumetric moisture content. Irrigation was applied to ensure application of a minimum of 535.4 mm of water per year, which corresponds to the maximum annual rainfall amount from the past 49 years.

Table 1: RMA Test Cover Characteristics

Cover	Soil Thickness (cm)	Average % Passing #200 Sieve	Range % Passing #200 Sieve	Average PL	Range PL	Average LL	Range LL
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
A	106.68	43.4	37-47	9	7-11	24.4	24-25
B	121.92	60.2	56-63	12.8	11-16	27.6	26-30
C	152.4	59.2	53-67	11.7	10-16	26.7	25-30
D	106.68	61.5	59-63	12	11-13	26.8	26-28

The test plots at the Rocky Mountain Arsenal have satisfied the percolation criterion over the period 1998-2001 of operation. That is, all four of the covers have shown a yearly percolation rate below the MQPV despite heavier-than-normal precipitation. The cumulative percolation collected from each of the four covers over the past three years is shown in Figure 2, with time starting in July of 1998. One of the covers showed a surface depression, possibly due to installation of moisture probes, yet the collected percolation over this cover was still within the percolation threshold. Full scale evapotranspirative covers are currently under design with the test plots as a base for design efforts.

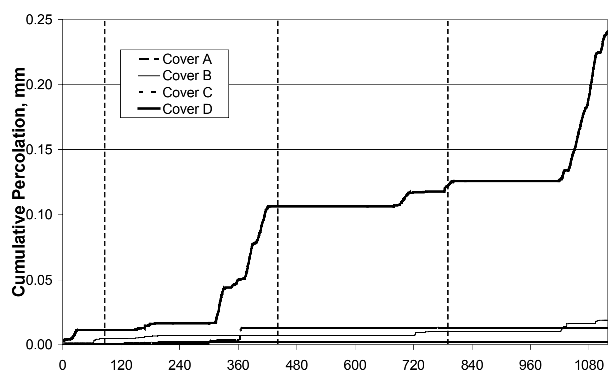

Figure 2: Cumulative Percolation for Each of the Four Test Covers at the Rocky Mountain Arsenal

3.3 *Assessment*

The definition of a quantitative percolation criterion is a difficult process. The basis of its definition must lie in the performance of prescriptive cover systems, but these cover systems perform differently under various climates. Ideally, the MQPV corresponds to the percolation through a prescriptive cover under local weather conditions. However, desiccation of prescriptive clay liners associated with arid climates may result in unacceptable performance. Also, it is also uncertain whether the MQPV should be the average percolation of the prescriptive cover over a certain period of time, or the maximum percolation through the prescriptive cover for individual precipitation events. Thus, agreement with regulators is necessary to determine the proper site-specific MQPV.

The choice of a quantitative percolation criterion implies that the cover must be designed for a wide range of possible meteorological conditions to ensure fulfillment of the criterion for worst case scenarios. On the other hand, if the MQRV is selected conservatively, the cover design may head to unrealistically high material and construction costs.

4 COMPARATIVE PERCOLATION CRITERION

4.1 *Definition*

A comparative percolation criterion for evapotranspirative covers involves defining the maximum ratio between the percolation through an evapotranspiration cover and that through a prescriptive cover. This percolation criterion recognizes that the performance of the evapotranspirative cover should be compared to that of a resistive cover under the same meteorological conditions.

To satisfy equivalence demonstration, the percolation through the evapotranspirative cover (P_e) should be less than the percolation through the prescriptive cover (P_p), affected by the maximum comparative percolation ratio (MCPR) established for the project. That is, equivalence can be ensured by fulfilling the following condition:

$$P_e < (MCPR)\, P_p \qquad (2)$$

where MCPR is dimensionless and P_e and P_p are percolation values typically obtained from field monitoring and/or from numerical simulations.

4.2 *Case Study*

A comparative percolation criterion was employed in the design of an evapotranspirative cover system at the OII Superfund site, located in the city of Monterey Park, California, approximately 16 km east of downtown Los Angeles. The evapotranspirative cover was the first such approved by the United States Environmental Protection Agency (EPA) for a hazardous waste Superfund site. The general approach to the design of the cover involved five phases that were undertaken to define the cover layout configuration, evaluate its performance, and perform equivalence demonstration. The phases included: (*i*) evaluation of a baseline evapotranspirative cover, (*ii*) equivalence demonstration of the baseline cover by comparison with the percolation through a prescriptive cover, (*iii*) evaluation of the sensitivity of different design parameters (cover thickness, soil characteristics, rooting depth, and potential use of irrigation schemes) on the percolation through the cover, (*iv*) compilation of the results of these analysis into the design of the final evapotranspirative cover, and (*v*) equivalence demonstration of the final evapotranspirative cover.

The design criteria for the cover system at the OII Superfund site required that the percolation through the proposed evapotranspirative cover be less than the percolation through a prescriptive, resistive cover. That is, the MCPR at this project was 1.0. The prescriptive cover, defined by a consent decree, consisted of a 1200-mm thick system, which included a 300-mm thick vegetative layer, a 300-mm thick clay layer, and a 600-mm thick foundation layer. The vegetative and foundation layers both had a saturated hydraulic conductivity of 1×10^{-4} cm/sec, and the clay layer had a saturated hydraulic conductivity of 1×10^{-6} cm/sec.

A laboratory testing program implemented to characterize the candidate borrow soils was performed using soil specimens remolded under different compaction and moisture conditions. The experimental program included determination of hydraulic, shear strength, desiccation potential, and agronomic properties. In order to illustrate the soil-specific equivalence demonstration, laboratory test results are presented herein for one of the candidate borrow soils used in the equivalence demonstration. The results are summarized in Table 2.

Table 2: OII Landfill Laboratory Soil Test Results

Series (1)	Dry Density, γ_d (kN/m^3) (2)	Gravimetric Moisture content, *w* (%) (3)	Volumetric Moisture content, θ [(1)] (%) (4)	Saturated Hydraulic Cond., K_s [(2)] (cm/sec) (5)	Campbell parameter *a* (6)	Campbell parameter *b* (7)
T1	13.9	23.6	33.6	2.8×10^{-6}	-4.89	7.028
T2	12.9	26.3	34.7	1.1×10^{-5}	-4.89	6.328
T3	12.3	25.7	32.1	3.7×10^{-5}	-4.89	5.495
T4	13.1	22.3	29.9	3.3×10^{-6}	-4.89	7.278
T5	13.0	27.1	36.2	1.7×10^{-5}	-4.89	6.463
T6	11.5	27.3	32.0	1.9×10^{-4}	-4.46	6.678

USCS Classification: CL (ASTM D2487) Fines Content: 66% (ASTM D 1140)
LL: 43%; PI: 18% (ASTM D4318) G_s= 2.79 (ASTM D 854)
Maximum dry density: 14.8 kN/m^3; w_{opt}: 23.0 % (ASTM D 698)

(1) $\theta = w \times \gamma_d / \gamma_w$ (2) ASTM D 5084

Following identification of the candidate soil borrow sources and determination of their hydraulic properties, soil-specific equivalence demonstrations of the proposed evapotranspirative cover were performed. Soil-specific parameters used in the unsaturated flow analyses included 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 evapotranspirative cover.

The percolation ratio values were estimated using the code LEACHM (Hutson and Wagenet, 1992) to define the percolation through the prescriptive and evapotranspirative covers in order to assess proper performance using site-specific soil and meteorological conditions. LEACHM uses Campbell's equation to describe the relationship between suction (ψ) and volumetric water content (θ) for soil:

$$\psi = a\,(\theta / \theta_s)^b \qquad (3)$$

where θ_s is the saturated volumetric water content, and a and b are constants obtained from curve fitting. The a and b values as well as the saturated volumetric water contents for the candidate evapotranspirative cover soils are listed in Table 2. The estimated a and b values for the clay layer in the prescriptive cover are -1.88 and 5.973, respectively. The initial volumetric moisture content adopted in the simulation for the clay layer was 30%, which corresponds to the optimum moisture content of the clay material.

Figure 3 shows the results, in terms of the percolation ratio, of the equivalence demonstration performed for an evapotranspirative cover system constructed using top deck stockpile soils placed under compaction conditions defined by series T1 in Table 2. The comparative percolation ratio is below 0.1 for each year of the soil-specific, 10-year simulation. The engineered evapotranspirative cover constructed using the top deck stockpile soils, and placed under conditions defined by the T1 series, was then deemed to satisfy compliance with the prescriptive cover according to this demonstration.

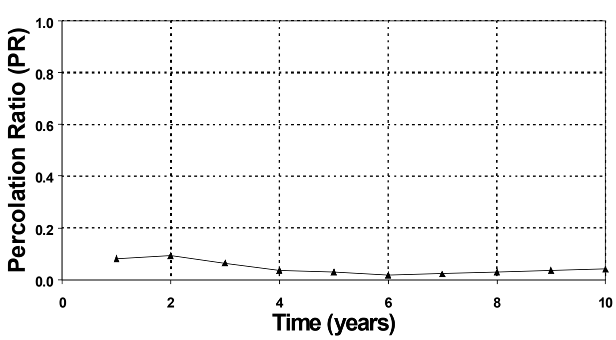

Figure 3: Comparative Percolation Ratio obtained for the Evapotranspirative Cover at the OII Landfill site.

4.3 Assessment

The definition of a comparative percolation criterion for an evapotranspirative cover project is straightforward, as it involves the recognition that the evapotranspirative cover should perform better than a prescriptive cover under the same weather conditions. However, discrepancies may arise in the methods to be used to define percolation values P_e and P_p. Designers and regulators must agree if the performance of the prescriptive cover should be simulated with a numerical model or monitored from test plots constructed in the field. The first approach may result in an unrealistic performance for the prescriptive cover if factors such as desiccation, surface settlement or animal infiltration are not considered. The second approach will result in additional design and construction costs and yet, not cover critical weather conditions.

5 PERFORMANCE CRITERIA USED FOR DESIGN AND COMPLIANCE DEMONSTRATION

The selection of a quantitative or comparative percolation criterion for an evapotranspirative cover project may have serious implications on the design process and on the compliance demonstration for the cover. Design parameters such as soil hydraulic characteristics, cover geometry, and vegetation requirements should be defined in accordance with the percolation criterion. Evaluation of the performance of the cover after construction, which requires field monitoring or numerical modeling, also requires the use of a percolation criterion.

Although the quantitative percolation criterion may be difficult to define, it provides a clear basis for the design of an evapotranspirative cover is straightforward. Design parameters for the cover may be optimized to meet the MQPV using numerical modeling. On the other hand, a comparative percolation criterion for the design of an evapotranspirative cover may not be as straightforward. Sensitivity analyses of both the evapotranspirative and the prescriptive covers are necessary to define the design parameters and their impact on the percolation through the cover.

As with the design of the evapotranspirative covers, the post-closure compliance demonstration using a quantitative percolation criterion is reasonably straightforward, as the simulated or monitored percolation for the evapotranspirative must be above the MQPV. However, limitations in field monitoring and numerical modeling must be understood in order to correctly interpret the data collected for compliance demonstration.

With respect to field monitoring, lysimetry and volumetric moisture probes have been adopted at several sites. Lysimeters are able to resolve small moisture fluxes and TDR probes use the difference in the dielectric constants of water, air and soil to measure the volumetric moisture content in a soil profile. Despite their resolution, lysimeters may create a capillary barrier effect, as they are an essentially impermeable layer placed beneath a relatively permeable layer. This may create a distribution of matric suction above the lysimeter uncharacteristic of the actual distribution. Also, warm surface temperatures in a lysimeter may cause a downward vapor gradient, forcing water vapor downward through the soil until it condenses on the lysimeter. Colder surface temperatures result in an upward gradient that may negate the effect of a downward gradient, yet the lysimeter causes a barrier to upward flow. The performance lysimeters may be complimented with moisture probes. TDR probes cannot measure the moisture flux directly, but can indicate trends in the volumetric moisture content profile. A major disadvantage of TDR probes is their long-term electrical durability.

Numerical models also have limitations in predicting small percolation values with a high level of accuracy associated the algorithms representing physical phenomena as well as limitations in the accuracy of soil, meteorological and vegetation input data. In addition, the mass balance errors for numerical models are typically on the order of millimeters for simulations longer than a year. Because of the limitations of field monitoring and numerical modeling, the accuracy of small percolation estimates is questionable.

Compliance demonstration using a comparative percolation criterion is particularly difficult, as two percolation values must be continuously compared over the lifetime of the evapotranspirative cover. Because of this, the time of compliance demonstration is a key factor. The average percolation value for a time period or the maximum percolation amounts associated with specific precipitation events may be used. Such selection may result in different percolation ratios due to the fact that an evapotranspirative cover and a prescriptive cover would most likely have different responses to a specific percolation event.

6 CONCLUSIONS

Quantitative and comparative percolation criteria for use in the design and compliance monitoring of evapotranspirative covers were introduced in this paper. Two recent case studies in the United States illustrate the applicability of the criteria. A quantitative percolation criterion was defined for the evapotranspirative cover development project at the Rocky Mountain Arsenal in Colorado, and was used for compliance demonstration of four evapotranspirative cover test plots. A comparative percolation criterion was defined at the OII landfill site in Southern California, and was successfully used for closure of the site. The quantitative percolation criterion is comparatively difficult to define based on equivalence demonstration, while it facilitates design and compliance demonstration. The comparative percolation criterion was shown to be suitable for straightforward equivalence demonstration, yet design and compliance demonstration using this percolation criterion are comparatively more complex.

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