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EQUIVALENCE DEMONSTRATION OF AN ALTERNATIVE COVER SYSTEM

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ABSTRACT: A site-specific unsaturated flow investigation was undertaken for the design of an evapotranspirative cover system at the Operating Industries, Inc. (OII) Superfund landfill in southern California. Infiltration control in an evapotranspirative cover system relies on the storage of moisture within the cover soils during the rainy season and on the subsequent release by evapotranspiration of the stored moisture during the dry season. The cover system at this site constitutes the first evapotranspirative cover approved by the US Environmental Protection Agency (EPA) for construction at a Superfund site. Unsaturated flow analyses performed in support of the closure design show that an evapotranspirative cover is feasible at the site for a wide range of conditions. Equivalence demonstration procedures implemented in this study using site-specific weather conditions and soil-specific hydraulic properties were useful to evaluate compliance of the proposed alternative cover with the prescriptive cover system.

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. 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 a low saturated hydraulic conductivity (typically 10^{-7} cm/s or less). Fig. 1(a) illustrates the water balance in this comparatively simple system: 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.

Fig. 1(b) illustrates schematically the components of the water balance in the evapotranspirative cover system to be evaluated in this investigation. Evapotranspiration and moisture storage, two components that do not play a major role in resistive barriers [Fig. 1(a)], become 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. Although 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. 1990; 1997; Ward and Gee 1997), procedures for quantitative evaluation of the variables governing the performance of this system have not been compiled in a systematic manner needed for final cover design at hazardous waste sites.

Evapotranspirative covers are also referred in the technical literature as monolithic soil covers, monocovers, and soil-plant covers (Hakonson 1997). Evapotranspirative covers are usually 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 then be attributed to the lower unsaturated hydraulic conductivity of the evapotranspirative cover soil. Additional advantages of evapotranspirative covers over typical clay barrier systems are that they are less vulnerable to desiccation and cracking during and after installation, they are relatively simple to construct, and they require low maintenance. Also, evapotranspirative covers are economical to implement since, as they can be constructed of a reasonably broad range of soils, they are typically constructed using soils from a nearby area. Finally, evapotranspirative covers may represent a technically superior alternative than prescriptive covers if cover design is governed by stability considerations, as is the case for the design at the OII Superfund landfill described herein.

PHASES IN THE INVESTIGATION

The unsaturated flow analyses in this investigation were performed using the computer program LEACHM (Hutson and Wagenet 1992). LEACHM (Leachate Estimation and Chemistry Model) is a one-dimensional finite-difference water balance model, which uses Richards' equation to simulate flow of water in unsaturated soils. The model has algorithms to predict evaporation from the soil surface and transpiration by plants from the root zone. Precipitation in excess of the infiltration capacity of the profile is shed as overland flow. The general approach followed in this investigation involved five phases that were undertaken to define the cover layout configuration, evaluate its performance, and perform the required equivalence demonstration. The phases were as follows:

(i) evaluation of the hydraulic performance of a baseline evapotranspirative cover, including quantification of percolation rates and assessment of moisture profiles;
(ii) equivalence demonstration of the baseline cover system by comparing the percolation values estimated through the evapotranspirative cover versus those estimated through the regulatory-mandated (prescriptive) cover;
(iii) sensitivity evaluation, in terms of percolation rate, of parameters governing the hydraulic performance of evapotranspirative covers;
(iv) compilation of the evapotranspirative cover design at the OII Superfund site, including determination of cover thickness, soil characteristics, rooting depth, and potential use of irrigation schemes; and

(v) equivalence demonstration of the selected evapotranspirative cover layout, performed using soil-specific hydraulic properties measured for candidate borrow soils identified for cover construction.

The aspects described herein are only those related to the equivalence demonstration undertaken at the OII Superfund site. Accordingly, only some of the analyses undertaken as part of the phases (iv) and (v) mentioned above are described. Specifically, and following a comprehensive experimental testing program undertaken to determine the hydraulic characteristics of potential borrow soils, a discussion is presented regarding demonstration of regulatory compliance using site-specific weather conditions and soil-specific hydraulic properties of soils identified for cover construction.

EVAPOTRANSPIRATIVE COVER DESIGN AT THE OII SUPERFUND SITE

Results from a generic evaluation of a baseline evapotranspirative cover, performed using site-specific weather information for southern California, were used as the basis for the design of the cover system at the OII Superfund site. The characteristics of the unsaturated flow analyses performed in this study will be presented elsewhere. The 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, which is when an interim soil cover of variable thickness (1 to 5 m), consisting of silty clay to silty sand, was placed on top of the landfill. The site has been undergoing final closure under the US EPA Superfund program since 1986. Fig. 2 shows a view of the steep landfill slopes before implementation of the final cover system.

A variety of site characterization and seismic studies were undertaken as part of compliance pre-design analyses for the final closure system at 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 an exposed geomembrane cover and an evapotranspirative cover system. 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). An evapotranspirative cover system was then selected because of aesthetic, economical, and technical considerations. Selection of this system allowed use of geogrid reinforcements on steep portions of the landfill, which were designed to satisfy static and seismic stability design criteria. Construction of an evapotranspirative cover at least 1,200 mm thick resting on top of a 600 mm foundation layer has been recently completed (April 2000). Fig. 3 shows view of the recently constructed evapotranspirative cover system at the South Parcel of the site. Performance monitoring of the cover, consisting of a series of time domain reflectometry probes, will be implemented during three years following construction to monitor moisture variations and percolation trends within the cover.

Unsaturated flow analyses were initially performed for a baseline cover considering weather conditions typical of southern California, which are characterized by an average precipitation of 379 mm/year and an average evapotranspiration of 1015 mm/year. A parametric evaluation indicated that an evapotranspirative cover is feasible for a wide range of conditions. The analyses also showed that the response of the estimated 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 can be defined such that percolation would not decrease significantly for cover systems designed using more stringent parameters than those specific values. Based on the unsaturated flow investigation, the selected design parameters and the rationale for their selection are as follows:

- *Rooting depth.* The analyses indicated that rooting depths larger than the one selected for the baseline case (300 mm) would not lead to major enhancement of the performance of the evapotranspirative cover system. 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 the unsaturated cover system, it is probably the only hydraulic parameter feasible of being incorporated into construction specifications. Based on the results of parametric evaluations, the evapotranspirative cover was required to have a minimum saturated hydraulic conductivity of 1×10^{-5} cm/sec. This requirement was usually achieved with standard compaction requirements specified for the cover soils, which typically called for a minimum density of 90% of the maximum Standard Proctor density and the optimum moisture plus or minus 2%.
- *Cover thickness*. Based on the evaluation of the performance of the baseline cover system and on the sensitivity of the cover thickness on percolation, a 1200-mm thick engineered evapotranspirative cover was selected for the site. Although the analyses indicated the feasibility of a thinner evapotranspirative layer, 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 evapotranspirative cover layer.
- *Placement moisture content*. Evaluation of the performance of the baseline cover system and the sensitivity of placement moisture content on percolation indicated no major influence of this parameter on the long-term percolation of the cover system. 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 the cover soils.
- *Irrigation.* Based on the results of the parametric evaluations, no permanent irrigation scheme will be considered for the final cover system at the site.
- *Degradation of hydraulic conductivity*. Although a post-construction maintenance program will be implemented at the site, evaluation of the potential degradation of

hydraulic conductivity indicated that no special needs are required regarding control of the maximum root penetration.

Fig. 4 shows a typical cross-section of the evapotranspirative cover selected at the OII Superfund site. Because of the difficulty in establishing moisture retention properties for use in construction specifications, the range of moisture retention properties of the cover soils was not specified based on unsaturated flow sensitivity analyses. Instead, the approach adopted to evaluate the suitability of cover soils included implementation of a comprehensive soil testing program using the candidate borrow soils and subsequent compilation of soil-specific equivalence demonstrations.

EQUIVALENCE DEMONSTRATION

The infiltration design criteria for the cover system at the OII Superfund site required that the percolation through the proposed alternative, evapotranspirative cover be less than the percolation through the prescriptive, resistive cover. The prescriptive cover at the site was defined by a consent decree as the State of California mandated prescriptive cover. The prescriptive cover consisted of a 1200-mm thick system, which included a 300-mm thick vegetative layer, a 300-mm thick clay layer having a saturated hydraulic conductivity of $1\text{x}10^{-6}$ cm/sec, and a 600-mm thick foundation layer. The vegetative layer and the foundation layer were both assumed to have a saturated hydraulic conductivity of $1\text{x}10^{-4}$ cm/sec. Campbell's parameters *a* and *b* for the clay barrier were defined using clay material properties reported for a typical clay material used in a liner system. The estimated parameters are $a = -1.88$ and $b = 5.973$. 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.

To satisfy the equivalence demonstration, the percolation through the evapotranspirative cover (P_e) should be less than or equal to the percolation through the prescriptive cover (P_p). In order to quantify equivalence, a percolation ratio (PR) was defined as the ratio between the estimated percolation values through the evapotranspirative and prescriptive covers, as follows:

$$\mathrm{PR} = P_e / P_p \tag{1}$$

The percolation ratio should be less than or equal to unity to satisfy equivalence. The percolation ratio was estimated on a yearly basis in order to assess whether the evapotranspirative cover performed better than the prescriptive cover for each year of the simulation.

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 ("top deck stockpile soils") used in the equivalence demonstrations compiled during the design process.

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 versus moisture curve. Table 1 shows the saturated hydraulic conductivity test results obtained for the top deck stockpile soils. Saturated hydraulic conductivity tests were performed using specimens remolded under different placement conditions (defined as T1 to T6 in the table) and tested under a confining pressure of 35 kPa, which was considered representative of cover conditions. The top deck stockpile 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 included 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 the hanging column test (Klute 1986) for comparatively low values of suction, the pressure plate extractor (ASTM D 2325-68) for medium values of suction, and the thermocouple test (Klute 1986) for comparatively high values of suction. Fig. 5 shows the test results obtained for the top deck stockpile 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. These results suggest that, while the saturated hydraulic conductivity is sensitive to the soil placement conditions, moisture retention properties are apparently not affected by initial density and moisture content conditions. The moisture retention experimental results were used to define the Campbell's parameters listed in Table 3. Fig. 5 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 defined by experimental moisture retention measurements. However, direct measurements of unsaturated hydraulic conductivity were also performed as part of this investigation in order to validate the indirect estimates. Open-flow centrifugation tests (Conca and Wright 1992) were performed to obtain direct measurements of the unsaturated hydraulic conductivity. This test method, recently accepted as a draft ASTM test standard, 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. 6 shows direct measurements of unsaturated hydraulic conductivity obtained using top deck stockpile soil specimens prepared at 90% of the maximum density (relative to Standard Proctor) and optimum moisture content.

The unsaturated hydraulic conductivity function defined using Campbell's parameters, obtained from moisture retention data, overpredicts slightly 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 percolation values in the 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 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 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 evapotranspirative cover. Fig. 7 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 3. The percolation ratio is lower than 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.

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 the top deck stockpile soils. Following evaluation of infiltration, as well as of stability and desiccation cracking susceptibility (not discussed herein), construction specifications for the top deck stockpile soils required a minimum relative compaction of 90% and a placement moisture of optimum plus or minus 2% (relative to Standard Proctor). As for the case of the top deck stockpile 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 construction of the evapotranspirative cover at the OII Superfund site.

CONCLUSIONS

Quantification of parameters for alternative cover design requires an objective process that demonstrates that a proposed cover outperforms (i.e., leads to a smaller percolation value than) a regulatory-prescribed cover system. The approach documented in this paper includes 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 of the alternative cover using site-specific weather conditions and soil-specific hydraulic properties. The rationale proposed in this investigation was implemented for the design of an evapotranspirative cover system for the former Operating Industries, Inc. (OII)

Landfill, now a Superfund site. This system constitutes the first evapotranspirative cover approved by the US Environmental Protection Agency for construction at a Superfund site.

Unsaturated flow analyses showed that an evapotranspirative cover design is feasible at the site for a wide range of conditions. In particular, a 1200 mm-thick evapotranspirative cover designed with a minimum rooting depth of 300 mm in the arid climate of southern California would satisfy stringent infiltration design criteria. A comprehensive 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. The experimental testing results suggested that, while soil placement conditions (initial density and moisture conditions) might affect significantly the saturated hydraulic conductivity of the candidate soils, moisture retention properties are apparently not affected by soil 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 the needs for understanding the expected performance of alternative cover systems, satisfying regulatory compliance, and compiling construction specifications.

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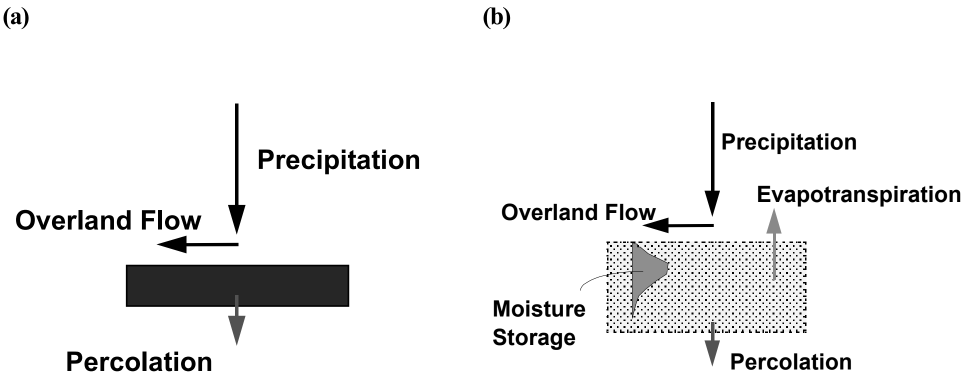

Fig. 1. Main Components in the Water Balance: (a) in a Conventional Resistive Barrier; (b) in an Evapotranspirative Cover System

Fig. 2. View of OII Superfund Landfill Before Construction of the Evapotranspirative Cover System

Fig. 3. View of OII Superfund Landfill shortly after Construction of Evapotranspirative Cover System

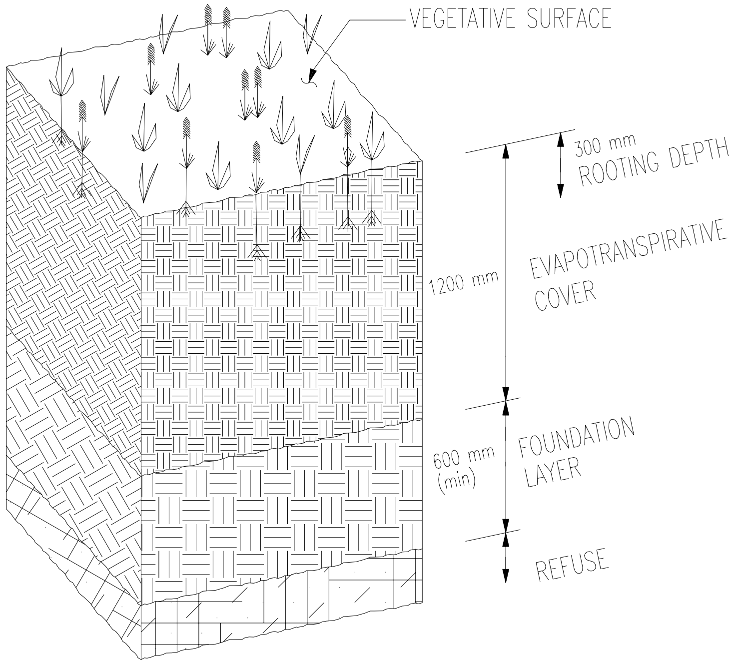

Fig. 4. Evapotranspirative Cover System at the OII Superfund Landfill

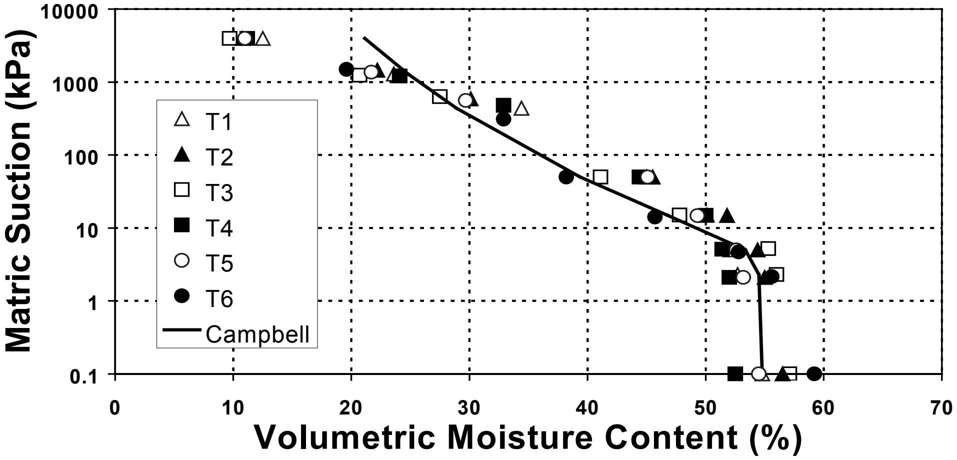

Fig. 5. Characteristic Curves of Top Deck Stockpile Soils used for Evapotranspirative Cover Construction. (Note: The Campbell curve is shown for specimen T1)

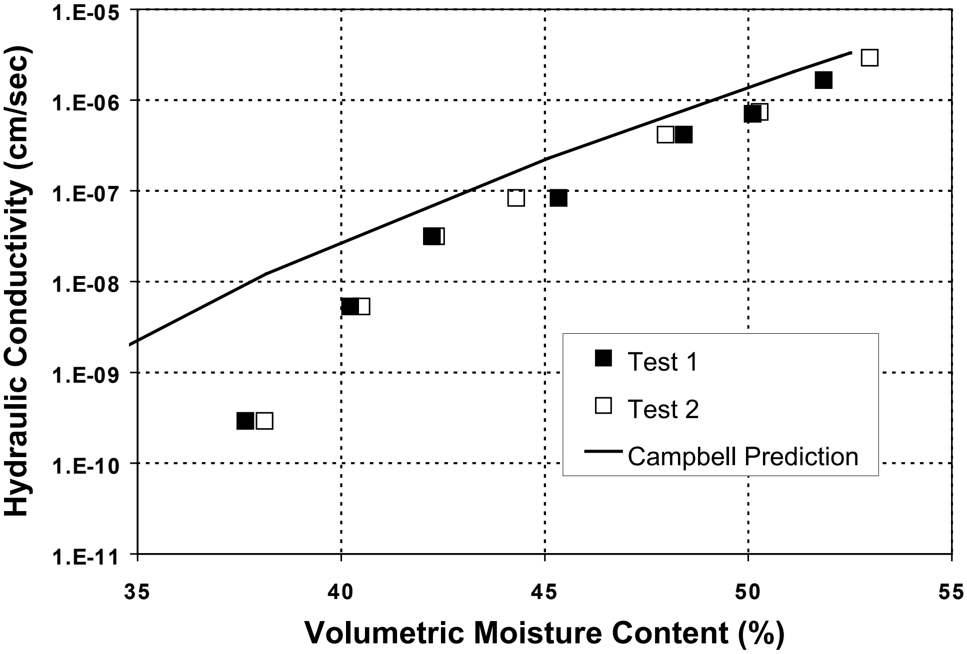

Fig. 6. Unsaturated Hydraulic Conductivity of Top Deck Stockpile Soils obtained Using Direct Centrifuge Measurements

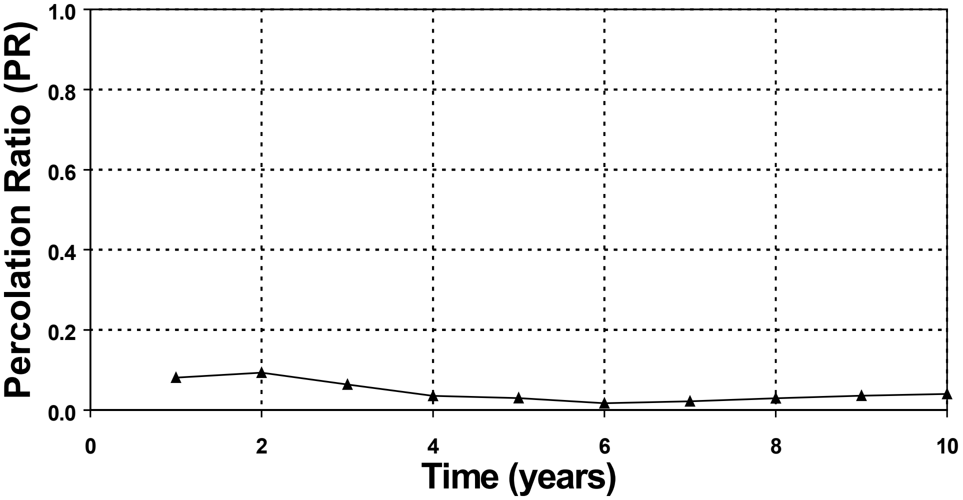

FIG. 7. Percolation Ratio obtained for the Evapotranspirative Cover Constructed Using Top Deck Stockpile Soils.

Table 1. Top Deck Stockpile Soils

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