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Evaluation of Cover Systems for the Remediation of Mineral Wastes

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1. Introduction

Lean ore and waste rock stockpiles, unless controlled, may pose significant environmental problems. Precipitation which enters a mining stockpile is a potential source of surface and groundwater contamination. Minerals present in the stockpile will dissolve in the presence of oxygen and water. Precipitation which percolates through the rock subsequently transports the dissolved minerals from the stockpiles downstream. The degree of transport of the dissolved minerals is dependent upon the chemistry of the component released, the chemistry of the transporting solution and the solids and biota which come in contact with the flow.

Often drainage from mineral wastes can be reduced by proper sitting or diversion of surface and groundwater. Further reduction can only be achieved by minimizing the rate of water infiltration into the waste itself. Infiltration reduction is generally the first step in stemming the water quality problem associate with stockpile drainage. One method of minimizing infiltration into mineral stockpiles is to cover the pile with a low permeability material and route the water off the pile before it becomes contaminated. The purpose of this study was to use the EPA HELP (Hydrologic Evaluation of Landfill Performance) model to simulate field conditions in order to identify the capping options that could be used to stem infiltration into mineral waste stockpiles.

2. Materials and methods

Numerous materials were sourced and screened for use as potential stockpile capping systems (Eger et. al, 1990). Laboratory tests were performed on the selected materials (which included, among others, glacial till, glacial till plus bentonite, fine tailings plus bentonite, paint rock and silty clay). Each material was subjected to a variety of tests using ASTM standards (Table 1). Material property criteria were proposed by the Minnesota Pollution Control Agency (MPCA) and are listed in Table 2. Additionally, each material was selected based on availability, cost, workability, expected hydraulic conductivity, and any potential environmental problems which could result from the use of that material. A summary of the physical properties of the materials for the stockpile capping study is shown in Table 3. Based on the final evaluation of laboratory data, cost and other potential environmental problems, glacial till, glacial till mixed with 5 per cent bentonite, and a 20 mil PVC

membrane were chosen for field evaluation. Fine tailings were rejected since the hydraulic conductivity was greater than 2 x 10^{-6} cm/sec., and they might contain asbestiform fibers. Paint rock, although having a suitable hydraulic conductivity, produces "red" water (suspended iron oxides), and was eliminated due to its prohibitively high cost. While the glacial till had an acceptable hydraulic conductivity, the till contained large boulders which would not be suitable for a barrier layer. Therefore, the glacial till was screened through a Read Screen-All to produce a more uniform sized material.

Test or Classification	Procedure	
Description of Soils	ASTM*	D-2488
Classification of Soils	ASTM	D-2487
Water Content Determination	ASTM	D-2216
Specific Gravity Determination	ASTM	D-854
Particle Size Analysis	ASTM	D-421, D-422
Including Sieve and Hydrometer	ASTM	D-1140, and D-4217
Modified Proctor Moisture - Density Relationship	ASTM	D-1557
Permeability Testing in Conjunction with the Falling Head Procedure	ASTM	D-1557
Atterberg Limits	ASTM	D-4318

*ASTM – American Society for Testing and Materials

Table 1. Material Testing Procedures.

Component of Cap	Specifications
Cover	1. Minimum thickness - 12 inches. 2. Must be capable of sustaining vegetation.
Barrier	1. Soil barriers must be at least 12 inches thick. 2. Each layer must be placed in 6-inch lifts and compacted at or above optimum moisture content to achieve greater than 90% Standard Proctor Density.
	3. Barrier material should not contain more than 1% by weight coarse sand and gravel.
	4. At least 3% dry mass bentonite must be used in bentonite-soil barriers.
	5. The hydraulic conductivity of the barrier must be less than or equal to 2 x 10^{-6} cm/sec.
Buffer	Buffers serve to protect the barrier from tears, cracks, punctures and other deteriorations. The buffer can not contain any coarse fragment greater than 6 inches. 12-inch thickness was chosen as a suitable buffer.

Table 2. Material Specifications for Stockpile Capping Program.

In order to study the effectiveness of the selected capping systems to stem infiltration, the HELP (Hydrologic Evaluation of Landfill Performance) model was used to simulate field conditions. To accomplish this objective, a three layer capping system consisting of a cover, a barrier and a buffer was required (Table 2). Laboratory results in Table 3 along with synthetic materials such as polyvinyl chloride (PVC) were used to simulate the field

Soil Type	Permeability* (cm/sec)	Natural Wc	Atterberg Limits (LL-PL)	Gradation				Modified Proctor		
				%Gravel	%Sand	%Silt	%Clay	Dry Density (pcf)	Moisture Content(%)	Specific Gravity
Glacial Till	1.69×10^{-6}, 1.55×10^{-6}	2.6	NP	15.5	63.4	17.2	3.9	134.4	8.0	2.74
Glacial Till + 3% Bentonite #	5.60×10^{-8}, 1.96×10^{-7}	N/A	N/A	N/A	N/A	N/A	134.8	8.0	N/A	+ 3%
Glacial Till + 5% Bentonite #	6.0×10^{-9}, 4.12×10^{-9}		N/A	N/A	N/A	N/A	N/A	135.0	8.0	N/A
Glacial Till +7% Bentonite #	3.17×10^{-9}, 4.73×10^{-9}	N/A	N/A	N/A	N/A	N/A	134.6	8.0	N/A	
Paint Rock	6.67×10^{-7}, 6.00×10^{-7}	35.1	NP	24.4	41.1	25.8	8.7	123.6	23.0	3.93
Fine Tailings	4.50×10^{-5}, 3.66×10^{-5}	7.7	NP	0.1	43.9	50.7	5.3	116.7	13.4	2.98
Fine Tailings**	4.4×10^{-6}, 6.6×10^{-6}									
Fine Tailings +1/2% Bentonite #	1.47×10^{-5}, 2.02×10^{-5}		N/A	N/A	N/A	N/A	N/A	120.8	12.2	N/A
Fine Tailings +1% Bentonite #	2.39×10^{-6}, 1.61×10^{-6}		N/A	N/A	N/A	N/A	N/A	122.2	12.3	N/A
Aurora Sity clay	20×10^{-9}, 2.0×10^{-9}	31.4	43.5-16.2	0.0	17.8	40.2	42.0	114.0	17.0	2.67

*Tests performed at approximately 95% of the maximum Modified Proctor dry density (ASTM – 1557).
**Test result is from previous STS testing.
#Wyo-Ben Bentonite used
NP - Non-plastic
N/A - Not appropriate

Table 3. Summary of Physical Properties of Materials for the Stockpile Capping Study.

conditions for the various stockpile capping options. Simulations were also performed for a control (untreated) stockpile, standard reclamation (two feet of cover), and the MPCA hydraulic conductivity barrier requirement of 2 x 10^-6 cm/sec. The HELP model is a sophisticated water balanced model that can model multilayered capping systems. The HELP model uses climatologic, soil and design data to produce daily estimates of water movement across, into, through and out of mineral stockpiles considered in this study. The climatologic data, which included daily precipitation and mean monthly temperatures in ^0F were from Babbitt, Minnesota (Udoh, 1993). The solar radiation data in langleys, were the monthly averages from Winton, Minnesota (Eger et. al, 1990). Other climatologic data such as leaf area indices, evaporative zone depth, and winter cover factors were selected from the HELP model built-in default data files. Leaf area index (which is the area of leaves per unit area of ground) affects the total evaporation from the stockpile capping systems. Maximum leaf area index ranges from about 1.5 for grass up to about 5 for a plant like soybeans. The maximum leaf area index used in the simulations ranged from 1 to 1.5. Typical default values for evaporative zone depth (which is related to root depth) range from 4 inches for bare ground to 18 inches for excellent grass. Fair grass, which is the general cover class found at most landfills (Eger et. al, 1990), has an evaporative zone depth of 10 inches, the default value used in the HELP model simulation. The soil data used in the simulation also came from the built-in default data files for soil texture classes 3, 6 and 20 for the top, drainage and barrier layers respectively. However, the hydraulic conductivities for each soil class were estimated to reflect the hydraulic conductivities required for typical mineral capping projects. The hydraulic conductivity of the buffer layer was computed as 70% of that of the top layer since the layer was assumed to be partially compacted.

The HELP program models a number of hydrologic processes by performing daily, sequential analysis using a quasi-two-dimensional, deterministic approach. The model computes surface runoff using the Soil Conservation Service (SCS) runoff curve number method. The equation developed relates daily runoff, Q, to daily precipitation, P and a watershed retention parameter, S, thus:

$$Qp = \frac{(P - 0.2S)^2}{(P + 0.8S)} \tag{1}$$

Where
Q, P, and S are in inches
Infiltration, I, is computed in the HELP model as:

$$I = P - Q - SE \tag{2}$$

Where:
- I = infiltration
- P = daily precipitation
- Q = daily runoff
- SE = surface evaporation

Potential evapotranspiration, E_0 is computed as:

$$E_o = \frac{1.28\, AH}{A + 0.68} \tag{3}$$

Where:

E$_o$ = potential evapotranspiration

A = slope of saturation vapour pressure curve

H = net solar radiation in langleys

Percolation, Qp, modeled as Darcian flow, is computed as:

$$Qp = Kp \frac{TH + T_c}{T_c}$$ (4)

Where:

Qp = the rate of percolation through the barrier soil layer

Kp = the saturated hydraulic conductivity of the barrier soil layer

TH = the total head in the profile above the barrier soil layer

T$_c$ = the thickness of the barrier soil layer

The lateral drainage rate, Q$_D$, based on a linearization of the steady-state Boussinesq equation is computed as:

$$Q_D = \frac{2K_D yho}{L^2}$$ (5)

Where:

- Q$_D$ = lateral drainage rate
- K$_D$ = hydraulic conductivity for lateral flow
- y = average thickness of flow
- ho = elevation of water surface
- L = maximum length to drain

With a correction factor, the lateral drainage equation rewritten as:

$$Q_D = \frac{2K_D y(0.510 + 0.00205\alpha L)[Y(y/l)^{0.16} + \alpha L]}{L^2}$$ (6)

Where: α = fractional slope at surface of cover

The surface vegetation was assumed to be fair grass. A default runoff curve number of 69.76 was determined by the HELP model based on surface vegetation and the minimum infiltration rate of the top soil, and this number was used in the simulations. Additionally, the total area of cover was considered to be 40,000 square feet with a drainage distance of 200 feet. The input parameter values along with the results obtained are summarized in Table 4.

3. Results and discussion

The HELP model is a water balanced model that models multilayered capping systems. Simulations are most accurate when actual field and laboratory data are available for many of the input parameters that are needed to simulate field conditions. However, since data were not available for all of the parameters, various estimates were made for some of the input parameters to the HELP model. By using the materials presented in Table 3 along with polyvinyl chloride (PVC) liners, simulations were carried out (using different scenarios) to evaluate the effectiveness of various capping design systems in minimizing water

Case	Cover Thickness (in.)	Cover Kh (cm/sec.)	Barrier Thickness (in.)	Barrier Kh (cm/sec.)	Buffer Thickness (in.)	Buffer Kh (cm/sec.)	Drainage Thickness (in.)	Drainage TSlope (z)	Drainage Kh (cm/sec.)	ET	Results (in.) Surface Runoff	Results (in.) Lateral Drainage	Results (in.) Infiltration
PCA Reference Case #1	12	7.1×10^{-4}	12	2×10^{-6}	6	5×10^{-4}	0	NAP	NAP	1.2	19.1	7.0	0
#2	12	4.7×10^{-3}	12	2×10^{-6}	6	3.3×10^{-3}	0	NAP	NAP	1.2	17.0	9.3	0
#3	12	1×10^{-2}	12	2×10^{-6}	6	$.7 \times 10^{-2}$	0	NAP	NAP	1.2	16.9	9.5	0
No Reclamation #1	0	NAP	0	NAP	6	7.1×10^{-4}	0	NAP	NAP	0.1	16.6	10.7	0
#2	0	NAP	0	NAP	6	4.7×10^{-3}	0	NAP	NAP	0	13.3	14.1	0
#3	0	NAP	0	NAP	6	1×10^{-2}	0	NAP	NAP	0	12.7	14.7	0
Standard Reclamation #1	24	7.1×10^{-4}	0	NAP	6	5×10^{-4}	0	NAP	NAP	0.1	18.7	8.6	0
#2	24	4.7×10^{-3}	0	NAP	6	3.2×10^{-3}	0	NAP	NAP	0	14.1	13.3	0
#3	23	1×10^{-2}	0	NAP	6	$.7 \times 10^{-2}$	0	NAP	NAP	0	13.2	14.3	0
PCA Reference Case with Drainage Layer At 3% Slope #1	12	7.1×10^{-4}	12	2×10^{-6}	6	5×10^{-4}	12	3	1.0	0.1	18.8	2.8	5.9
#2	12	4.7×10^{-3}	12	2×10^{-6}	6	3.3×10^{-3}	12	3	1.0	0	14.3	3.3	10.0
#3	12	1×10^{-2}	12	2×10^{-6}	6	$.7 \times 10^{-2}$	12	3	1.0	0	13.2	3.3	10.9
At 5% Slope #1	12	7.1×10^{-4}	12	2×10^{-6}	6	5×10^{-4}	12	5	1.0	0.1	18.7	2.5	6.1
#2	12	4.7×10^{-3}	12	2×10^{-6}	6	3.3×10^{-3}	12	5	1.0	0	14.2	2.8	10.4
#3	12	1×10^{-2}	12	2×10^{-6}	6	$.7 \times 10^{-2}$	12	5	1.0	0	13.2	2.9	11.4
PCA Reference Case – Barrier With Liner #1	12	7.1×10^{-4}	12	2×10^{-6}	6	5×10^{-4}	0	NAP	NAP	4.5	22.3	0	0
#2	12	4.7×10^{-3}	12	2×10^{-6}	6	3.3×10^{-3}	0	NAP	NAP	4.3	22.4	0	0
#3	12	1×10^{-2}	12	2×10^{-6}	6	$.7 \times 10^{-2}$	0	NAP	NAP	4.3	22.5	0	0
Lower Permeability Barrier with Liner #1	12	7.1×10^{-4}	12	1×10^{-7}	6	5×10^{-4}	0	NAp	NAp	4.5	22.3	0	0
#2	12	4.7×10^{-3}	12	1×10^{-7}	6	3.3×10^{-3}	0	NAp	NAp	4.4	22.4	0	0
#3	12	1×10^{-2}	12	1×10^{-7}	6	$.7 \times 10^{-2}$	0	NAp	NAp	4.4	22.4	0	0
PVC Liners Case #1*	12	3×10^{-3}	18	2.9×10^{-4}	NAp	NAp	6	3	5.8×10^{-3}	0.3	15.4	11.0	0.7
#2*	12	3×10^{-3}	18	2.9×10^{-4}	Nap	Nap	6	3	5.8×10^{-3}	0.8	17.0	4.0	5.3
Higher Permeability Barrier with Drainage Layer (Base case) #1	12	7.1×10^{-4}	12	1×10^{-5}	6	5×10^{-4}	0	NAp	NAp	0.5	18.7	8.1	0
#2	12	4.7×10^{-3}	12	1×10^{-5}	6	3.3×10^{-2}	0	NAp	NAp	05	14.6	12.4	0
#3	12	1×10^{-2}	12	1×10^{-5}	6	$.7 \times 10^{-2}$	0	NAp	NAp	0.4	13.9	13.1	0
Higher Permeability Barrier Drainage Layer at 3% Slope #1	12	7.1×10^{-4}	12	1×10^{-5}	6	7.1×10^{-4}	12	3	1.0	0.1	18.7	6.4	2.2
#2	12	4.7×10^{-3}	12	1×10^{-5}	6	4.7×10^{-3}	12	3	1.0	0	14.2	9.2	4.1
#3	12	1×10^{-2}	12	1×10^{-5}	6	1×10^{-2}	12	3	1.0	0	13.2	9.6	4.7
At 5% Slope #1	12	7.1×10^{-4}	12	1×10^{-5}	6	7.1×10^{-4}	12	5	1.0	0.1	18.7	5.7	2.9
#2	12	4.7×10^{-3}	12	1×10^{-5}	6	4.7×10^{-3}	12	5	1.0	0	14.2	8.1	5.2
#3	12	1×10^{-2}	12	1×10^{-5}	6	1×10^{-2}	12	5	1.0	0	13.2	8.5	5.9

Table 4. Summary of Preliminary Results with HELP Model.

infiltration into mineral stockpiles. Simulations were run for the MPCA barrier requirement of 2×10^{-6} cm/sec, 20 mil PVC liner, a control (untreated) stockpile, standard reclamation (2 feet of cover), MPCA reference case with drainage layer at 3% and 5% slope, and lower permeability with liner, etc. All the materials (Table 3) except fine tailings alone and mixed with 1/2% bentonite had permeability which were equal to or less than 2×10^{-6} cm/sec, which was the maximum value established by Minnesota Pollution Control Agency.

The first scenario involved the Minnesota Pollution Control Agency (MPCA) case which was a barrier with hydraulic conductivity of 2×10^{-6} cm/sec. Results from model simulations indicated an average infiltration of 8.6 inches with a surface runoff of 1.2 inches and no lateral drainage. With a 3% drainage slope, the MPCA case registered an average infiltration of 3.1 inches with lateral drainage of 8.4 inches. With a 5% drainage slope, the MPCA case recorded an average infiltration of 2.7 inches with drainage of 9.3 inches. With the PVC liner, the MPCA case had neither infiltration nor drainage but the surface runoff was 4.4 inches.

With no reclamation, the average infiltration from model simulations was 13.7 inches with neither surface runoff nor lateral drainage. The standard reclamation, which required a cover thickness of at least 24 inches, had an average infiltration of 12.1 inches with neither surface runoff nor lateral drainage. The lower permeability barrier with liner with hydraulic conductivity of 1×10^{-7} cm/sec had a surface runoff of 4.4 inches with neither infiltration nor lateral drainage. The results obtained from the HELP model are presented in Table 4, and the simulated annual infiltration into stockpiles using the various capping options is graphically depicted in Figure 1. Thus far, synthetic liners appear to be the perfect cover systems, since if intact, they would not transmit any water. Regrettably, a leak-proof liner does not really exist. In general, the thicker the liner system and the better the installation, the smaller the leakage. For the synthetic liner barrier system used in this study, the effective hydraulic conductivity is a function of the leakage factor, f. A leakage factor, f is directly proportional to the area of opening and inversely proportional to the area of the liner system. Typical values for liners range from 0.01 for a 20 mil PVC liner poorly installed to 0.00001 for an 80 mil HDPE with a perfect installation (Eger et. al, 1990). The results from the HELP model simulation imply that the 20 mil PVC liner system has a leakage factor of about 0.001, which is within the expected range. When the flow from a stockpile has been reduced, more efficient use can be made of additional passive treatment systems such as alkaline and wetland treatment. Thus, uncontaminated surface and barrier flow from a stockpile capping system could be collected and used to augment flow downstream of additional passive treatment systems.

From the foregoing results, the three variables that have the greatest effect on the amount of water that infiltrate the cap are the hydraulic conductivity of the barrier layer, the hydraulic conductivity of the cover, and the type and rooting depth (evaporative zone depth) of the vegetation. From the results of the HELP model simulation, none of the barriers reduced flow to a level consistent with a barrier with hydraulic conductivity of 1×10^{-7} cm/sec. The United States Environmental Protection Agency's guidelines for capping landfills require a barrier layer with an effective hydraulic conductivity of 1×10^{-7} cm/sec. This value is also required for new landfills by present MPCA solid waste rules. Simulations conducted with the HELP model showed that when the hydraulic conductivity of the barrier was reduced from 2×10^{-6} cm/sec to 1×10^{-7} cm/sec, infiltration decreased by over 90 per cent. Therefore, to minimize the volume of contaminated flow in any stockpile capping system, the hydraulic conductivity of the barrier should be less than or equal to 1×10^{-7} cm/sec.
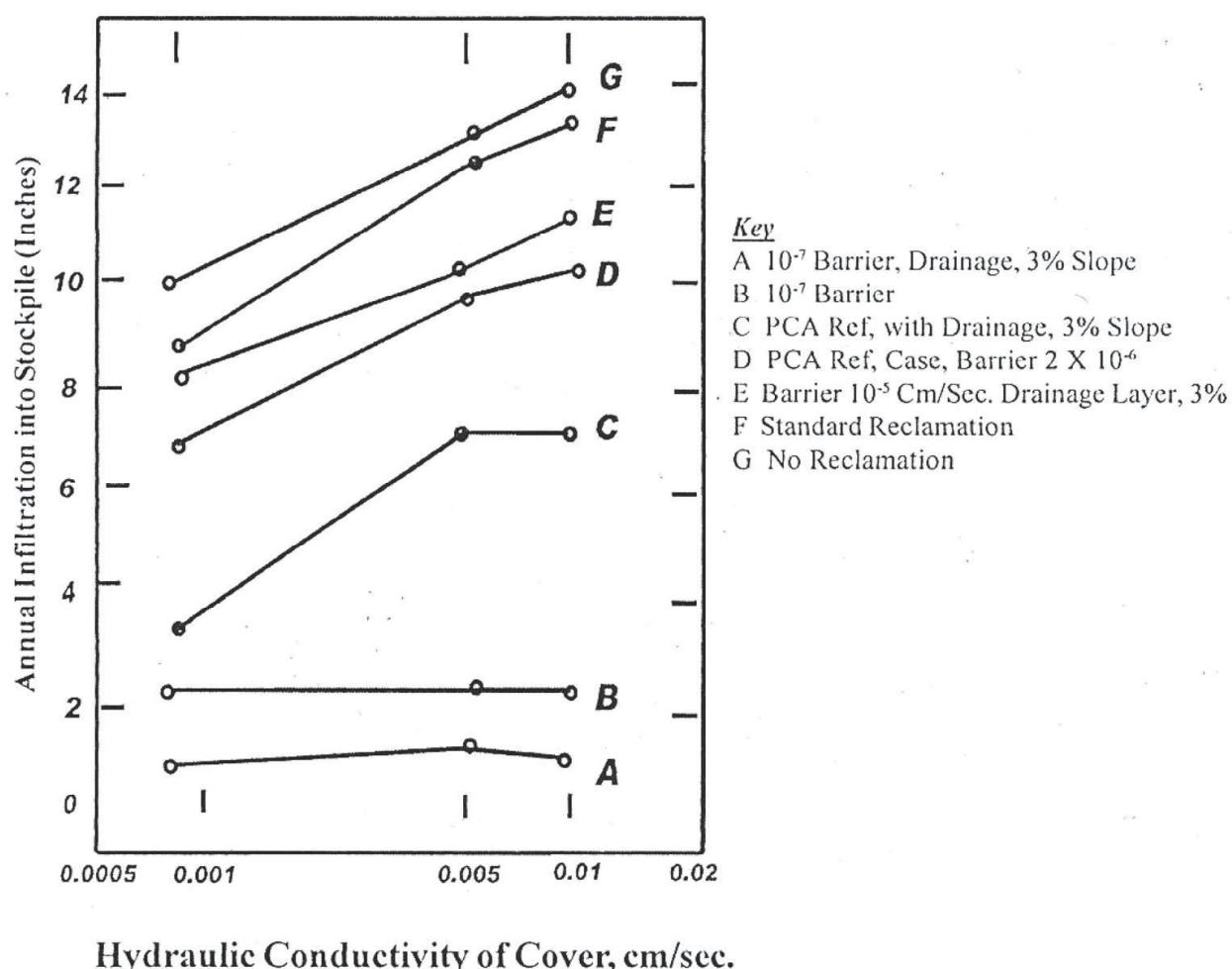
Fig. 1. Simulated annual infiltration into stockpiles using various capping options.

4. Conclusion and recommendations

One key component in mitigating the water quality problem associated with stockpile drainage is the reduction of the amount of water which infiltrates into the stockpiles. While a reduction in infiltration will not change the drainage water quality, the overall mass of contaminants released per year will be reduced as the drainage flow is reduced. Based on the results from the HELP model simulations, the three variables that have the greatest effect on the amount of water that will infiltrate the cap are the hydraulic conductivity of the barrier layer, the hydraulic conductivity of the cover, and the type and rooting depth (evaporative zone depth) of the vegetation. The results from the model simulations showed that, when the hydraulic conductivity of the barrier was reduced from 2×10^{-6} cm/sec to 1×10^{-7} cm/sec, the infiltration reduced by over 90%. Therefore, to minimize bottom flow, the hydraulic conductivity of the barrier layer should be less than or equal to 1×10^{-7} cm/sec.

As earlier alluded to, simulations are most accurate when actual field and laboratory data are available for the many input parameters needed to run the HELP model. Unfortunately, data was not available for all the parameters and various estimates had to be made. Additional field and laboratory data are needed to better determine and model the effectiveness of the various capping alternatives to stem infiltration. Generally, infiltration parameters are often established based on samples which are not representative of field profiles. In other words, laboratory test samples are homogeneous, and thus lack the variability that is associated with similar samples in the field (Udoh, 2008). Since field permeability tests are more likely to yield accurate estimates of hydraulic conductivity than laboratory test, they are recommended as part of either the final design process or construction verification.

Based on the results obtained, a cap design consisting of a three-layer soil barrier is recommended for final capping of any mineral stockpile capping project. Therefore, the selection of materials for the capping of any mineral stockpile and/or waste disposal site should be based on optimizing those properties that have the greatest influence on the long-term performance of the material.
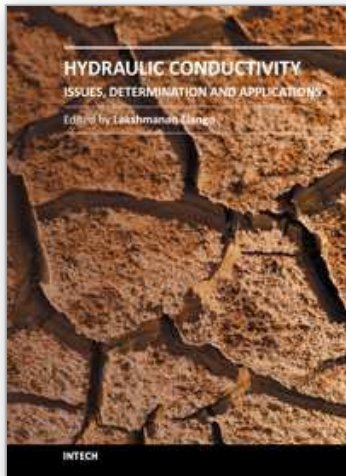
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Hydraulic Conductivity - Issues, Determination and Applications

Edited by Prof. Lakshmanan Elango

There are several books on broad aspects of hydrogeology, groundwater hydrology and geohydrology, which do not discuss in detail on the intrigues of hydraulic conductivity elaborately. However, this book on Hydraulic Conductivity presents comprehensive reviews of new measurements and numerical techniques for estimating hydraulic conductivity. This is achieved by the chapters written by various experts in this field of research into a number of clustered themes covering different aspects of hydraulic conductivity. The sections in the book are: Hydraulic conductivity and its importance, Hydraulic conductivity and plant systems, Determination by mathematical and laboratory methods, Determination by field techniques and Modelling and hydraulic conductivity. Each of these sections of the book includes chapters highlighting the salient aspects and most of these chapters explain the facts with the help of some case studies. Thus this book has a good mix of chapters dealing with various and vital aspects of hydraulic conductivity from various authors of different countries.

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