APPLICATION OF UNSATURATED ZONE HYDROLOGY AT WASTE ROCK FACILITIES: DESIGN OF SOIL COVERS AND PREDICTION OF SEEPAGE [1]

by

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Abstract: The design of soil covers and the prediction of seepage for waste rock facilities are important components of permitting and closure at mines situated in arid climates. This design and prediction require an understanding and application of unsaturated zone hydrology, which, in many respects is counter-intuitive compared to the saturated conditions that are predominate in groundwater hydrology. For example, water under saturated conditions prefers to flow through course textured materials, whereas, under unsaturated conditions, water may prefer to flow through finer textured materials. To ensure accurate and defensible soil cover design and seepage prediction for waste rock facilities, methods must be employed using conceptual models based on unsaturated zone hydrology.

Additional Key Words: unsaturated soils, soil covers, seepage, acid mine drainage.

Introduction

Improvements in the understanding of unsaturated zone hydrology have led to practical application in the area of mine waste management. Examples include the use of capillary barriers and store-and-release cover systems (Benson and Khire 1995; Morris and Stormont 1997; Swanson et al. 1997) to limit the infiltration of meteoric water into waste rock and tailing facilities. In addition, hydrologic models are being used to predict the fate and transport of constituents through the vadose zone to groundwater for environmental assessments and to establish boundary conditions for regional groundwater fate and transport models.

It is important that consultants, as well as mine environmental coordinators and state regulators, understand the fundamental processes of unsaturated flow that are used as the basis for analysis and design in mine waste management. Also important to note, is that the fundamental processes of unsaturated flow are often counter-intuitive, and therefore, a knowledge of saturated flow as it relates to groundwater does not necessarily lend to an understanding of water flow under unsaturated conditions.

This paper discusses the fundamental processes of unsaturated zone hydrology as they pertain to soil cover design and prediction of seepage from waste rock facilities. Specific attention is given to aspects of unsaturated zone hydrology that are counter-intuitive and have seen mis-application in the past.

Conceptual Model

A conceptual model of the hydrology of a reclaimed waste rock facility is illustrated on Figure 1. Four components comprise the waste rock hydrology: 1. Net infiltration through the soil cover; 2. Percolation through the bulk waste rock; 3. Seepage at the base of the facility; and 4. Migration of seepage through the vadose zone. These components are introduced in the following paragraphs.

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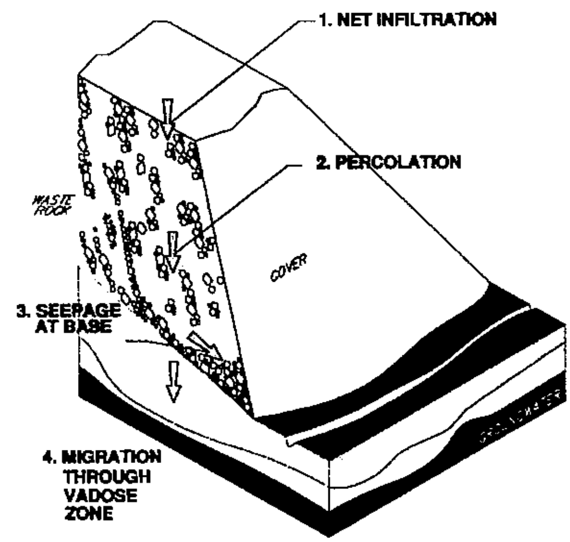

Figure 1. Hydrologic components of a waste rock facility

1. Net Infiltration through the Cover

Precipitation in the form of rain or snowmelt either infiltrates at the soil surface or moves laterally as runoff (Figure 2). Water that infiltrates the soil surface is stored in the soil pores. This water can be removed from the soil by surface evaporation and plant transpiration. The amount of water that is removed via evapo-transpiration is a function of climate and the soil properties (soil-water characteristics and hydraulic conductivity). Water that is not extracted via surface evaporation and plant transpiration moves through the active soil zone and infiltrates into the underlying waste rock (commonly referred to as net infiltration).

Water that infiltrates from the active soil zone percolates through the waste rock facility, gradually wetting it over time. Waste rock is typically deposited in a dry state, and as such, has an inherent moisture storage potential.

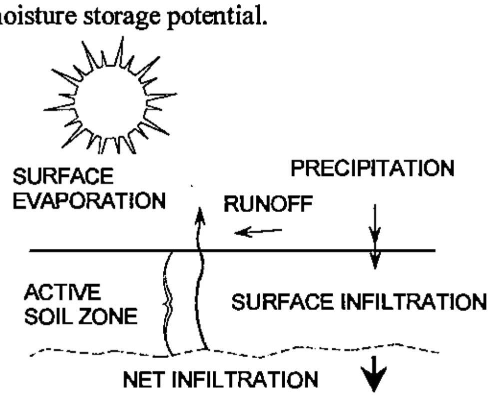

Figure 2. Schematic of net infiltration

2. Percolation through the Waste Rock Facility

The conceptual model used to describe the percolation of water within waste rock facilities is based on the model developed by Herasymuik (1996). Herasymuik studied the internal hydraulic structure of a 15-million-ton waste rock facility at the Golden Sunlight Mine in Montana. A unique opportunity arose when a historical landslide surface was activated, forcing Golden Sunlight Mine to excavate and move the waste rock facility to stop the landslide. The excavation exposed the internal structure of the facility and allowed visual logging and sampling of waste rock throughout its depth.

The exposed waste rock facility was composed of an inter-fingered and bedded system of coarse and fine waste rock that dips at the angle of repose (Figure 3). Herasymuik's conceptual model suggested that under unsaturated conditions, water flows primarily through fine-textured waste rock in dry climates (i.e., waste rock containing appreciable fines that surround the larger particles), rather than through the coarse waste rock (i.e., waste rock lacking a fine matrix to surround the larger particles). This concept was supported by numerical modeling and laboratory column studies conducted by Newman et al. (1997). Newman also noted that preferential flow through fines in a coarse- and fine-layered system has been confirmed in studies dating back to the 1960s (i.e., Hortons and Hawkins 1965).

Figure 3. Inter-bedded and layered waste rock

3. Seepage at the Base

When the moisture storage potential of the waste rock has been depleted, seepage will begin to occur from the base of the facility at a rate equivalent to the net infiltration at the surface. Seepage from the base of the facility will seep laterally above the native foundation contact, and/or seep vertically downward. Lateral and vertical seepage will depend on the percolation rate through the waste rock and the saturated/unsaturated hydraulic properties of the waste rock and the native foundation.

4. Migration through the Vadose Zone

Seepage that moves vertically from the base of the waste rock facility will migrate downward through the vadose zone. For areas undisturbed by mining, the moisture contents in the vadose zone will be in equilibrium with the long-term climatic conditions and groundwater recharge rates will be relatively constant. This equilibrium is upset when the net infiltration at the ground surface is interrupted by the construction of a waste rock facility. The moisture storage potential of the waste rock pile prevents precipitation that infiltrates through the cover from infiltrating the native ground surface at the base of the waste rock facility. This situation continues until the available moisture storage in the waste rock facility has been depleted.

After construction of the waste rock facility, the pore-waters of the vadose zone can drain in response to the interruption of net infiltration at the native ground surface. Recharge to groundwater continues at a lower rate for some time following the interruption of infiltration at the native ground surface. When the available moisture storage in the waste rock facility has been depleted, seepage may occur from the base at a rate equivalent to the net infiltration through the cover at the surface of the waste rock facility. At this point, the moisture contents of the vadose zone will increase until they reach an equilibrium with the new net infiltration rate at the native ground surface– a rate now equal to the seepage from the base of the waste rock facility and the net infiltration through the cover at the surface of the waste rock facility.

Fundamentals of Unsaturated Flow

Many readers, technical and non-technical alike, may not be familiar with the fundamental processes of water flow in unsaturated soils. The theory of water flow in unsaturated soils is well defined (Freeze and Cherry 1979, Guymon 1994; Fredlund and Rahardjo 1993), and although counter-intuitive in some respects, is a logical extension of saturated flow theory. Fundamental processes and hydraulic properties for unsaturated flow are briefly introduced below.

Saturated Versus Unsaturated Flow

Water flow in soils occurs through a series of interconnected and continuous conduits. Figure 4 shows a saturated soil where all of these conduits are used and the ability of the soil to conduct water is at its maximum. A decrease in the moisture content reduces the size and number of these conduits. Therefore, the hydraulic conductivity of a soil is a function of moisture content. This concept is discussed in the sections that follow with the objective of introducing the two fundamental hydraulic properties of an unsaturated soil: the soil-water characteristic curve and the hydraulic conductivity function.

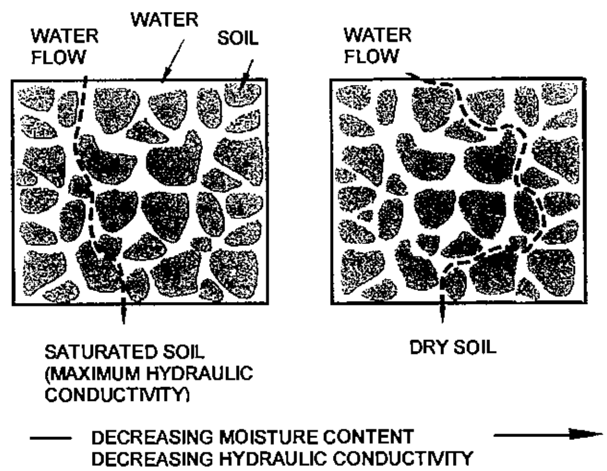

Figure 4. Movement of water through saturated and unsaturated soil.

Soil-Water Characteristic Curve and Hydraulic Conductivity Function

A soil is at its highest moisture content (i.e., saturated) when the water pressure in the soil pores (i.e., pore-water pressure) is zero or positive. Positive pore-water pressures exist below the groundwater table, which is analogous to the pressure one feels in the ears when submerged in a deep pool. Zero pore-water pressures exist at the water table, or, at the surface of a pool.

What happens to pore-water pressure above the water table? Above the water table, water is held in the soil pores under capillary tension. Consider if one were to place a small diameter tube at the surface of a swimming pool (Figure 5). The water rises above the height of the swimming pool due to capillary tension. It would logically follow that the smaller the diameter of tube placed in the water (i.e., smaller the particle size), the higher the water will rise above the surface of the pool (Figure 5). This is capillary tension and it is often referred to as negative pore-water pressure. When this negative pore-water pressure is presented as a positive magnitude by referencing it to a pore-air pressure equal to zero (i.e., 100 bars versus −100 bars), the condition can be referred to as matric suction.

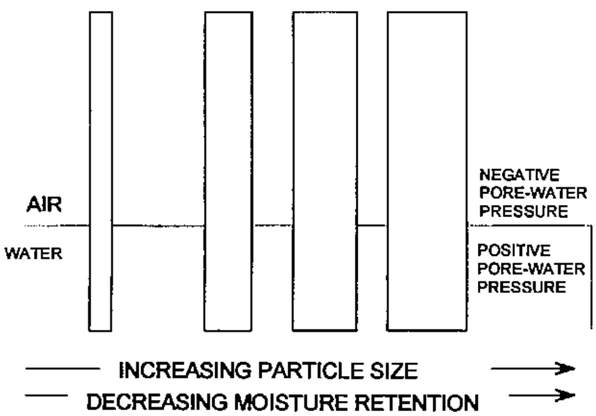

Figure 5. Capillary rise in tubes illustrating the concept of negative pore-water pressure in soils

Moisture content and negative pore-water pressure are related to the size of the soil pores. Based on this discussion, the relation between moisture content and pore-water pressure defines the soil-water characteristic curve (Figure 6a). This relation has also been called the moisture retention curve. The finer the soil the flatter the curve, and conversely, the coarser the soil the steeper the curve.

Hydraulic conductivity is a function of moisture content, and moisture content is a function of pore-water pressure. Hence, hydraulic conductivity is a function of pore-water pressure. This relationship is called the hydraulic conductivity function (Figure 6b). Important to note is the intersection of the hydraulic conductivity functions for different soils. For example, a sand may have a higher hydraulic conductivity than a clay near saturation (i.e., low negative pore-water pressures), but may have lower hydraulic conductivity when dry (i.e., high negative pore-water pressures).

Counter-Intuitive Nature of Unsaturated Flow

Unsaturated flow is counter-intuitive to saturated flow that is typically encountered in groundwater. It is important to be aware of these instances to ensure accurate and defensible analysis, design and review. For example, a common misconception is that potential evaporation rates represent actual evaporation rates from uncovered and covered waste rock facilities. This condition may be accurate if the surface were always saturated; however, it is not representative of unsaturated conditions that are predominate in dry and also wet climates. This and other common misconceptions are discussed in the paragraphs below.

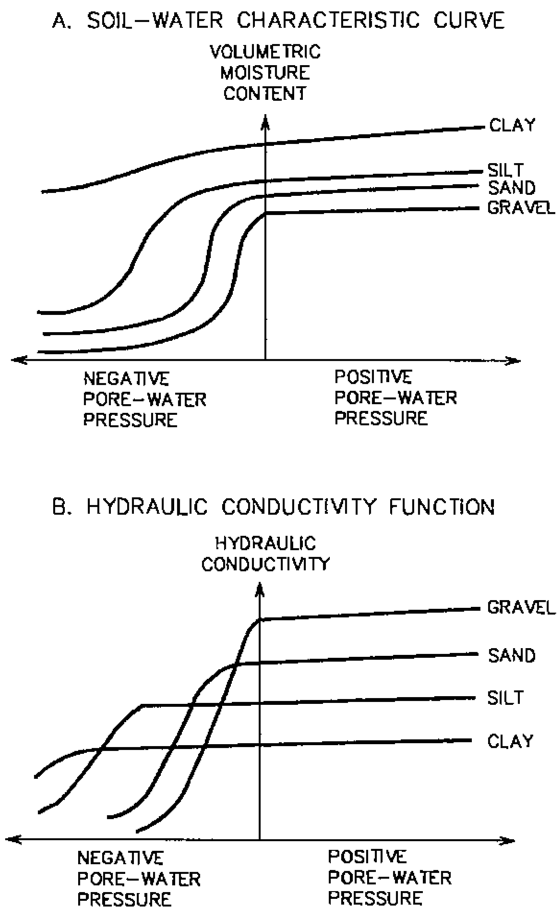

Figure 6. The soil-water characteristic curve and hydraulic conductivity function for different soil types

Evaporation

Evaporation is sometimes misused in assessing soil cover performance and seepage potential, and its misuse is based on a misunderstanding of the fundamental processes of unsaturated flow. This misunderstanding is based on the following: actual evaporation from a soil surface will not equal the potential evaporation.

Potential evaporation can be measured directly using evaporation pans (Maidment 1993) or calculated based on measured air temperature, relative humidity, wind speed and solar radiation (Penman 1948).

Consider a typical site in southwest United States with an annual precipitation of 10 inches per year and a annual potential lake evaporation of 70 inches per year. This information is useful in classifying seepage potential on a relative scale (i.e., this site will more than likely have a lower seepage volume than a site having 70 inches of precipitation and 10 inches of evaporation). However, by no means can these annual totals be used to perform a water balance to estimate net infiltration. For example, one cannot conclude from the above numbers that there will be a net loss of 60 inches of water, nor can it be assumed that net infiltration will be zero. This is because soils can sustain evaporation rates equal to potential evaporation rates for only short periods of time.

Column test data for evaporation from an initially saturated soil, reported by Wilson et al. (1991) and shown on Figure 7, illustrates this concept. The laboratory data define the classical curve describing evaporation from soils (Hillel 1980). The data show that the soil evaporated at a rate close to potential for only a few days. The evaporation rated dropped quickly to rates that were less than ten percent of the potential rate once the soil surface began to dry.

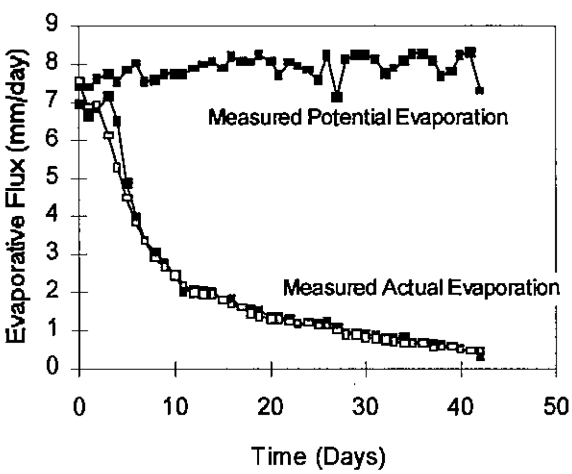

Figure 7. Evaporation from an unsaturated soil

Evaporation is often described by three stages. Koliasev (1941) stated that the rate of evaporation in the first stage is governed by atmospheric conditions with the near saturated conditions making the situation similar to evaporation from a free water surface. He also stated that important variables influencing evaporation in this stage are solar radiation, air temperature, vapor pressure gradient and wind speed. The second stage is described as a period of rapid decline in the evaporation rate. He stated that during this stage a dry surface layer forms because moisture flow is being restricted from below. It is noted that in this stage the soil conditions, which did not play a major role in the first stage are now the dominant factor controlling evaporation. The third stage is described as a slow decline in the rate of evaporation which is governed by the molecular attraction between soil and water.

Note that potential evaporation is a function of atmospheric conditions only (i.e., not dependent on soil conditions). A soil will evaporate at this rate only as long as the soil remains saturated at the surface.

Preferential Flow

Understanding preferred flow under unsaturated conditions is necessary for an understanding of capillary barriers used in the design of soil covers (Morris and Stormont 1997), design of lysimeters for monitoring soil cover performance (Bews et al. 1999) prediction of seepage from waste rock facilities (Swanson et a. 1998) and also, the prediction of ore recovery rates in heap leach piles (O'Kane 1999).

Consider the following question: Given the option, will water prefer to flow through a gravel or a clay? Based on an understanding of saturated flow, it is correct to assume that water will prefer to flow through the gravel (high saturated hydraulic conductivity) rather than the clay (low saturated hydraulic conductivity). However, with unsaturated conditions this assumption is not necessarily correct. The reason is that the hydraulic conductivity of a soil is not constant at the saturated hydraulic conductivity (highest possible value), but rather, the hydraulic conductivity decreases as a soil dries out (i.e., increase in soil matric suction). A better way to approach answering the question of whether water will prefer to flow through gravel or clay is to ask, what would make a better wick, a gravel or a clay?

To illustrate the counter-intuitive nature of water flow in unsaturated soils, preferential flow is illustrated in a similar manner as done by Newman et al. (1997). Consider a layered system of gravel and a fine sand subjected to a steady percolation rate as shown on Figure 8. The hydraulic conductivity function for the two materials is also presented on Figure 8.

The fundamental physical law describing the flow of water states that water flow occurs due to differences in hydraulic head. More specifically, water flows from high hydraulic head to low hydraulic head. This law, known as D'Arcy's law, applies to both saturated and unsaturated soils (Freeze and Cherry 1979).

At a percolation rate of 1 inch/year ($8x10^{-7}$ cm/s), the layered system of gravel and fine sand will equilibrate to the pore-water pressures shown on the hydraulic conductivity function on Figure 8. Water will flow from high pressure head to low pressure head; therefore, water flows from the gravel to the fine sand. For this range of pressures, it is apparent from the hydraulic conductivity functions that the finer material has the higher hydraulic conductivity, which occurs despite gravel having a much higher saturated hydraulic conductivity. This illustrates that under unsaturated conditions, one must think in terms of unsaturated hydraulic conductivity, and not saturated hydraulic conductivity.

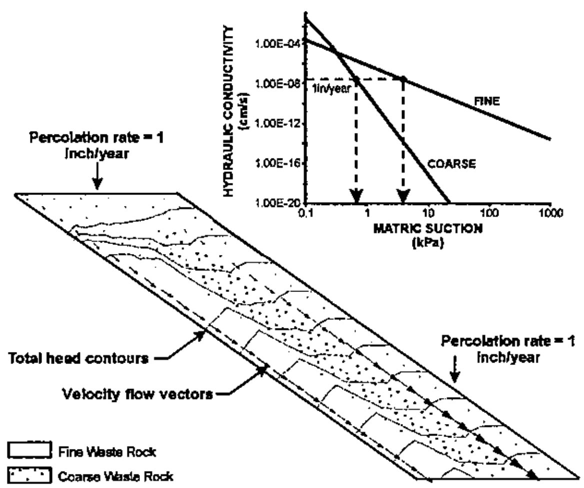

Figure 8. Preferential flow through layered waste rock

Capillary Barriers

The preferential flow concepts for unsaturated soils described above have seen practical application in mine waste management for many years. Consider the use of capillary barriers in soil cover design. If it were not possible for gravel to have a lower hydraulic conductivity than a clay, as illustrated in the previous example on preferential flow, capillary barriers would be of no use in soil cover design. A capillary barrier can consist of a layer of gravel placed below and/or above a compacted clay as illustrated on Figure 9.

A capillary barrier below the compacted layer will limit drainage from the clay and keep it saturated so that it acts as a barrier to oxygen diffusion (Yanful et al. 1994; Nicholson et al. 1989). A capillary barrier placed above the clay can also be used to reduce evaporation from the compacted layer.

Store-and-Release Covers

Soil cover design is climate specific and a common misconception in soil cover design is the use of compacted clay covers. Low-permeability barriers such as clay are not necessarily the most effective covers in dry climates (Swanson et al. 1997). This is due to the high potential for drying and cracking, which results in water bypassing the soil matrix (Morris et al. 1992; Daniel and Wu 1993). The end result can be a failed cover system.

In dry climates, covers designed to store and release water can be the most effective for the long term (Swanson et a. 1997; PTI and WESTEC 1996; GSM 1995). These covers often consist of a layer of native soil designed to store infiltrating waters in the root zone long enough to allow evapo-transpiration to remove the majority of water before it infiltrates into the waste (Figure 9).

PTI and WESTEC (1996) reported on a cover system consisting of 1.5 m of alluvium (silty, clayey gravel with sand) used to cover waste rock facilities at a site in Nevada. The U.S. EPA's HELP model was used to estimate infiltration rates through the cover once vegetation was established. Model results revealed that infiltration rates were likely to range from 0.3 to 7.9 mm/yr (0.1 and 3.9 percent of annual precipitation).

Similar infiltration rates were reported for a layered cover system consisting of 60 cm of topsoil (20% silt and clay, 15% sand, and 65% gravel) underlain with 60 cm of oxide waste rock (10% silt and clay, 10% sand, and 80% gravel) at a site in Montana (GSM 1995). Infiltration rates were predicted using three different hydrological models. Results showed that infiltration rates through the cover ranged from 2.5 to 6.3 mm/yr (GSM 1995). Model results were supported by moisture contents measured in field test plots over a three-year period.

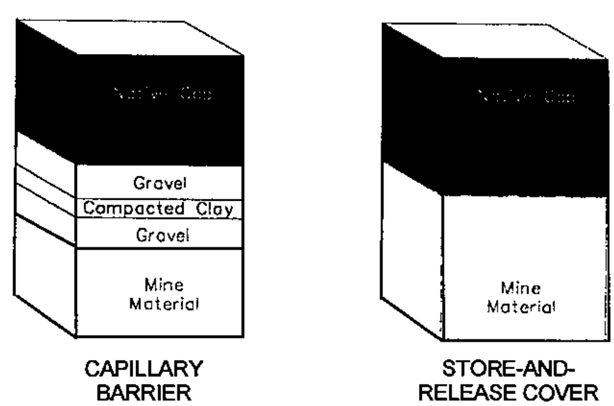

Figure 9. Capillary barriers and store-and-release cover designs

Wetting

Confusion regarding the term "field capacity" has occurred and is due to simplified definitions that the term has been given. As a simplification, field capacity is sometimes defined as the moisture content of a soil corresponding to 0.33 bars of negative pore-water pressure. This definition implies that "field capacity" is a fixed value for a particular soil type. The following examples illustrates how "field capacity" depends on the infiltration rate (i.e., climate) as well as the type of soil.

To study how an unsaturated soil wets, consider the scenario depicted on Figure 10. Fifty feet of silty sand is deposited above an impermeable base. The sand is deposited at a volumetric moisture content of 5 percent. The infiltration rate at the surface is constant at 1 inch per year. When may water begin to seep from the base of the sand?

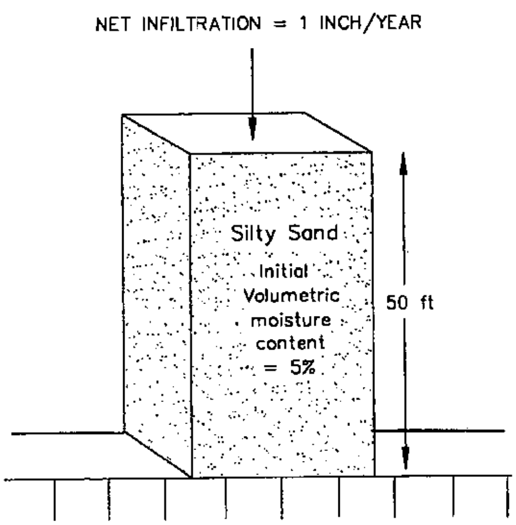

Figure 10. Example profile of sand to illustrate wetting

Depending on the moisture content of the sand, it is possible that water will seep immediately under the applied infiltration. If seepage did occur, it would not be the water that just infiltrated the surface, but rather, the seepage would consist of water at the bottom that is displaced by the infiltration (i.e., piston effect observed by Horton and Hawkins 1965). To determine if the sand wishes to drain or wet in response to the infiltration, the initial hydraulic state of the sand is first determined using the soil-water characteristic curve and the hydraulic conductivity function of the sand (Figure 11).

The initial moisture content of the sand is 5 percent, and is plotted on the soil-water characteristic curve on Figure 11. The hydraulic conductivity of the sand corresponding to this moisture content is approximately 1×10^{-13} cm/s. The sand prefers to come to equilibrium with the rate water is infiltrating, which is 1 inch per year (8×10^{-8} cm/s). The hydraulic conductivity of the sand is equal to the infiltration rate at this equilibrated state. The moisture content corresponding to this equilibrated state is approximately 11 percent. Therefore, the soil has a propensity to wet, and a wetting front will advance through the sand at a moisture content of 11 percent.

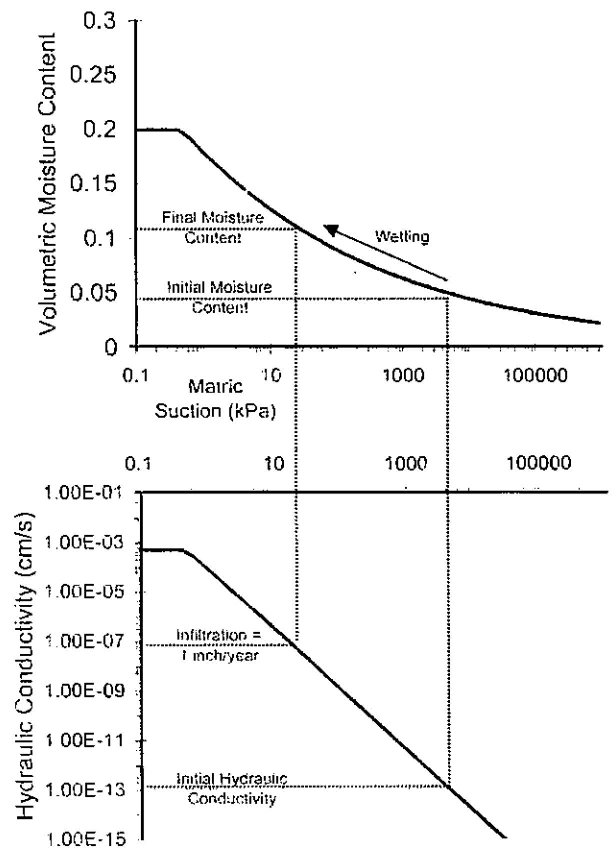

Figure 11. Estimating wetting moisture contents from the soil-water characteristic curve and hydraulic conductivity function.

The example considered here did incorporate the assumption that the wetting front is abrupt. This is a reasonable assumption for a relatively coarse soil such as the one considered because the hydraulic conductivity beneath the wetting front is very low (1×10^{-13} cm/s). If the soil were a fine silt or a clay, the wetting front would not be as abrupt, because the clay can hold water at high negative pore-water pressures and would likely have a much higher hydraulic conductivity beneath the wetting front.

Basal Inflow

A common oversight in the design of soil covers and prediction of seepage from waste rock facilities in dry and wet climates is not assessing the potential for basal inflow from groundwater and ephemeral surface water.

Failure of some soil cover systems has been assumed based on the observation that seepage was not reduced following placement of the cover. But, in fact, the seepage was due to groundwater flowing through the base of the facility. Time and money spent in determining the source of infiltrating water at the onset of a project (i.e., meteoric, groundwater or surface water inflow) will undoubtedly save time and money during closure of the facility.

Lateral and Vertical Seepage

Partitioning the long-term seepage at the base of the facility into lateral and vertical components requires a two-dimensional modeling approach (Swanson et al. 1998). Seepage at the base of the facility can be vertically downward under long-term conditions, despite a saturated hydraulic conductivity of the native foundation being several orders of magnitude lower than the waste rock. The basis for this potential seepage direction was discussed previously for preferential flow.

The partitioning of seepage at the base of the facility can be complicated by the coarse cobble zone that is typically present at the base of facilities due to segregation during end dumping. The coarse cobble zone may act as a capillary barrier under unsaturated conditions (slowing the percolation of water to the base of the facility), or as a drain if saturated conditions develop.

Pore-Water Velocity

A common misconception is assuming that infiltration from beneath the active soil zone equals the velocity of pore-waters migrating through the soil, when in fact, the pore-water velocity must account for the cross sectional area available for flow.

Actual pore-water velocity and the rate of infiltration are related by the volumetric moisture content as shown below (Guymon 1994; Maidment 1993). For example, if net infiltration from the active soil zone was equal to 1 inch per year, and the moisture content of the vadose zone was 10 percent, the average pore-water velocity through the vadose zone would be equal to 10 inches per year.

$$v = \frac{q}{\theta_v}$$

where:

v = Average pore-water velocity;
q = Net infiltration rate; and
θ_v = Volumetric moisture content of the vadose zone.

Water flow in soils will only occur through pathways that are filled with water. In other words, soil particles and air voids are barriers to flow and reduce the volume capable of transmitting water. If there were no soil particles or air voids, then 100 percent of space can be filled by water and pore-water velocity would equal the net infiltration rate.

Summary and Conclusions

An understanding of unsaturated flow is important for development and review of mine waste management designs. Unsaturated flow is counter-intuitive to saturated flow encountered in groundwater.

Some important points to note regarding unsaturated flow include:

- Actual evaporation from a soil surface is seldom equal to potential evaporation;
- Water may prefer to flow through fine textured materials rather than coarse textured materials;
- Compacted clay covers may not be effective in dry climates;
- Preferential flow paths need to be assessed when predicting the wetting of waste rock facilities. Preferential flow through coarse or fined textured materials is dependent on the net infiltration rate and the hydraulic properties of the waste rock;
- Seepage from waste rock facilities is quite often the result of saturated basal inflow from springs or ephemeral surface water, as opposed to infiltration of meteoric water;
- Seepage at the base of a waste rock facility may be vertical, lateral or both. Due to the relative difference in unsaturated hydraulic conductivity between waste rock and bedrock, a bedrock foundation does not

necessarily guarantee lateral seepage beneath the waste rock facility; and

- The pore-water velocity in the vadose zone (and within the waste rock facility) is *not* equal to the net infiltration rate, but rather, is equal to the net infiltration rate divided by the moisture content.

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