USE OF TENSION INFILTROMETERS FOR ESTIMATING UNSATURATED FLOW PROPERTIES OF MINE WASTES[1]

by
J.Mitchell Linne[2]

Abstract. Estimating the amount and rate of metals transport through the unsaturated zone in mine waste materials requires knowledge of the unsaturated hydraulic conductivity/moisture-content or the conductivity/water potential relationship of the material. This information can be obtained from the moisture characteristic curve (the relationship between moisture content and water potential) that describes the material. Current lab techniques for determining the moisture characteristic can be used in pressure range between 30 and 1000 millibars but require from weeks to months to obtain enough readings to construct a curve. Because of the length of time required to obtain enough readings or because of the cost of analysis, models or analytical calculations for predicting metals transport often are based on guesses of unsaturated conductivity values or on the assumption that infiltration reaches the water table immediately. These assumptions often lead to erroneous conclusions or excessive calibrations. This paper describes a technique developed by agricultural scientists for determining the soil tension (water potential)/conductivity relationship in the field using an infiltration test. A field capable tension infiltrometer can provide measurements of water infiltration rates for a material subjected to a particular tension up to about 15 millibars. The entire measurement process often takes less than 1 hour. Using this method, the unsaturated conductivity characteristics can be estimated at many locations across a site in a short period of time allowing for a thorough spatial characterization of the waste site.

Additional Key Words: unsaturated hydraulic conductivity, infiltrometer, contaminant transport

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[2]J. Mitchell Linne is a Hydrologist with the US Bureau of Mines, Western Field Operations Center, Spokane, WA 99208

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Introduction

Characterizing the transport of metal contaminants through the unsaturated zone in mine wastes requires an understanding of the unsaturated hydraulic conductivity of the waste material. The most commonly used method for obtaining this knowledge involves developing the moisture characteristic curve (the relationship between moisture content and suction). Data for construction of this curve are often obtained by pressure desorption of a saturated core. This method yields results for a range of water potential between 30 and 1000 millibars (the full range expected in the field) but often requires from weeks to months to obtain enough readings to construct a curve. The curve is used to interpret unsaturated conductivity relationships using one of a variety of schemes.

Because of the time required to get such results or the cost of analysis, models or analytical calculations for predicting metals transport often are based on guesses of unsaturated conductivity values or on the assumption that infiltration reaches the water table immediately. These assumptions can lead to erroneous conclusions or excessive model calibrations before reasonable results can be obtained.

A method recently was developed by agricultural scientists for estimating the soil-tension/conductivity relationship in the field using a type of infiltration test. A field instrument known as a tension infiltrometer can be used to measure the rate at which water will infiltrate a material at a particular tension. Although the infiltrometer only functions in the 0 to 15 millibar range, the time required for a complete run is approximately 30-60 minutes. Using this method the unsaturated conductivity/ tension relationship can be estimated at many locations across a site in a short period of time. Values for unsaturated conductivity at these locations provide a database for subsequent spatial characterization or for input to numerical models.

The tension infiltrometer only operates in the wet end of the water potential range so estimates for conductivities can only be obtained in this end of the tension range.

The purpose of this paper is to present the background and methods for use and application of the tension infiltrometer and to describe the results of a study of unsaturated conductivity on a mine waste site using this technology. The theory applied and necessary calculations are also presented.

Work is in progress which will explore applicability of this technique to the range of materials found in mining waste and to compare the results of infiltrometer investigations with those from desorption experiments using Tempe cells.

Previous work

As early as 1911 (Green & Ampt, 1911) soil scientists were describing the flow of water through unsaturated materials.

Innumerable articles have been published on the subject in soil science and hydrology periodicals over the last nine decades. Many soil physics texts and fluid flow texts also address the subject. Some of these articles and texts are listed in References. Field measurement of unsaturated fluid flow properties has been addressed in papers by Ankeny et al (1988, 1990, 1991), Clothier and Smettem (1990), Clothier and White (1981), Perroux and White (1988), Scotter and Clothier (1983), and White and Perroux (1987, 1989).

Theory

The theory and design for the tension infiltrometer are presented primarily in the articles by M. D. Ankeny and others (1988, 1991). To obtain values for hydraulic properties of unconsolidated materials, such as conductivity (K_h), matric flux potential ($\phi=K_h/\alpha$), and sorptivity, the rate, Q, at which water infiltrates the soil under a particular tension must be measured. The tension infiltrometer uses a Marriotte tube to deliver water to the soil surface under tension.

Woodings (1968) presented an algebraic approximation for saturated steady-state unconfined infiltration rates from a circular source:

$$Q = \pi r^2 K \left(1 + \frac{4}{\pi r \alpha} \right) \qquad (1)$$

Where Q is the volumetric infiltration rate at steady state, K is the hydraulic conductivity, r is the radius of the ring or disk within which the infiltration occurs (the radius of the infiltrometer head), and α is a pore-size distribution parameter. This expression applies for either saturated or unsaturated flow.

The saturated and unsaturated hydraulic conductivities are assumed to have an exponential relationship as proposed by Gardner (1958):

$$K(h) = K_{sat} \exp(\alpha h) \qquad (2)$$

Where h is soil tension, K(h) is tension-dependent conductivity and K_{sat} is saturated conductivity.

Replacing K in equation 1 with the expression from equation 2 we obtain:

$$Q(h) = \pi r^2 K_{sat} \exp(\alpha h)\left[1+\frac{4}{\pi r \alpha}\right] \qquad (3)$$

Using the tension infiltrometer we measure Q for several different tensions. For any pair of measurements, $Q(h_1)$ and $Q(h_2)$, the combination of the two individual flow equations (equation 3 for h_1 and h_2) yields an expression for estimating the pore-size distribution parameter, α:

$$\alpha = \frac{\ln\left[Q(h_2)/Q(h_1)\right]}{h_2-h_1} \qquad (4)$$

Using this value of α and the corresponding values for h_i and $Q(h_i)$ in equation 3, we can calculate a value for K_{sat}.

$$K_{sat} = \frac{Q_h}{\pi r^2 \exp(\alpha h)\left[1+\frac{4}{\pi r \alpha}\right]} \, cm/hr \qquad (5)$$

Entering values for K_{sat} and α in equation 2 we obtain a value for K(h). Using several values for h yields the graph (curve) showing the relationship between soil tension, h, and hydraulic conductivity, K_h. A computerized spreadsheet can be used efficiently to perform the necessary calculations, as shown by the example in Table 1. The details of calculations and an example calculation are presented in the appendix.

Other useful soil hydraulic parameters such as sorptivity and soil water diffusivity can also be derived from these relationships or from the flow and suction values measured. If the cumulative infiltration is plotted as a function of the square root of time, the slope of this line is the sorptivity. These parameters were not calculated in this study.

Materials and Methods

The tension infiltrometer used in this study is shown in Figure 1. It consists of a 20-cm diameter infiltration head that supplies water to the soil under tension from a Marriotte tube arrangement of a 5-cm outside diameter (OD) water tower and a 3.8-cm OD bubbling tower. The two towers each have a centimeter scale attached for reading water level or tension head. Three air-entry tubes in the stopper on top of the bubble tower are used to set the operating tension. All major parts are constructed of polycarbonate plastic, and the base of the infiltration head is covered with a very fine nylon mesh fabric. The infiltrometer used in this study is also equipped with pressure transducers at the top and bottom of the water column. These were used to more accurately measure the infiltration rate as described by Ankeny and others (1988). The transducers were connected to an electronic datalogger to allow for real-time data acquisition.

The first step in setting up the infiltrometer for a field test is site preparation. The infiltration site should be level bare soil. A fine sand (100 mesh) is used under the head to provide intimate contact between the head and soil. Site preparation may require grubbing of vegetation, removal of surface organic material, or scraping off an armored surface layer. It should be noted, however, that any disturbance of the soil surface may effect the hydraulic properties of the material. Enough area should be cleared to accommodate the head and towers because it is important to keep the base of the water tower at the same elevation as the head in order to maintain consistent tension settings.

A thin template with a 20 cm diameter hole or a very shallow ring is placed over the site and fine sand is placed in the hole and smoothed. When the template or ring is carefully removed, a thin, uniform layer of sand a few mm thick remains, providing good contact between the head and soil surface.

The second step is to submerge the infiltrometer head completely in water for several minutes to saturate the fine nylon mesh and remove all

Tension pair	alpha (1/cm)	Ksat (cm/hr)	Kh table h (cm)	Kh table Kh (cm/hr
h1-h2	0.1057	19.7824	-3	14.408
			-6	10.493
			-15	4.054
h2-h3	0.0254	5.0603	-3	4.689
			-6	4.344
			-15	3.456
h1-h3	0.0388	7.5405	-3	6.712
			-6	5.974
			-15	4.213

h (cm)	Kh Average	Std. Dev
-3	8.603	4.187
-6	6.937	2.601
-15	3.908	0.326

Site 2

Table 1. Example of site calculations from spreadsheet

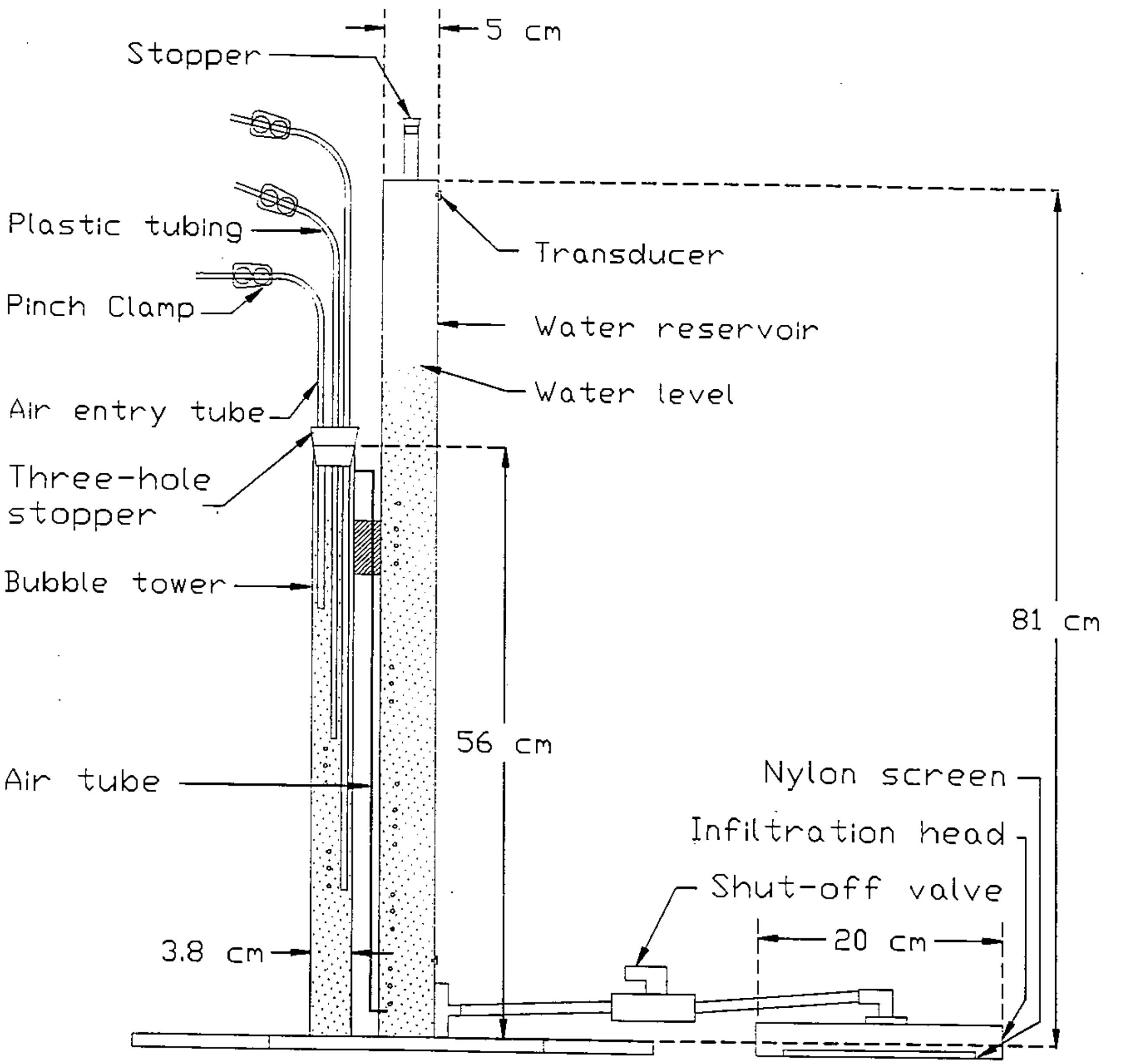

Figure 1. Schematic of Tension Infiltrometer

possible air bubbles in the head. Then, with the shut-off valve closed, the water and bubble towers are filled and the head is attached to the connecting tube under water in order to eliminate all air bubbles in the system.

Next, the unit is moved to the site and the infiltrometer head is placed on the thin layer of sand. In our experience using a dry 100-mesh sand, the best results are obtained by momentarily opening the top of the water tower with the shut-off valve open to initially wet the sand; this allows for a smoother transition toward steady-state infiltration. With the shut-off valve open, the air inlet tube representing the first tension (lowest if proceeding from low to high tension) is opened to initiate the test. Air will begin bubbling in the bubble tower and water will flow from the water tower through the head and in to the soil.

The rate of infiltration can be recorded in a variety of ways. The simplest is the recording of visual observations of water levels in the water column at regular time intervals using the attached centimeter scale. This can be difficult and imprecise if the water in the column is falling rapidly but is relatively "foolproof". Another method for recording the rate of infiltration is by use of a single pressure transducer or other pressure recording device at the top of the water column. The change in tension at this point in the water column is related to the change in water level (Soil Measurement Systems, 1992). Bubble formation at the bottom of the water column and the transit time of this bubble to the top of the column can cause great fluctuations in the tension recorded by one transducer at this location. By placing another transducer at the bottom of the water column and recording the difference between the readings of the two transducers, this fluctuation can be nearly eliminated (Ankeny et al., 1988). Before the transducer data can be used to record infiltration rate the transducers must be calibrated according to standard procedures (eg., OMNIDATA, 1992). Errors in calibration of the transducers can significantly affect the infiltration data so the manual method mentioned above should also be used on a few sites to verify accuracy. When using pressure transducers, the data from them should be recorded in an electronic datalogger for later interpretation.

By recording the pressure changes (i.e., height of water column) as a function of time, the point at which quasi-steady-state infiltration is reached can be estimated by noting a negligible difference in readings between sequential time steps. Experience indicates that this is reached near the time when ⅓ to ½ of the water column has drained. When steady-state has been reached, the air inlet tube representing this tension is closed. If most of the water column has drained the shut-off valve is also closed, the top of the water column opened, and the column refilled. (If the measurement began at low tension this should be the greatest amount to be used at this site.) The water column stopper is replaced, the shut-off valve is opened, and the air entry tube representing the next tension is opened. In operation we observed that the water level in the bubble tower did not remain static and so preset tensions were not always attained. At each setting the water level and the preset level were recorded so that actual tensions could be used in calculations.

This same procedure is followed for three different tension settings. During this test we began with the lowest tension setting and worked toward the highest. This provides complete wetting of the entire profile during the first setting. However, it does necessitate a short delay between settings to allow some draining. Figure 2 shows this wetting at the first setting. The figure also shows that significant drainage did not occur between the first and second or between the second and third settings. The time for a complete measurement is about 30 to 60 minutes. Steady-state infiltration rates for each tension are used in the equations given above to determine unsaturated-conductivity/tension relationships for each site. These estimates then can be used directly in a numerical model or treated statistically to obtain a composite value for use in an analytical equation for fluid flow or contaminant transport.

Case Study

Field testing for this type of tension infiltrometer was conducted on a large flotation tailings pile near Anaconda, MT. In the past the tailings were treated with crushed limestone spread over the surface. The limestone has partially reacted with the tailings to form a thin crust and more dense material several centimeters thick on top of the tailings. The material immediately under this surface layer consists of yellow to orange fine sand and silt with some clay. This material appears to be locally layered to a depth of 50 to 70 centimeters and probably consists of weathered semi-dry tailings. Layers are between one centimeter and 10 centimeters thick and vary only in color and silt content. At a depth near 70 centimeters the material is dark gray, nearly saturated, and appears to be unweathered tailings. This unweathered material may be many meters thick. Tire tracks from the limestone spreading equipment are present across the site and the color and density of material is different at sites (3 and 14) located on these tracks.

A sample area 20 meters by 30 meters (Fig. 3) was selected and 20 sites were chosen in an irregular pattern for use in spatial characterization. Data from five of the sites (1, 4, 18, 19, 20) were unusable because of equipment malfunction.

Summary and Conclusions

We make several assumptions in using this technique. One of the major ones is the relationship between saturated and unsaturated hydraulic conductivities described in the

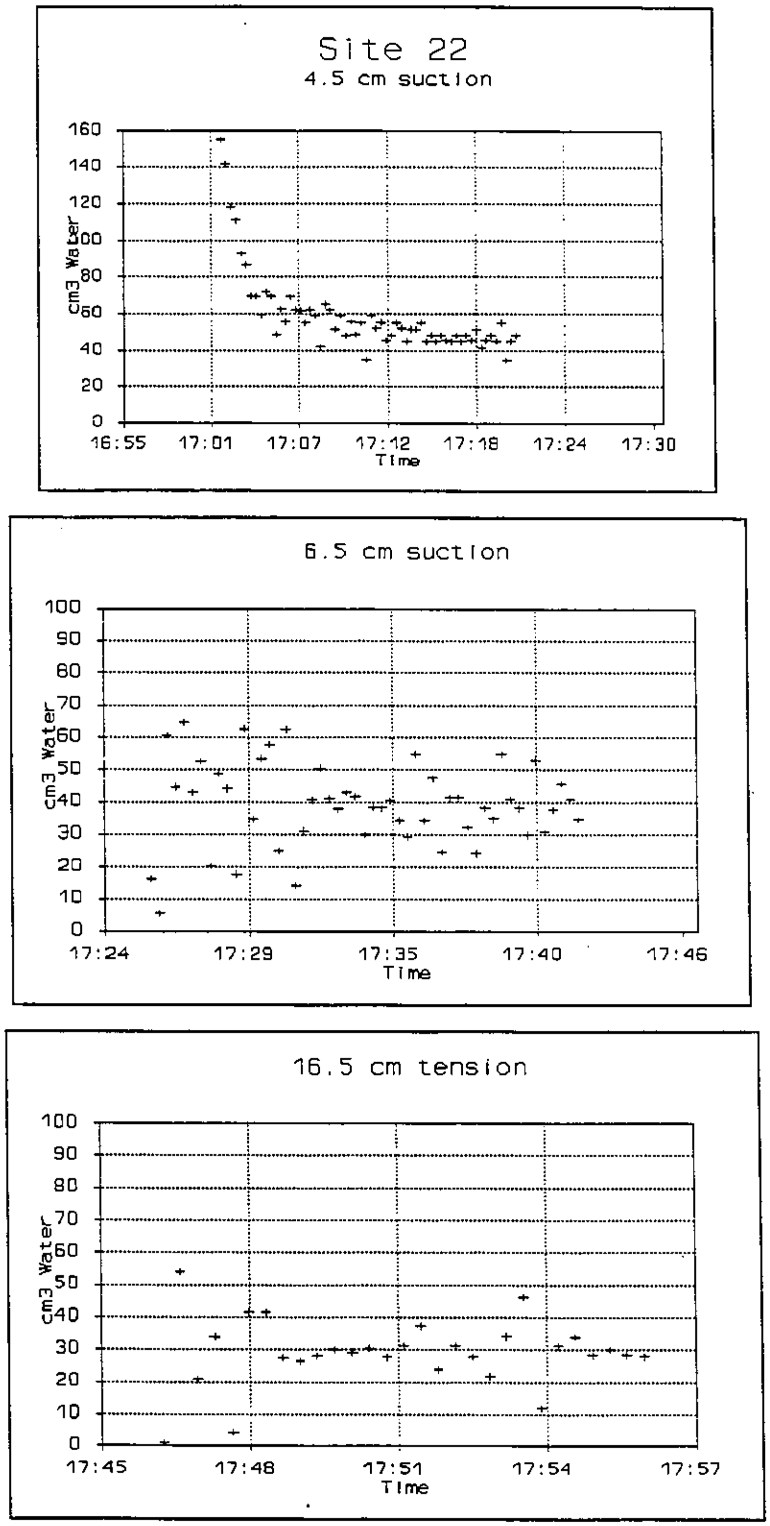

Figure 2. Example of flow graphs used to determine steady state

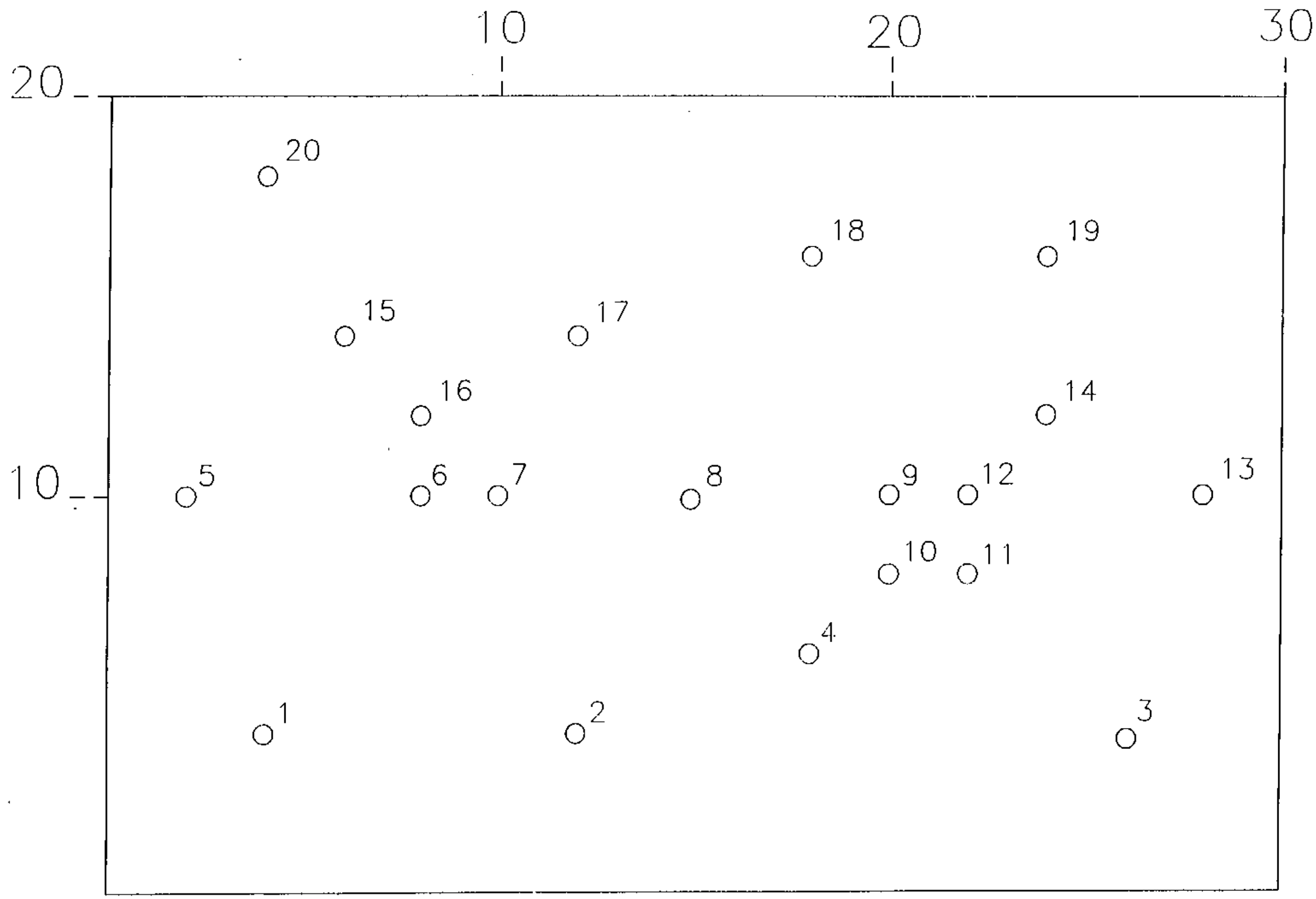

Figure 3. Sample grid

Theory section. Another is that the material measured, that is wetted by the infiltration bulb, is homogeneous and isotropic. The flow rate Q used in the calculations is a steady-state flow. The matric potential or suction must be constant.

Because the calculation scheme uses infiltration and tension values in pairs and three measurements were taken at each site, three sets of values are obtained at each site (Table 1). Table 2 shows the average values for K_h and the range of values for K_{sat} for the 15 sites evaluated. Because of the wide variation in values used in this average (the standard deviation is often as large as the mean) this may not be the most representative value. Generally the value obtained from the h_1 - h_3 pair is between that obtained from the other two pairs. This is also the value obtained over the widest range of tensions and may be a more representative value.

Because the flow measured in the tension infiltrometer method is dependent on tension setting, a sensitivity analysis was performed on the data from site 2. In order to determine the effect of a variation in one tension setting, the measured tension for the second setting was decreased by 1, 5, and 10 percent and the resulting change in calculated unsaturated conductivity was noted. As a further test, the values for tension 1 and tension 2 were each decreased by 1, 5, and 10 percent and the change noted. Table 3 shows the results of the sensitivity analysis.

Changing a single tension value by even a small amount appears to significantly affect some conductivity values. For example decreasing the second tension by 5 percent causes a nearly 13 percent increase in the -3 cm conductivity from the first pair. However, a simultaneous similar change in two tension values appears to change the resulting conductivity values very little.

The calculated K_{sat} values, although not representative of any measured value all appear to lie within the range expected for a fine-to-medium sand. In the future the results of this test will be compared with those from Tempe-cell analysis of samples from the same sites to help verify the validity of the method.

Although the tension infiltrometer can only function reliably in a narrow tension range near the wet end of the water potential range, this range is where contaminant transport can be expected to occur. Hydraulic conductivity at tensions greater than 15 millibars are negligible in terms of contaminant transport.

Field operation of the tension infiltrometer is fairly simple and can be partially automated. As many as 12 sites were measured in one day by one person familiar with the method using two infiltrometers equipped with pressure transducers connected to an electronic datalogger. However, setup and operation do require an understanding of the processes at work.

Station	Kh (cm/hr) Tension 3 cm	6 cm	15 cm	Ksat range cm/hr
2	8.60	6.94	3.91	5.06 - 19.7
3	16.13	9.05	2.93	6.88 - 75.5
5	1.71	1.53	1.10	1.82 - 2.03
6	9.73	7.17	3.32	6.17 - 24.5
7	27.83	9.93	3.32	7.32 - 281
8	14.49	10.31	4.56	8.91 - 39.1
9	4.06	2.80	1.19	2.27 - 12.2
10	23.93	15.00	5.33	11.6 - 87.8
11	12.05	6.47	1.01	21.2 - 24.3
12	0.89	0.73	0.42	0.809 - 1.96
13	11.91	8.50	3.70	7.42 - 32.2
14	1.91	1.08	0.36	0.209 - 9.22
15	1.04	0.62	0.15	.069 - 3.44
16	3.22	2.18	0.89	0.646 - 12.5
17	23.40	16.07	6.23	15.5 - 64.1

Table 2. Summary of Results

Tension Pair	Tension cm	Change in tension -1% in h2	-5% in h2	-10% in h2	-1% h1 & h2	-5% h1 & h2	-10% h1 & h2
	-3	2.54	12.94	31.24	0.28	1.16	2.12
h1 - h2	-6	1.37	6.33	12.66	-0.04	-0.51	-1.41
	-15	-2.07	-11.29	-28.73	-1.01	-5.37	-11.29
	-3	-0.61	-2.72	-5.37	-0.61	-3.23	-6.37
h2 - h3	-6	-0.56	-2.49	-4.91	-0.58	-3.02	-5.94
	-15	-0.39	-1.78	-3.58	-0.45	-2.33	-4.62
	-3				-0.43	-2.31	-4.62
h1 - h3	-6				-0.39	-2.11	-4.21
	-15				-0.27	-1.48	-3.00

Table 3. Sensitivity analysis - Percent change in conductivity

Calculations can be performed in a spreadsheet and results obtained within a matter of days.

Additional studies are planned to analyze the response of other mine waste types to this technique.

Appendix

EXAMPLE CALCULATION:

Using data collected for site #2 and the equations presented in the Theory section above, the following is an example of the calculations as performed.

Millivolt readings from each of the two transducers recorded in the datalogger were converted to a pseudo-height of water using a straight-line calibration developed in the lab:

Top transducer
(cm = 22.25 * mV + 23.34)

Bottom transducer
(cm = 21.37 * mV + 20.44).

The difference between the two height readings is the height of water. The datalogger records the millivolt readings at regular intervals (20 seconds). The difference between height of water at two adjacent time intervals multiplied by the cross-sectional area of the water tower gives the cm^3 of water which has flowed during this time interval. The flow in cm^3/sec is obtained by dividing this value by the time interval (20 sec.).

In order to determine the steady-state flow value for each suction setting, the cm^3 column was plotted vs. time (Fig. 2). The time period for which the flow values could be averaged was chosen from these graphs visually.

Using the values for the average Q at two of the three suction settings, and the suction values for these settings in equation 4 yields a value for α:

$$\alpha = \frac{\ln[6894/8517]}{-6.5-(-4.5)}\ cm^{-1}$$

$$\alpha = 0.105\ cm^{-1}$$

Substituting values for h_1 and Qh_1 in equation 5:

$$K_{sat} = \frac{8517}{3.141*100\ \exp(0.105*(-4.5)\left[1+\frac{4}{3.141\ *\ 10.0\ *\ 0.105}\right]}\ cm/hr$$

$$K_{sat} = 19.8\ cm/hr$$

Using this value for K_{sat} and each value for h (suction) in equation 2 yields a corresponding value for K_h.

These calculations are shown, for each pair of suction values, in table 1. Also shown are overall statistical parameters for this site.

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