Nordic Hydrology, 23, 1992, 193-208

No part may be reproduced by any process without complete reference

Evaluating the Effectiveness of a Mine Tailing Cover

Roger B. Herbert, Jr.

Dept. of Quaternary Geology and Hydrogeology
University of Uppsala, Sweden

This study presents a method for evaluating the effectiveness of a mine tailing cover. The cover is designed with a 0.5 m layer of clay covered by a 1.5 m layer of glacial till; full water saturation of the clay layer is assumed to be necessary for the maximal reduction of oxygen transport through the cover. The evaluation of cover effectiveness is based on: 1) the reduction of leachate production, and 2) the ability of the clay layer to remain water saturated and avoid cracking. Using 1990 precipitation data, the numerical model SUTRA simulates unsaturated flow in the cover, with results interpreted in terms of pressure head variations and vertical discharge from the cover. The modeling results indicate that this cover design would adequately reduce leachate production from a tailing deposit. In addition, the water saturation of the clay layer remains above its plastic limit during a simulated year of normal recharge conditions; it is therefore not likely that the clay layer would crack. A sensitivity analysis with different hydraulic parameter values is performed, and shows that leachate production is most sensitive to clay hydraulic conductivity, while the water saturation of the clay layer is sensitive to both clay hydraulic conductivity and till porosity.

Background

The province of Dalarna in central Sweden has been the location of many of Sweden's most productive sulfide ore mines. Alongside the recovery of metals from the sulfide ores is the production of large quantities of mill tailings. The tailings are the fine-grained remnants of the original sulfide ore, which are discharged from the mill to tailing dams after most of the metals have been extracted from the ores during the concentration process. These waste sands, however, may still contain significant concentrations of such sulfide minerals as pyrite (FeS_2), galena (PbS) or sphalerite (ZnS). The oxidation of these minerals leads to a decrease in pH of the soil solution and the release of heavy metals from the tailings. Investigations have shown that leachate from tailing dams and other mine waste deposits in Dalarna are major sources of cadmium, copper, lead, and zinc contamination in the region (Södermark 1986, Lundgren and Hartlén 1990).

The production of leachate can be significantly reduced, however, with the installation of a cover over the tailing dam. The release of heavy metals is facilitated by the diffusion of oxygen and the percolation of rainfall into the deposits, so a cover should be designed which hinders the effect of both these processes.

Because of the environmental and economic issues involved in the construction of a cover, it is necessary to evaluate the leachate reduction potential of a cover prior to it's installation. This study presents a method for evaluating the effectiveness of cover designs. Cover effectiveness is judged by: 1) the cover's ability to reduce general leachate production, and 2) the sealing layer's ability to remain water saturated and avoid cracking during periods of low recharge and high evapotranspiration. A numerical model is used to simulate the flow of water in the cover in response to recharge for one year. One result of these simulations is the generation of a 'leachate hydrograph', which is used to judge the leachate reduction capacity of the cover. In order to determine the sensitivity of the simulations to choices of the cover's hydraulic parameters (hydraulic conductivity and porosity), several model simulations with different parameter values are compared.

Previous Investigations

A number of authors have investigated the effectiveness of cover designs in reducing the oxidation of sulfides in mine tailings. Magnusson and Rasmuson (1983) studied the relationship between gas diffusivity and the water content of a soil cover. Their results showed that effective gas diffusivity decreases rapidly with increasing water content, indicating that the presence of a saturated layer within the cover would significantly reduce oxygen diffusion to the tailings. Lundgren and Elander (1986) discussed practical aspects of cover design, stating that cover effectiveness may be judged on the basis of annual leachate production; 50-100 mm/year is often considered an acceptable production level. Collin and Rasmuson (1988) reviewed different gas diffusivity models.

Numerical models have been used by many investigators (Collin 1987, Cartwright *et al.* 1988, Herbert 1991b, Krapac *et al.* 1991) as a means of simulating water movement in a cover. In general, one- or two-dimensional models of saturated/unsaturated flow simulate the infiltration and seepage of water through a cover, in order to compare the results to field-scale experiments (Cartwright *et al.* 1988, Krapac *et al.* 1991) or investigate the reduction of oxygen diffusion to the tailings (Collin 1987).

The model designed for this investigation strongly resembles the hillslope models of Johansson (1985) and Calver (1988), and the mine tailing cover studies of Collin (1987). The first two studies modeled saturated-unsaturated flow on a hillslope, and generated storm hydrographs. Johansson's study focused on the calculation of groundwater discharge to a stream during and after a rainfall event, while the study by Calver investigated the sensitivity of model simulations to changes in the main physical variables (*e.g.* hydraulic conductivity, porosity, and surface roughness). Collin (1987) performed a detailed investigation of pyrite oxidation and gas diffusivity processes that may occur in mine tailing covers, and presented a method for evaluating the efficiency of the soil covers to block oxygen transport.

None of these previous studies, however, have investigated the potential for the formation of cracks in the sealing material, which could cause the failure of the cover. This study uses numerical simulations to evaluate the cover's ability to reduce leachate production, and the clay layer's ability to remain water saturated and avoid cracking.

Modeling Methodology

Cover Design

A simple cover design is used in this study, consisting of a 0.5 m layer of clay covered by a 1.5 m layer of glacial till (Fig. 1). The clay layer functions as the main sealing barrier against the flow of water and oxygen to the tailings, while the till material hinders erosion of the clay. The cover is designed with two distinct surface gradients (0.005 and 0.02) and is symmetrical about a longitudinal axis, which serves as both a groundwater and surface-water divide. Because of this symmetry,

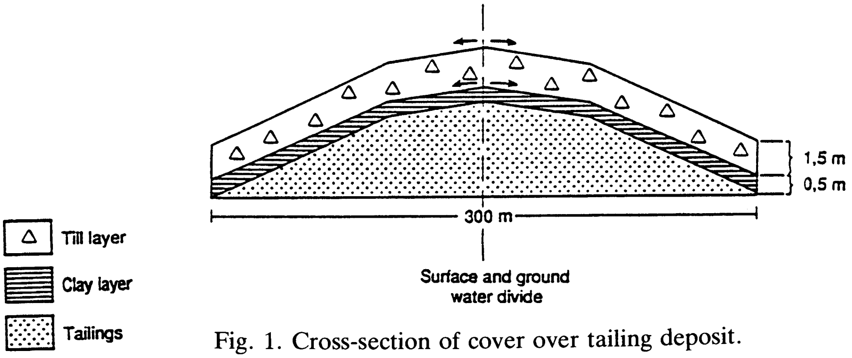

Fig. 1. Cross-section of cover over tailing deposit.

and for the simplification of calculations, half of the sealing layer is studied in cross-section, with a width of 150 metres and unit thickness. Many other cover designs are possible (*e.g.* Magnusson and Rasmuson 1983, Lundgren and Elander 1987, Cartwright *et al.* 1988, Krapac *et al.* 1991), but this design is a popular choice in Sweden, given the abundance of clay and glacial till. The effectiveness of similar designs have been tested in field-scale experiments (Markström and Börgesson 1988, Cartwright *et al.* 1988, Krapac *et al.* 1991).

The design of a mine tailing cover should be chosen so that leachate production is minimized. It is important that the sealing layer (clay) remain continually water saturated, so that the diffusion of oxygen and flow of water to the tailings is minimized (Magnusson and Rasmuson 1983). This is also vital since various sealing materials, such as clay or sewage sludge, may actually form cracks which could channel water to the tailings, if the materials remain unsaturated for a prolonged period of time. The hydraulic properties of the clay and till layers will determine if the cover will make an effective barrier.

Modeling Parameters and Functions

This investigation uses a numerical model which simulates the response of groundwater to variable recharge, and is capable of simulating flow under saturated and unsaturated conditions. The following parameters must be defined for the model simulations: water saturation, S_w, relative permeability, k_r, saturated hydraulic conductivity, K_s', and total porosity, ϕ. The saturated hydraulic conductivities used for the clay and till layers are chosen from values representative of these materials ($K_1 = 10^{-8} - 10^{-8}$ m/s and $K_2 = 10^{-5} - 10^{-9}$ m/s, respectively, see *e.g.* Freeze and Cherry 1979). The total porosity and water retention curves for these materials were obtained from investigations of Swedish soils (till from Høstmark *et al.* 1990, clay from Lindström and McAfee 1987). Mean total porosities of 0.55 and 0.40 and mean hydraulic conductivities of 10^{-9} m/s and 10^{-5} m/s were selected for the clay and till layers, respectively.

The model used in this study calculates solutions in terms of water pressure, p_w (kg/(m s^2)), which in turn is used to calculate the water saturation, described below. The pressure head, h_p, at any point in the cover can be defined as

$$h_p = \frac{p_w}{\rho_w g} \qquad (1)$$

where ϱ_w is the water density (taken as 1,000 kg/m^3), and g is gravitational acceleration (9.81 m/s^2); h_p is in metres.

The water saturation S_w of a soil is the ratio of the volume of water to the volume of voids. If a soil's pore spaces are completely filled with water, the soil has a water saturation of 100 % ($S_w = 1.0$); a soil is considered unsaturated if $S_w < 1.00$. Since the water saturation of a soil depends on the soil's water retaining properties, as reflected in the water retention curves for that material, a function is needed in order to calculate the water saturation for a given fluid pressure. The water saturation is calculated as a function of water pressure p_w as follows (van Genuchten 1980)

$$S_w \equiv S_{\mathrm{wres}} + (1-S_{\mathrm{wres}})\left[\frac{1}{1+(-a\,p_w)^n}\right]^{(n-1/n)} \tag{2}$$

where S_{wres} is the residual water saturation, below which the saturation is not expected to fall, and a and n are regression parameters. The water retention curves have been fitted to data published for Swedish tills and clays, as cited above, and are shown in Fig. 2a. The residual water saturation is taken as 0.04 for till and 0.715 for clay. The regression parameters a and n have been assigned the values 2.0×10^{-5} (m s^2)/kg and 2.00 for the clay layer, and 1.0×10^{-4} (m s^2)/kg and 1.55 for the till layer, respectively.

A soil's permeability, k, refers the ease with which a fluid may pass through the void spaces of that porous media. The permeability is independent of the properties of the fluid flowing within it; it depends solely on the properties of the soil matrix. If a soil is unsaturated, the pores are only partially filled with water, and the hydraulic connection between pore spaces is not complete. A material is then defined by a relative permeability k_r, which is a function of the soil's water saturation and represents a fraction of the saturated permeability, which is always greatest. Since the cover's water saturation will fluctuate with the variations in recharge, the relative permeability of the cover materials will fluctuate as well. The relative permeability is calculated as a function of water saturation (van Genuchten 1980)

$$k_r \equiv S_w^{*\frac{1}{2}}[1-(1-S_w^{*\,(n/n-1)})^{(n-1/n)}]^2 \tag{3a}$$

where $S_w{}^*$ is a dimensionless saturation given by

$$S_w^* \equiv \frac{S_w - S_{\mathrm{wres}}}{1-S_{\mathrm{wres}}} \tag{3b}$$

The k_r functions for till and clay are shown in Fig. 2b. Within the model, permeability is converted to hydraulic conductivity.

Hydraulic conductivity K is a measure of the resistance of the porous media to fluid flow through it. The hydraulic conductivity (m/s) is a function of the fluid's viscosity (μ) (kg/(m s)) and water density ρ_w, and can be calculated from the permeability

$$K_s = \frac{k\,\rho_w\,g}{\mu} \tag{4}$$

The hydraulic conductivity of an aquifer relative to water at 25°C is therefore numerically about 10^7 times larger than the permeability (in mks units).

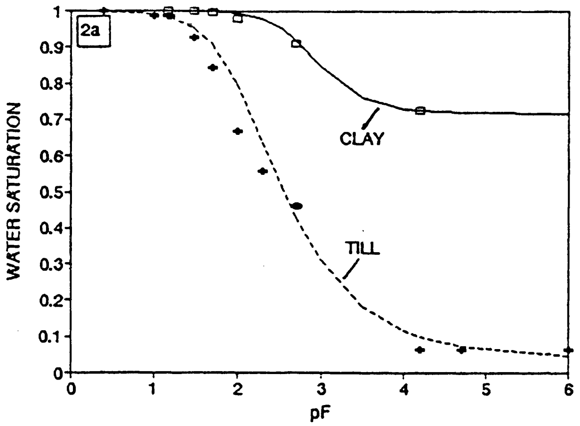

Fig. 2a. Water retention curves for glacial till and clay, fitted to experimental data from Høstmark *et al.* (+, 1990) and Lindström and McAfee (□, 1987). pF is the negative common logarithm of the pressure head, measured in cm.

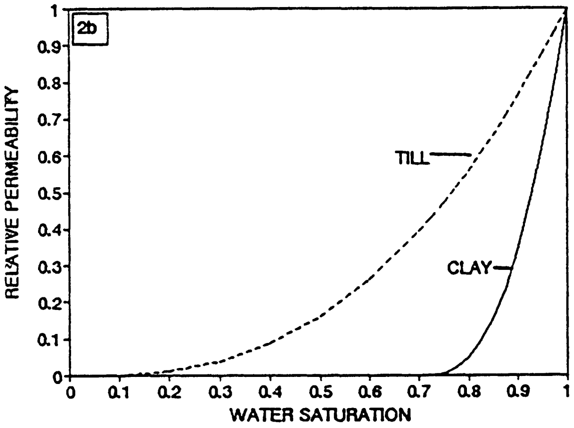

Fig. 2b. Relative permeability as a function of water saturation.

The net recharge to the cover is modeled as the sum of the precipitation and actual evapotranspiration. During the summer months of low rainfall and high evapotranspiration, this often leads to a net flow of water away from the cover. Actual evapotranspiration, E_a, is calculated as a function of the water saturation S_w on the surface of the cover (Karlqvist and Olsson 1983)

$$E_a = E_p \frac{S_w}{(S_{fc}-S_{wp})} \quad \text{if} \quad S_w < S_{fc} \qquad (5a)$$

$$E_a = E_p \quad \text{if} \quad S_w \geq S_{fc} \qquad (5b)$$

where E_p is an approximate mean value for the potential evapotranspiration (Eriksson 1981) for a year of normal recharge. S_{fc} and S_{wp} are the water saturation at the field capacity and the wilting point for the till material, respectively. It is assumed that S_{fc} is equal to the water saturation in the till at pF 2 (pF is the negative common logarithm of the pressure head, measured in cm) and S_{wp} at pF 4.2. According to the water retention curves shown in Fig. 2a, $S_{fc} = 0.79$ and $S_{wp} = 0.09$ for the till layer (Høstmark *et al.* 1991).

Recharge to the cover is simulated over the course of a whole year. Since it is assumed that the construction of a cover would take place during the summer months and finish in the autumn, the simulations begin with the month of October. It is assumed that there will be no recharge to the cover during the months December to March, when precipitation is stored as snow on top of the cover. During April, the snow melts at a constant rate during the entire month, in addition to the normal precipitation. The precipitation simulated in this study is taken from the rainfall record for the Ställdalen meteorological station in Dalarna for the year 1990 (SMHI 1990, data uncorrected for measurement errors caused by wind and evaporation). The Ställdalen meteorological station lies on the southern border of Dalarna, and its observations are assumed to be fairly representative of the climatic conditions over most of Dalarna. For the Ställdalen station, the total 1990 precipitation was 898 mm, while the mean for the period 1967-1989 was 725 mm (SMHI 1967-1989, data uncorrected).

Table 1 shows a comparison of monthly rainfall for 1990, the mean monthly values from 1967-1989, and monthly potential evapotranspiration. The values in Table 1 indicate that the 1990 measurements fluctuate significantly about the 22-

Table 1 – Climatic data from the Ställdalen station. Columns show sequence of days for simulations, mean monthly precipitation (mm) from 1967-1989, precipitation (mm) from 1990, and potential evapotranspiration (mm)

	Days	1967-1989	1990	E_p
October	1- 31	67	55	12
November	32- 61	67	60	1
December	62- 92	60	50	0
January	93-123	53	79	1
February	124-151	38	119	3
March	152-182	30	41	11
April	183-212	42	66	40
May	213-243	44	31	97
June	244-273	70	118	130
July	274-304	85	96	115
August	305-335	93	80	86
September	336-365	76	103	41
Total		725	898	537

year mean for several of the months. In this study, however, daily rainfall data is used, in order to observe the effect of rainfall 'spikes' on leachate production. The 1990 measurements are intended to be used as a basis for comparing many different simulations using the same recharge data, not as an absolute measure of yearly cover performance. The results from these simulations should not be considered representative of solutions for all years.

Crack Formation in the Clay Layer

Since the performance of the cover is partially evaluated on the ability of the clay layer to avoid cracking, it is necessary to be able to predict the pressure head, h_p, or water saturation, S_w, values at which cracks would begin to form in the clay layer. As a rough estimate, it is assumed that the clay layer would begin to crack when its water saturation falls below its plastic limit. At water saturations greater then the plastic limit, the clay has the property of flowing after a threshold stress has been exceeded. At water saturations lower than the plastic limit, the clay is friable, and may fracture after a threshold stress is exceeded. Pressure heads at the plastic limit have been reported in the range from -6 m to -10 m for clays (Croney and Coleman 1954, Greacen 1960, Towner 1987).

The formation of cracks has been studied by Towner (1987), who showed that kaolinite bars consistently cracked at essentially the same pressure head ($h_p = -18$ m); which was much below the plastic limit ($h_p = -6$ m) for that material. Based on Towner's investigation, it seems that the probability of cracking is very small above the plastic limit, with an increasing risk for cracking as the water saturation decreases below the plastic limit. If it is assumed that the plastic limit lies at $h_p = -6$ m, this corresponds to $S_w = 0.91$ for the clay used in this study (see pF = 2.78, Fig. 2a). Thus, if the pressure head in the clay layer remains greater than -6 m, the probability is small that the clay layer would crack.

The Flow Model

The saturated/unsaturated flow and solute transport model, SUTRA (Voss 1984), is used to simulate water movement in the mine tailing cover. The model uses a two-dimensional hybrid finite element and integrated finite difference method to solve the governing flow equations. The finite element mesh is designed with 861 nodes and 800 quadrilateral elements, with 20 elements aligned vertically in 40 element columns. The bottom five elements in each element column represent the clay layer, and the remaining 15 elements are till material. Such a relatively fine vertical discretization is required for unsaturated flow simulations since, as a rule, there should not be a water saturation difference of more than 0.1 between adjacent nodes in the model (Voss 1984). Node 615 is often referred to in this investigation; it lies on the boundary between the clay and till layer at the point where there is a change in the surface gradient. This node is chosen because it is most likely that the clay layer would become unsaturated first at this point. A pressure head of 1.5

m at node 615 would therefore signify complete saturation of the till layer.

The discharge of water from the cover will occur as vertical seepage through the till and clay layers and lateral flow on top of the clay layer, which discharges at the end of the cover into soil that surrounds the tailings. At the time of cover installation, the groundwater level in the tailing deposit will lie several metres below the ground surface. It is therefore assumed that the tailings closest to the cover will remain unsaturated after the installation of the cover, so that the water pressure in the uppermost part of the tailings will be slightly less than atmospheric pressure.

Boundary conditions have been assigned to the finite element mesh as follows: 1) the nodes along the bottom and left boundary are at atmospheric pressure; 2) the nodes along the right boundary lie on a groundwater divide, and are no-flow nodes; 3) the nodes along the top boundary are specified flux nodes. The SUTRA code has been modified to accommodate switching boundary conditions on the upper boundary (cover surface) during the simulations. If the groundwater table rises to the cover surface during a period of intense recharge, the boundary conditions will be locally switched to a constant pressure boundary (atmospheric pressure). Ponding and surface flow are not considered in these simulations. In Collin (1987), the boundary conditions along the lower boundary are assigned to simulate a capillary barrier effect, when this process is relevant, with no vertical flow into the tailings. However, since the clay layer will be completely saturated for the simulations in this study, such effects are ignored.

At the beginning of its operational period, the clay layer would be completely saturated, and the till layer would be mostly unsaturated. These initial conditions are obtained from a long-duration transient run (approximately 1000 years at a recharge of 62 mm/year) which has attained a steady-state position. The transient simulations are performed using 2.4 hour timesteps (10 per day).

Modeling Results

The numerical solutions to the saturated/unsaturated flow problem are presented with regard to pressure head variations at node 615 and vertical discharge from the cover. The vertical discharge from the cover was calculated every five days by the numerical model, and is reported in units of mm/day. For this study, leachate production from the mine tailings is estimated to be equal to the vertical discharge from the cover, which assumes that there will be no leachate sources or sinks in the tailings.

The results of the simulations using the expected porosity and hydraulic conductivity values are shown in Figs. 3a and 3b, which show pressure head and vertical discharge variations, respectively. The pressure head reaches a maximum in November following the autumn rains, and then decreases during the winter months (days 62-182) when there is no flux of water to the phreatic surface and

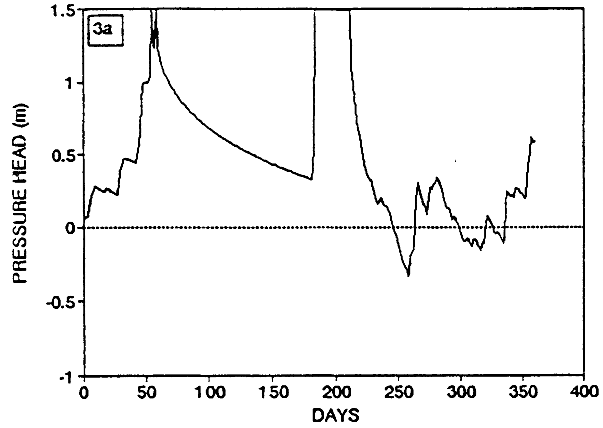

Fig. 3a.
Pressure head at node 615 for the mean model.

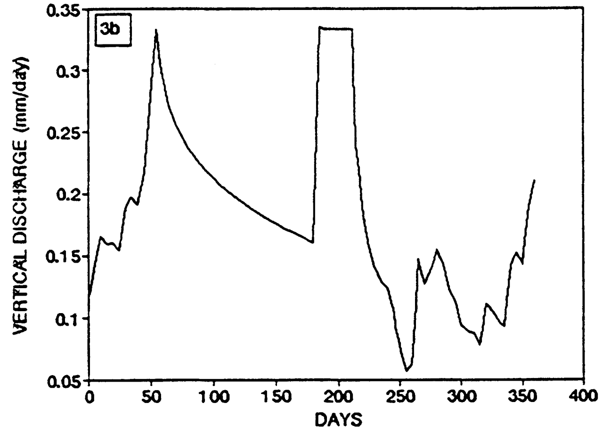

Fig. 3b.
Vertical discharge from the cover for the mean model.

water drains freely from the cover. The cover is completely saturated at node 615 during April when the snow on the cover melts. After the end of April (day 212), the pressure head at node 615 sinks rapidly, illustrating that evapotranspiration from the cover generally exceeds the rainfall during the summer months. As is expected, a comparison of Figs. 3a and 3b indicates that the fluctuations in vertical discharge closely follow the variations in pressure head, such that, for example, an increase in pressure head coincides with an increase in seepage through the cover.

Sensitivity Analysis of Parameter Values

In order to investigate the sensitivity of the numerical solutions to choices of the cover's hydraulic parameters, the results from the simulations using the expected hydraulic parameters are compared to the results for different till porosities (0.30 and 0.50) and clay conductivities (10^{-8} m/s and 10^{-10} m/s). For convenience, these five different cover models will be referred to by abbreviated names, as listed in Table 2. Since it is assumed that the clay layer will remain saturated during most of

Table 2 – Abbreviated titles for the simulations. For all simulations, $\phi_1 = 0.55$ and $K_2 = 10^{-5}$ m/s

Model	ϕ_2	K_1
Mean	0.40	10^{-9}
Low ϕ_2	0.30	10^{-9}
High ϕ_2	0.50	10^{-9}
Low K_1	0.40	10^{-10}
High K_1	0.40	10^{-8}

ϕ_1 = Clay porosity

$\phi_2 \equiv$ Till porosity

$K_1 \equiv$ Clay hydraulic conductivity

$K_2 \equiv$ Till hydraulic conductivity

the year, different clay porosities would not result in significant variations in leachate production. A previous investigation (Herbert 1991a) has shown that K_1 has a much larger effect on leachate production than K_2; the effect of different K_2 values on the model results are therefore not discussed in this study.

A comparison of the pressure head variations at node 615 for three different till layer porosities and three different clay layer conductivities are shown in Figs. 4a and 4b, respectively. In each case, the pressure head exhibits variations similar to the mean model. Although there is no significant overall difference between the three curves in Fig. 4a, the three cover models drain and reach saturation at different rates. Since the porosity of the till layer is related to its specific yield, a cover with a higher porosity becomes saturated more slowly than covers with lower porosities, and will likewise drain more slowly. However, the porosity of the till layer does not, to a large degree, affect the seepage of water through the clay layer.

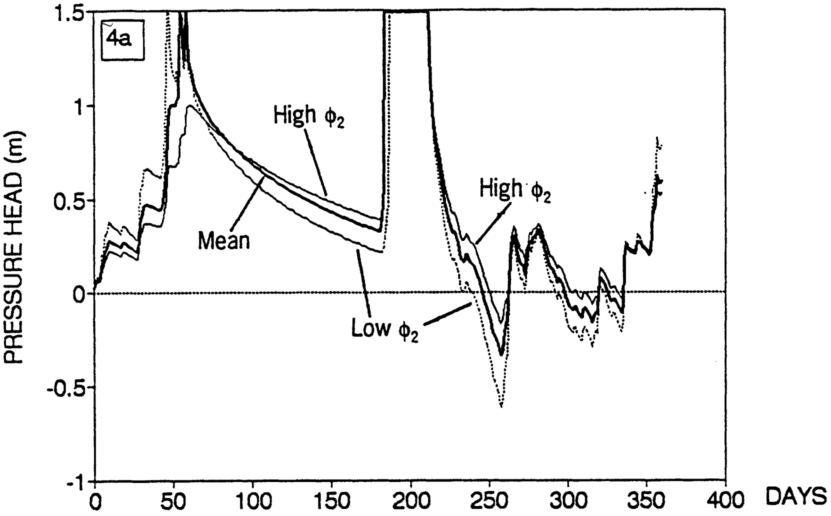

Fig. 4a. Pressure head at node 615 for mean, high ϕ_2, and low ϕ_2 models.

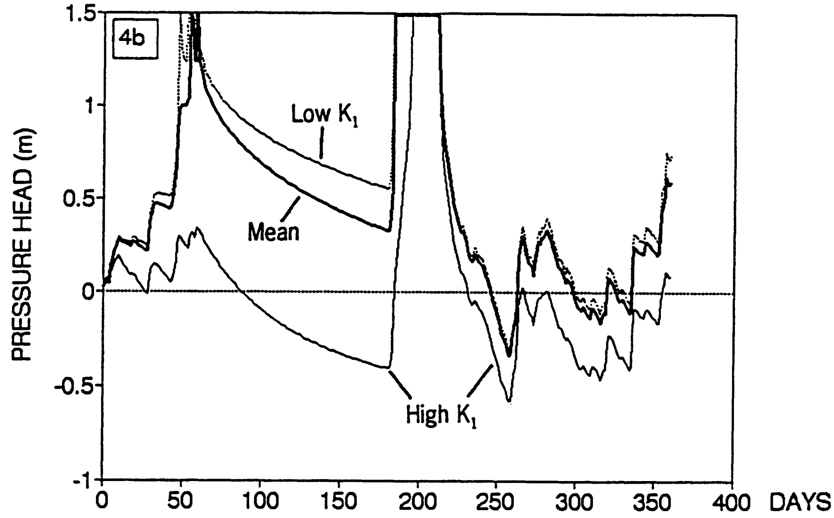

Fig. 4b. Pressure head at node 615 for mean, high K_1, and low K_1 models.

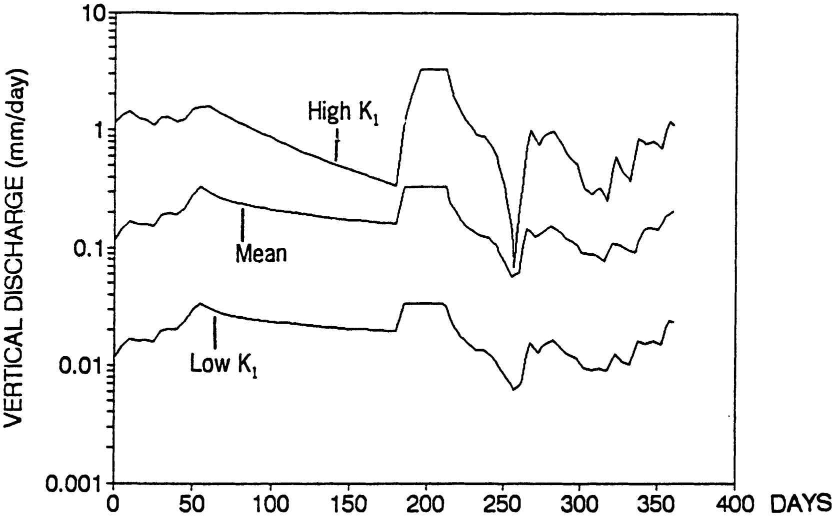

Fig. 5. Vertical discharge from the cover for the mean, high K_1, and low K_1 models.

The leachate production calculated for these three simulations is quite similar.

Pressure head variations from the high K_1 and low K_1 model differ significantly from the mean model, as shown Fig. 4b. The high K_1 model drains much more quickly than the two with lower K_1 values; the low K_1 model drains the slowest. Following day 212, the low K_1 and mean models are almost identical, while the high K_1 model shows that node 615 remains unsaturated during most of the summer and winter months. The high K_1 model permits a greater volume of water to seep through the clay layer, reducing the pressure head along the top of the clay layer to a much greater extent than either the mean or the low K_1 model. The vertical discharge calculated from these three simulations is presented in Fig. 5, which indicates that there is approximately an order of magnitude difference between the discharges of the low K_1 and high K_1 models and the mean model (vertical axis is logarithmic), and reflects the K_1 values chosen for the models. Since vertical discharge from the high K_1 model is ten times greater than the mean model and one hundred times greater than the low K_1 model, there would be an asymmetric distribution of the pressure head calculations about the mean model curve (see Fig. 4b).

Estimation of Leachate Production

Monthly calculations of leachate production are shown in Fig. 6 (vertical axis is logarithmic). Results are not shown for the low ϕ_2 and high ϕ_2 cover models since they are almost identical to the mean model results. Annual leachate production and leachate reduction for the five different simulations are shown in Table 3. Leachate reduction is calculated as leachate production divided by the net recharge to the cover (423, 415, 407, 447, and 440 mm/year for low ϕ_2, mean, high ϕ_2, high K_1, and low K_1 models respectively). Based on these calculations, the most signifi-

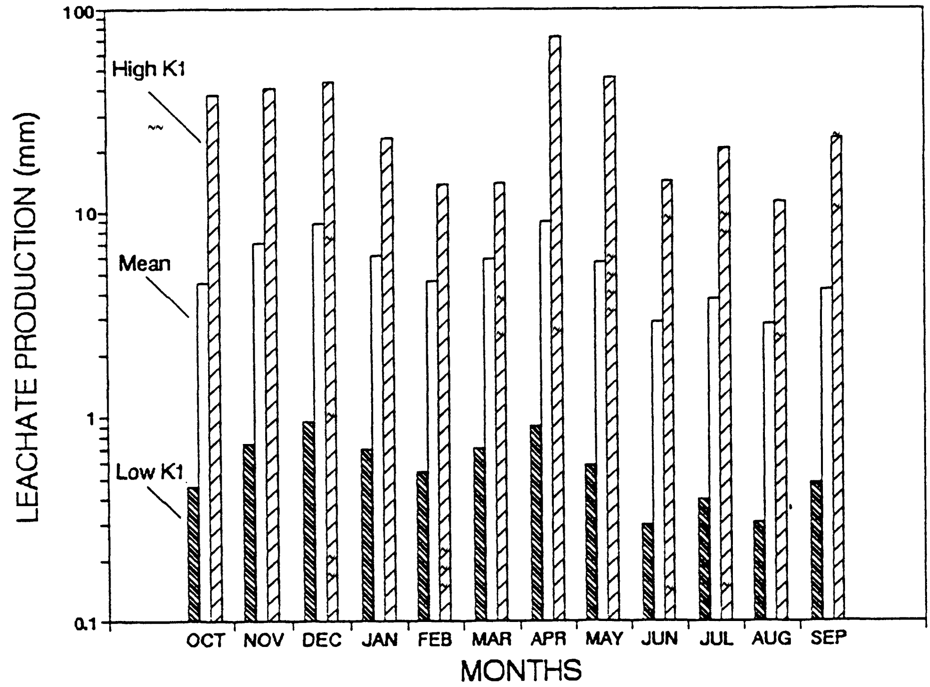

Fig. 6. Leachate Production for the mean, high K_1, and low K_1, models.

Table 3 – Annual leachate production for each of the simulations

Model	Leachate Production	Leachate Reduction
Mean	65.4 mm	84.1%
High ϕ_2	66.5 mm	83.7%
Low ϕ_2	63.0 mm	85.1%
High K_1	362.8 mm	18.8%
Low K_1	7.1 mm	98.4%

cant reduction in annual leachate production is with the low K_1 model ($K_1 \equiv 10^{-10}$ m/s), as expected. All of these leachate production estimates, with the exception of the high K_1 model, lie within the limits for 'acceptable' production levels discussed by Lundgren and Elander (1986).

Conclusions

This study presents a method for evaluating the effectiveness of cover designs. Cover effectiveness is judged on the reduction of leachate production and on the clay layer's ability to remain water saturated and avoid cracking. The maintenance of full saturation in the clay layer is assumed to be necessary for the maximal reduction of oxygen transport through the cover. The results indicate that the cover design using the expected porosity and conductivity values for the clay and till layers, respectively, can reduce the flow of water to the tailings by approximately 84 %. The clay layer unsaturates during the summer months for a total of 48 days, with single episodes of unsaturation of up to 21 days. The pressure head on the surface of the clay layer, however, never falls below -0.3 m. It is concluded that this cover design would adequately reduce leachate production, and would probably not fail (*i.e.* form cracks) during the dry periods.

The sensitivity analysis shows that the leachate production calculations are relatively insensitive to choices of ϕ_2, being mostly dependent on the value of K_1. The fluctuations in pressure head, however, reflect more strongly the different choices for porosity. In general, leachate production can be significantly reduced with low clay layer conductivities; a conductivity greater than 10^{-9} m/s is required to prevent excessive unsaturation of the clay layer and leachate production, as has been shown by Lundgren and Elander (1986). The duration of unsaturation of the clay layer can be reduced with high ϕ_2 values.

As shown in Figs. 4a and 4b, it seems that at least brief periods of unsaturation are unavoidable during the summer months, unless external methods are imposed to maintain saturation in the clay layer, such as irrigation of the cover. To maximize the performance of the tailing cover, a sealing material (*i.e.* clay, sludge, or bentonite) should be chosen which has a low hydraulic conductivity ($< 10^{-9}$ m/s) so that leachate production is reduced during periods of high recharge, yet is able to withstand extended periods of dryness without cracking. It is difficult, however, to actually predict the duration of unsaturation that a clay layer could withstand without failing, once the water saturation decreases below the plastic limit for that material. There is unfortunately little experimental data on the resistance of certain materials to drying and crack formation; if accurate predictions of cover effectiveness are to be performed, additional data must be acquired.

The actual simulation results from this study are only reflective of climatic conditions during 1990; the leachate production calculations should therefore be used only as a means for evaluating the effectiveness of different cover designs and parameter designations. If actual projections of future leachate production are desired, a geostatistical model could be applied which considers the recharge data as a random variable (see *e.g.* Destouni and Cvetkovic 1989, Gómez-Hernández and Gorelick 1988).

References

Calver, A. (1988) Calibration, sensitivity and validation of a physically-based rainfall-runoff model, *J. Hydrol., Vol. 103,* pp. 103-115.

Cartwright, K., and Larson, T., Herzog, B., Johnson, T., Albrecht, K., Moffett, D., Keefer, D., Stohr, C. (1988) Trench covers to minimize infiltration at waste disposal sites, Circular 541, Illinois State Geological Survey.

Collin, M. (1987) Mathematical modelling of water and oxygen transport in layered soil covers for deposits of pyritic mine tailings, Swedish Royal Institute of Technology, Department of Chemical Engineering, Licentiate Treatise.

Collin, M., and Rasmuson, A. (1988) A comparison of gas diffusivity models for unsaturated porous media, *Soil Sci. Soc. Am. J., Vol. 52,* pp. 1559-1569.

Croney, D., and Coleman, J. D. (1954) Soil structure in relation to soil suction (pF), *J. Soil Sci., Vol. 5,* pp. 75-84.

Destouni, G., and Cvetkovic, V. (1989) The effect of heterogeneity on large scale solute transport in the unsaturated zone, *Nord. Hydrol., Vol. 20,* pp. 43-52.

Eriksson, B. (1981) Sveriges vattenbalans, Årsmedelvärden (1931-1960) av nederbord, avdunstning, och avrinning, The National Meteorological and Hydrological Institute. RMK nr. 18. 30 pp. Norrköping (in Swedish).

Freeze, A., and Cherry, J. (1979) *Groundwater,* Prentice-Hall, Inc., Englewood Cliffs, New Jersey, USA.

Gómez-Hernández, J., and Gorelick, S. (1988) Influence of spatial variability of aquifer and recharge properties in determining effective parameter values, in: Consequences of spatial variability in aquifer properties and data limitations for groundwater modelling practice (Peck *et al.,* ed.), IAHS Publication No. 175.

Greacen, E. L. (1960) Aggregate strength and soil consistence, Trans. 7th Int. Congr. Soil Sci., Vol. 1, pp. 256-64.

Herbert, R. (1991a) Analytical and numerical modeling of water flow in a sealing layer, unpublished manuscript.

Herbert, R. (1991b) Numerical modeling of a sealing layer with water saturation requirements, *International Mine Waste Management News, Vol. 1(1).*

Høstmark, A-K., Breuning-Madsen, H., Lundin, L., and Riley, H. (1990) Water retention curves on Nordic till soils, from 'Hydrogeological properties of Nordic tills' (S. Haldorsen, editor), Nordic Hydrological Programme, NHP Report No. 25.

Johansson, B. (1985) Soilwater and groundwater flow on hillslopes – using a mathematical model, *Nordic Hydrology, Vol. 16,* pp. 67-78.

Karlqvist, L., and Olsson, T. (1983) Hydrological Conditions for the Reduction of Leachate Production, Statens Naturvårdsverk Report PM 1647 (in Swedish with English summary).

Krapac, I., Cartwright, K., Hensel, B., Herzog, B., Larson, T., Panno S., Risatti, J., Su, W.-J., and Rehfeldt, K. (1991) Construction, monitoring, and performance of two soil liners, Environmental Geology 141, Illinois State Geological Survey.

Lindström, J., and McAfee, M. (1987) Air and water movement in covers for mine wate, Department of Soil Sciences Report 153, Swedish University of Agricultural Sciences.

Lundgren, T., and Elander, P. (1986) Deposition of waste from coal and peat combustion, Swedish Geotechnical Institute Report No. 28 (in Swedish with English summary).

Lundgren, T., and Hartlén, J. (1990) Gruvavfall i Dalälvens Avrinningsområde, Swedish Geotechnical Institute Report No. 39 (in Swedish with English summary).

Magnusson, M., and Rasmuson, A. (1983) Transportberäkningar på vittringsförloppet i gruvavfall, Statens Naturvårdverk report PM 1689 (in Swedish).

Markström, I., and Börgesson, L. (1988) Provanläggning för undersökning av tät- och täckskikts funktion vid avfallsdeponering, Sveriges Geologiska AB, Rapport IRAP 88506 (in Swedish).

SMHI (The Swedish meteorological and hydrological institute) (1967-1990) data from the Ställdalen meteorological station.

Södermark, B. (1986) Gruvavall, Statens Naturvårdsverket Informerar No. 9019 (in Swedish).

Towner, G. D. (1987) The mechanics of cracking of drying clay, *J. Agric. Engng. Res., Vol. 36,* pp. 115-124.

van Genuchten, M. Th. (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, *Soil Sci. Soc. Am. J., Vol. 44,* pp. 892-898.

Voss, C. (1984) SUTRA: A finite-element simulation model for saturated-unsaturated, fluid-density-dependent ground water flow with energy transport or chemically-reactive single-species solute transport, United States Geological Survey, Water Resources Investigations Report 84-4369.

Received: 4 March, 1991
Revised version received: 31 January, 1992
Accepted: 11 May, 1992

Address:
Department of Quaternary
Geology and Hydrogeology,
University of Uppsala,
Box 555,
S-751 22 Uppsala, Sweden.