MASTER

Solute-travel Time Estimates for Tile-drained Fields

III. Removal of a Geothermal Brine Spill from Soil by Leaching ^{1/}W. A. Jury and L. V. Weeks ^{2/}

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ABSTRACT

The time required to leach a slug of saline, sodic geothermal brine from the point of injection to the tile outlet of an artificially drained field is calculated. Sprinkler, complete, and partial ponding leaching methods are compared as a function of drain spacing and initial location of the spill, with ponding requiring more water but less time to leach brine out of the system for all situations except where the brine spill occurs near the midpoint between tile lines. Calculation results are presented in dimensionless parameters which scale the drainage system dimensions and the soil water transport properties.

A simple calculation is proposed to estimate the volume of leaching fluid required to remove excess Na^+ from the exchange complex, and was found to be in good agreement with the results of laboratory soil column experiments. For fine-textured soils in the Imperial Valley of California it may require up to 30 pore volumes of leaching fluid to lower Na^+ concentrations if saturated gypsum solution is used in reclamation.

The results of these calculations suggest that reclamation of fine textured soils could require a prohibitive amount of time unless the brine spill is localized around a drain.

INTRODUCTION

Heat extraction from geothermal brines has been proposed as a future source of energy production in the United States, with a number of sites available in the Imperial Valley of California. The soils in this area are predominantly fine textured, and a substantial land area is under irrigation and is drained by artificial tile lines.

At present, little attention has been paid to the possible environmental and economic consequences of a brine spill in this area. The brines are highly saline and sodic and will be under high pressure in the pumping lines of any geothermal energy plant. A pipe rupture or well blowout could conceivably dump a large volume of brine on agricultural land adjacent to the well, and the land could be lost to production for a substantial period of time until the brine is leached from the soil. The purpose of this article is to estimate the time required to remove the spilled brine by artificial leaching as a function of the method of leaching, the properties of the soil, and the properties of the drainage system underlying the spill.

THEORY

Simulation of simultaneous transport of salt and water through a natural field soil may be attempted at different levels of sophistication. The most exact formulation involves solution of the simultaneous differential equations

Water Transport

$$\frac{\partial \theta}{\partial t} = \nabla \cdot (K \nabla (h+Z)) \quad [1]$$

where θ is volumetric water content (cm^3 solution/ cm^3 soil)

h is water pressure head ($\text{cm H}_2\text{O}$)

z is gravitational head ($\text{cm H}_2\text{O}$)

K is hydraulic conductivity (cm/day)

Salt Transport

$$\frac{\partial}{\partial t} (\rho_b S_a + \theta C) = \nabla \cdot [\theta D_e \nabla C - C J_w] - S_s \quad [2]$$

where C is salt solution concentration (meq/cm^3 soln)

S_a is adsorbed salt concentration (meq/gm soil)

ρ_b is soil bulk density (gm soil/cm^3 soil)

J_w is water flux (cm^3 soln/ cm^2 soil/day)

D_e is the effective diffusion-dispersion coefficient (cm^2/day)

S_s is a generalized reaction term ($\text{meq/cm}^3/\text{day}$)

Equations [1] and [2] require further information before they can be solved. Values must be furnished for K , $h(\theta)$, D_e , S_a , ρ_b , and S_s as functions of x , y , z , t , and C . Furthermore, S_a and S_s and D_e depend on the concentration of individual ionic species as well as on the total electrolyte concentration C .

1 Under certain conditions it may be possible to obtain sufficient
2 data to solve [1] and [2] with reasonable accuracy. However, for the
3 vast majority of applications only a small amount of data will be avail-
4 able to characterize the soil physical conditions (K , $h(\theta)$, ρ_b) and even
5 less will be available to characterize solute transport (S , S_s , D).
6 For this reason we have chosen to analyze an ideal system in order to
7 estimate the residence time of a brine injection under continuous leach-
8 ing, as a function of a set of scaled parameters which will simul-
9 taneously represent solutions to a variety of soil, drainage, and
10 management conditions. The assumptions used in solving our simplified
11 system are as follows:

12 1) Soil physical conditions $K(h)$, $h(\theta)$, ρ_b are isotropic and
13 homogeneous from the surface to a depth H where an impermeable barrier
14 blocks any further vertical drainage.

15 2) Water is artificially drained from this system by a set of
16 long, parallel tile lines of radius r , spaced a distance $2s$ apart and
17 buried at a depth d below the soil surface.

18 3) Water flow from the leaching process is assumed to be in
19 steady state throughout the system. The starting time for the simu-
20 lation will have a brine spill located at some shallow depth in the
21 soil.

22 4) Salt precipitation, dissolution, and ion pair formation are
23 negligible during the simulation.

24 5) Diffusion and dispersion influences on salt transport are
25 small relative to convective transport by solution.
26
27

6) Cation exchange will be superimposed on transport using a simple chromatographic column model.

None of these assumptions will be rigorously correct in a real system. However, residence times calculated for this ideal system will be useful for determining the influence of various parameters on salt movement. Further, calculated leaching times should be representative of those for more complex systems unless extreme soil heterogeneity is encountered.

Description of the model

The assumptions of steady state water flow, isotropic and homogeneous soil, and long parallel tile lines reduce Eq. [1] to

$$\frac{\partial}{\partial X} \left[K(h) \frac{\partial h}{\partial X} \right] + \frac{\partial}{\partial Z} \left[K(h) \left(\frac{\partial h}{\partial Z} + 1 \right) \right] = 0 \quad [3]$$

Boundary conditions for this equation common to all problems are:

- 1) No vertical water flow across the barrier at $Z = -H$

$$\frac{\partial}{\partial Z} [h+Z] = 0 \quad [4]$$

- 2) Symmetric tile lines located at $X = 0, \pm 2S, \pm 4S, \dots$
and $z = -d$

$$a) \frac{\partial h}{\partial X} = 0 \quad X = 0; -(d-r) \leq Z \leq 0, -H \leq Z \leq (d+r)$$

$$b) \frac{\partial h}{\partial X} = 0 \quad X = S; -H \leq Z \leq 0 \quad [5]$$

3) Tile lines open to the atmosphere and running 1/2 full

$$h + Z = 0 \quad x^2 + (Z+d)^2 \leq r^2 \quad [6]$$

Conditions at the soil surface depend on the method of leaching.

We consider three irrigation methods in our calculations

1) Sprinkler irrigation over entire tile unit at rate

$$R \text{ cm}^3/\text{cm}^2/\text{day}$$

$$\text{B.C. 4) } -K(h) \left[\frac{\partial h}{\partial Z} + 1 \right] = R \quad -S \leq X \leq S; Z = 0 \quad [7]$$

2) Ponded water to height ϵ over entire tile unit

$$h = \epsilon \quad -S \leq X \leq S; Z = 0 \quad [8]$$

3) Ponded water to height ϵ over part of the surface

a) directly over tile

$$h = \epsilon \quad -b \leq X \leq b; Z = 0$$

$$-K(h) \left[\frac{\partial h}{\partial Z} + 1 \right] = 0 \quad -S \leq X \leq b, b \leq X \leq S; Z = 0$$

b) midway between tile lines

$$h = \epsilon \quad -S \leq X \leq -S+b, b \leq X \leq S; Z = 0$$

$$-K(h) \left[\frac{\partial h}{\partial Z} + 1 \right] = 0 \quad -S+b \leq X \leq S-b; Z = 0 \quad [9]$$

Sprinkler leached systems

Since we are calculating convective solute transport, it is necessary only to determine the water flow streamlines in order to estimate salt movement. Kirkham (1958) calculated streamlines in the saturated region below the water table for the steady surface flux case (eq. [7]) assuming that water flow was vertical between the tile lines. Jury (1974a, b) used the Kirkham solution along with the assumption that the time required to reach the depth of the tile lines d from the surface was

$$t = d \theta_u / R \quad [10]$$

where θ_u is the average unsaturated volumetric water content between the surface and the tile lines. Streamlines for this system are shown in Fig. (1).

The travel time for an inert solute injected at the surface between two adjacent streamlines to reach the tile line is calculated by determining the volume of water required to replace the water contained in the stream tube bounded by the two streamlines. Jury (1974a, b) produced a dimensionless travel time solution $T = Rt/\theta_s S$ where θ_s is saturated water content as a function of the surface injection point x/S and the drain half spacing to barrier depth ratio $\eta = S/D$ where D is the distance from the tile to the barrier. This solution is shown in Fig. 2, assuming $S/d = 20$ and $\theta_u = .75 \theta_s$. A further restriction for this system is the requirement that the maximum water table height remain below the surface. If we restrict the water table height above the

drain depth to $0.8 d$ at the midpoint between lines, then the water table height equation in Kirkham (1958) may be used to calculate maximum allowable values of R/K_s as a function of d , D , S , and r . A plot of R/K_s vs. S and η is shown in Fig. 3, assuming $r = 10$ cm and $d = 200$ cm. Figures 2 and 3 may be used together to calculate travel time for sprinkler leached inert solutes as a function of S , D , θ_s , and K_s .

Ponded systems

Fully ponded systems differ from the steady rate systems above in that the entire soil profile is saturated and that the infiltration rate at the surface varies as a function of distance from the tile. Kirkham (1950) published an analytic solution to steady state ponding of a tile system with a uniform barrier at some depth below the tile. Figure 4 shows streamlines calculated from this solution for the case $d = D = S/5$. As part of his analysis, Kirkham (1950) calculated infiltration rate along the surface and total discharge into the tile as a function of the soil and drainage characteristics. For the geometry shown in Fig. 4, the surface infiltration rate drops off sharply away from the tile, as shown in Fig. 5. The explanation for this nonuniform infiltration rate is that with a continuous liquid phase through the system most of the water enters the surface near the tile where the hydraulic head gradients are largest. For example, the system in Fig. 4 and 5 receives 88% of the water from locations within $X = \pm S/2$ of the drain.

The total discharge Q from the tile is a complex function of r , S , d , D , and K_s . Assuming $r = 10$ cm and $d = 200$ cm, Fig. 6 gives

values of Q/SK_s for various combinations of r/S , d/S , and d/D . By combining Fig. 5 and 6, the infiltration rate between adjacent streamlines in Fig. 4 may be estimated and the travel time calculated similarly to the sprinkler case.

Partial ponding system

Solutions to eq. 1 and 9 were obtained for steady water flow by the finite element method adapted from Reeves and Duguid (1975). Calculations were made for spills of 400 cm along the surface for drain spacings of 1000 and 2000 cm, tile depths of 120 cm, barrier depths of 240 cm and drain radius of 20 cm. Three soil types were used in the simulation; Pachappa sl, Panoche ls, and Chino cl, with saturated hydraulic conductivities of 1.65, 0.80, and 0.08 cm/hr, respectively. All streamlines and dimensionless infiltration rates fell on the same curves to within 5% for all soils so that a single calculation would serve for all systems. Figure 7 shows streamlines for the case of $\eta = 1.2$ and Fig. 8 is the corresponding dimensionless infiltration rate i/K_s . Travel times are calculated in the same way as for the ponded system.

Reclamation times

The ionic composition of a number of wells where geothermal plants are proposed or operating is shown in Table 1. The Sinclair well in the Imperial Valley is extremely high in Na^+ , so that a spill of this composition would be likely to saturate the exchange complex with sodium

over the entire flow path from spill site to drain. To reduce exchangeable sodium levels to the point where soil properties will not be adversely affected will require an applying amount of Ca^{++} sufficient to replace the sodium. As indicated by Bolt and Bruggenwert (1976), an approximate estimate of the number of pore volumes of a solution containing a concentration Ca^{++} meq/cm³ solution is $N = Q / \theta \text{Ca}^{++}$ where θ is the volumetric water content and Q is the cation exchange capacity in meq/cm³ soil.

EXPERIMENTAL DESCRIPTION

A soil column 30 cm high and 80 cm² surface area was packed to a uniform bulk density of 1.5 gm/cm³ with Pachappa sandy loam soil (CEC = 8 meq/100 gm). The column was initially saturated to a volumetric water content 0.40 with a saturated NaCl solution ($\text{Na}^+ = 3000$ meq/l) and leached with a concentrated gypsum solution ($\text{Ca}^{++} = 30$ meq/l). Drainage water was analysed periodically for Ca^{++} and Na^+ . The experiment was later repeated with various concentrations of CaCl_2 as the leaching solution.

RESULTS

Table 2 gives the travel time from various points along the surface in days calculated for the three leaching methods for the following geometric and soil characteristics: $d = 200$ cm, $D = 200$ cm, $S = 2000$ cm, $r = 10$ cm, $K_s = 5$ cm/day, $\theta_s = 0.5$, $\theta_u = 0.375$. These

parameters are representative of many California tile systems and soil properties in the Imperial Valley (Jury, 1974b).

Several points may be made from this table. First, with the exception of ponded leaching near the tiles, travel times are prohibitively long for this system, even assuming perfect leaching efficiency. Second, full field sprinkler leaching requires longer to remove salt than either of the other two methods, except at extreme distances from the tile where full field ponding requires longer leaching times. This is a result of the requirement that the water table remain below the surface in the sprinkler irrigated system.

Table 3 gives travel times for a narrower tile spacing of 2000 cm, with all other characteristics the same as in Table 2. The pattern is similar to Table 2, except that the fully ponded system travel times do not increase as much at lateral distances from the tile. In both cases the partially ponded system is able to remove salt more rapidly at distances far from the tile.

Leaching experiment

The column experiment with Pachappa sandy loam ($\text{CEC} = 8 \text{ meq}/100 \text{ gm}$) was set up to test the validity of eq. 11 for estimating the number of pore volumes required to remove Na^+ from the exchange complex. Figure 9 shows Ca^{++} and Na^+ concentrations in the column effluent as a function of the number of pore volumes drained. The arrow at 11 pore volumes marks the point at which Eq. 11 predicts removal of the Na^+ ions. The sharp decrease in Na^+ concentration after one pore volume corresponds to the leaching of all excess salt from solution, after which the

1 concentration, but not the composition of the effluent is similar to the
2 leaching solution. The decrease of Na^+ and corresponding increase of
3 Ca^{++} occurring before 11 pore volumes of solution were added may be a
4 result of mixing occurring in the column, as suggested by Nielsen and
5 Biggar (1967).

6 Figure 10 shows Ca^{++} and Na^+ concentrations in the drainage water
7 when CaCl_2 is used as the leaching solution in successive concentration
8 ranges of 1200 meq/l for 2.5 pore volumes, 30 meq/l for 2.3 pore volumes,
9 and 8 meq/l for 4.1 pore volumes. In this case the Na^+ concentration
10 has dropped to an acceptably low level after 5 pore volumes, or about
11 1/2 as much leaching solution as in the experiment with saturated gypsum.
12 As before, the arrow indicates the point at which sufficient solution
13 has been added to replace and leach all Na^+ out of the column. In this
14 case the exchange efficiency is considerably less than perfect, and high
15 Ca^{++} concentrations appear in the drainage before all Na^+ has left the
16 column.

17 Many of the soils in the Imperial Valley are high in clay content
18 and have a large cation exchange capacity. If we assume a $\text{CEC} = 30$
19 $\text{meq}/100 \text{ gm}$ $\theta_s = 0.5$, and use saturated gypsum as the leaching solution,
20 eq. 11 predicts that 30 pore volumes of influent will be required to
21 replace the Na^+ on the exchange complex, assuming perfect efficiency.
22 In this case, all time estimates in Tables 2 and 3 should be multiplied
23 by 31 to give the time required for reclamation of the affected soils.
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26
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DISCUSSION

The results of this investigation indicate that a prohibitive amount of time would be required to reclaim heavy soils under tile drainage following an accidental spill of geothermal brine, unless the spill was confined to the immediate vicinity of a drain. The economic consequences of such a spill will depend on the productivity of the affected land, and this in turn will influence the options possible in reclamation. For example, it may be worthwhile to install additional drain lines in the vicinity of the spill at the time of reclamation to aid in the removal of the brine. Furthermore, the time saved in using a concentrated source of Ca^{++} ions such as in the CaCl_2 leaching solution may more than offset the increased expense of the salt used in reclamation. Finally, the leaching methods examined in this study do not exhaust the possibilities for reclamation methods. Talsma (1967) found that cycles of alternate ponding and drainage without irrigation leached the region far away from the tile more effectively than full ponding. However, this method is also limited by the time required for recession of the water table following cessation of ponding. We may estimate this time from the Glover equation (Van Schilfgaarde, 1974)

$$t = \frac{4f \ln (4d/\pi m) S^2}{\pi^2 K_s (D + d/2)} \quad [12]$$

where f is drainable porosity, m is final height of water table above drain height, t is time required for the water table to fall from the

1 surface $Z = d$ to a depth $Z = m$ above the tile, and other symbols have
2 been defined above. Assuming the properties used in Table 2 and f
3 $= .125$, $m = 100$ cm, we calculate $t = 126$ days for the water table
4 to fall from the surface to a depth of 100 cm. Since at most one
5 pore volume may be passed during this falling process, we are still
6 faced with a prohibitive reclamation time.
7

8 It should be noted, however, that the times calculated in this
9 article are for complete removal of the brine to the drain. Partial
10 reclamation may be possible by clearing the top 100 cm of salt,
11 which would require considerably less time than the estimates given
12 in Tables 2 and 3. However, this situation would open up the possi-
13 bility of future permeability degradation if water of moderate con-
14 centration interacted with the salt still in the soil (McNeal, 1968).
15 Furthermore, upward flow could redeposit the salt in the root zone.

16 Not covered in this investigation is the possibility of irre-
17 versible chemical weathering or organic matter deterioration resulting
18 from the interaction of the brine with the soil. This problem should
19 receive future study.
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Table 1. Composition of Some North American Geothermal Brines

Component or property	Brine Source/Content (ppm)				
	Shell No.1 (Ca, USA)	Shell No.2 (Ca, USA)	Cerro Prieto (Mexico)	Mesa 6-1 (Ca,USA)	Sinclair No.4 ⁺ (Ca, USA)
Sodium	53000	47800	4450-6100	7960-10940	62600-80500
Calcium	28800	21200	210-390	1020-1635	25700-35200
Potassium	16500	14000	504-1860	1047-1412	14000-19100
Barium	250	190	12	-	1200-1600
Iron	2000	1200	0.2	-	1130-1680
Manganese	1370	950	0.6	-	1470-1820
Chloride	155000	127000	7420-11750	14300-20730	130725-172200
TDS	259000	219500	12800-23300	26200-35110	238500-314600
SAR	86	90	84	82	115

⁺ after flashing.

Table 3. Travel time in days to leach inert solutes from soil surface to
tile drain $d = 200$ cm, $D = 200$ cm, $S = 1000$ cm, $K_s = 5$ cm/day,
 $\theta_s = 0.50$, $\theta_u = 0.375$.

Method of leaching	SURFACE LOCATION (cm)							
	0	125	250	375	500	625	750	875
Sprinkler R = 0.16S cm/day Q = 330 cm /cm/day	455	491	567	693	849	1046	1197	1894
Complete ponding Q = 3000 cm /cm/day	10	26	57	130	246	418	697	1362
Partial ponding over tile $-400 < X < 400$ Q = 1705 cm /cm/day	16	33	96	255	--	--	--	--
Partial ponding over midpoint $600 < X < 1400$ Q = 676 cm /cm/day	--	--	--	--	--	328	573	974

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10