BRINE MOVEMENT DURING FREEZING OF SALINE SAND COLUMNS

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Abstract

A finite difference numerical model for determining brine expulsion in soils during freezing was developed for application to saline sands. This model was similar to that developed by Cox and Weeks (1975) for the freezing of sodium chloride solutions but adapted to account for the presence of a sandy matrix. Application of the model revealed that brine expulsion alone could account for only a few percent of the total salt movement within the partially frozen region during freezing. This was observed for several constant freezing rates ranging from about 1 mm d^{-1} to 20 mm d^{-1}. In addition, the results further suggest that brine drainage, probably by salt fingering, is primarily responsible for salt redistribution during the freezing of saline sands. This paper is a progress report which discusses the experimental observations of brine movement during the freezing of saline sand columns, the current interpretation of these observations, and initial results from additional laboratory freezing tests under simulated natural freezing conditions.

Résumé

Un modèle numérique aux différences finies permettant de représenter l'expulsion de la saumure dans les sols pendant le gel a été mis au point en vue de son application aux sables salins. Ce modèle est semblable à celui mis au point par Cox et Weeks (1975) pour le gel de solutions de chlorure de sodium, mais a été adapté pour tenir compte de la présence d'une matrice sableuse. L'application du modèle a révélé que l'expulsion par le gel de la saumure ne pouvait à elle seule expliquer que quelques pour cent du mouvement total de la saumure dans la zone partiellement gelée. L'observation a été répétée pour plusieurs taux de congélation constants allant d'environ 1 mm/j à 20 mm/j. En outre, les résultats indiquent que le drainage de la saumure, probablement par digitation du sel, est la principale cause de la redistribution du sel pendant le gel des sables salins.

Introduction

The mechanism by which brine movement occurs in freezing saline sands is not well understood. While it is thought that the mechanisms of brine expulsion and/or brine drainage may be occurring, it is unclear as to the contribution of each. Cox and Weeks (1975) developed a finite difference numerical model for determining the extent of brine expulsion in freezing columns of pure sodium chloride solutions. This model was modified and applied to the results of laboratory experiments (Baker, 1987; Baker and Osterkamp, 1989) in order to determine the contributions of brine expulsion and brine drainage in freezing saline sands. The term "brine" refers to saline solution and represents the unfrozen soil solution in a partially frozen soil.

Laboratory experiments which simulate freezing of saline sand columns under natural freezing conditions are presently underway. Some preliminary results from these tests are also presented and discussed.

Experimental procedure

Several saline sand columns were frozen downward at constant rates. A brief summary of the procedures is presented in this paper. Additional information is given in Baker (1987) and Baker and Osterkamp (1989).

Columns of clear plastic tubing measuring 63.5 mm OD with a 32 mm wall thickness were filled with 30-grit silica sand which was sieved to produce a grain size ranging from 250 to 600 μm. Sand porosity was about 40%. The columns were saturated with a 35 ppt (parts per thousand by weight) sodium chloride solution.

Freezing of the columns was conducted in the freezing apparatus shown in Fig. 1. The columns were placed in the bath which was kept above the freezing point of the soil solution at -0.6 °C. A constant downward freezing rate was achieved by pulling the columns upward into the freezing box which was kept at about -14 °C.

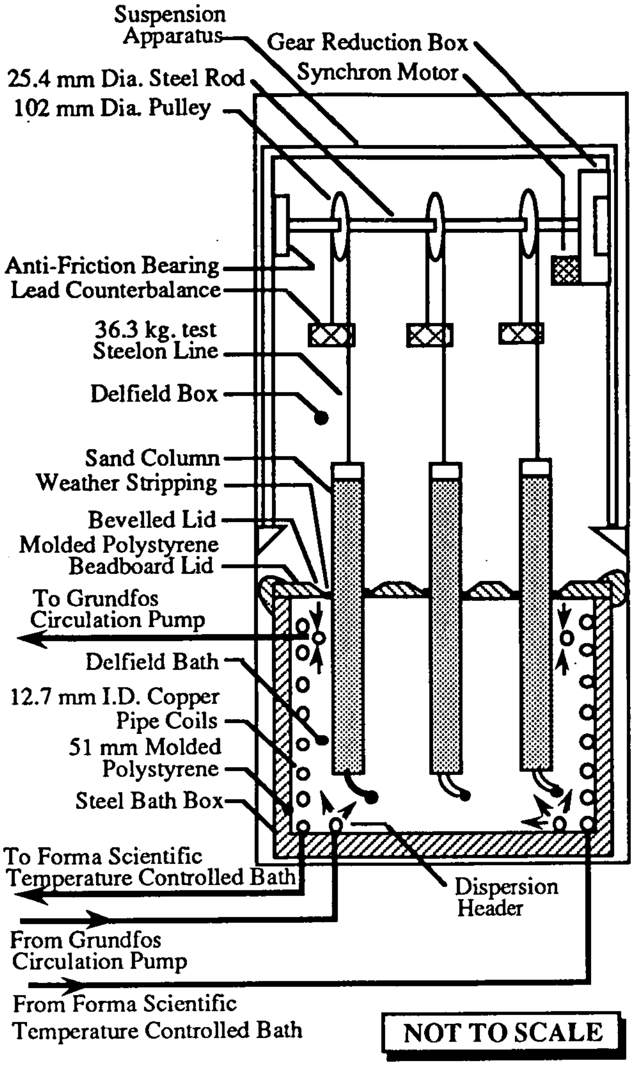

Figure 1. Schematic diagram of the apparatus used in the freezing experiments with constant freezing rates.

Six columns were placed in the freezing apparatus for each test. At various times during the test a column was removed and cut into 10 or 20 mm thick sections for determining gravimetric water content and soil solution salinity. One column was instrumented for temperature and was not sectioned for analyses so that for each constant freezing test there were five columns sectioned. This allowed five bulk soil solution salinity, S_b, profiles to be obtained for each test. There were four freezing tests conducted for brine expulsion studies. The freezing rates for these tests were 1.0, 5.0, 9.7, and 19.3 mm d^{-1}.

A one-dimensional finite difference model was developed for determining the extent of brine expulsion in freezing saline sands. This model was similar to that developed by Cox and Weeks (1975) for the determination of brine expulsion in freezing sodium chloride solutions. It is based on the salt and brine conservation equations and a known rate of temperature change and was modified to account for the presence of a sandy matrix (Baker, 1987). For application of this model to freezing saline sands the following modifications and additional assumptions were made:

1. The sand porosity remained constant. There was no rearrangement of the soil matrix during freezing so as to change the porosity.
2. The sand was saturated with unfrozen soil solution (brine) and/or ice within the pore spaces at all times.
3. The ice and unfrozen soil solution were in equilibrium.
4. The bulk ice salinity, S_{ice}, was replaced by the bulk soil solution salinity, S_b.
5. Brine properties were replaced with the corresponding unfrozen soil solution properties.

A description of the continuity equations that apply and the general procedure are given by Cox and Weeks (1975) and Baker (1987). Briefly, given the initial and final temperature profiles and the initial bulk soil solution salinity profile of the frozen portion of the column, the predicted final bulk soil solution salinity, S_{be}, profile can be determined assuming salinity changes are due solely to unfrozen soil solution expulsion. The salinity difference between the initial S_b and predicted S_be is the contribution to salinity changes due to expulsion. The salinity difference between S_{be} and the final S_b is assumed to the contribution to salinity changes by gravity drainage. Further discussion of this procedure is given by Baker (1987).

The rate of change of temperature between initial and final temperature profiles was assumed to be constant. Consequently, the calculated change in porespace porosity (the change in the porespace represented by unfrozen soil solution), Δn, represents an average value over the time period.

The position increment, Δz, was set at 1 mm and the time increment, Δt, was varied between 1 and 10 minutes. Smaller values for Δz and varying Δt values within this interval produced little change in the results. Also, setting the unfrozen soil solution velocity to zero produced little change in the results.

Results and discussion

Fig. 2 shows the results of the model for test FT-2 which was conducted at the constant freezing rate of 5 mm d^{-1}. The solid line curves represent measured S_b profiles and the dashed lines represent calculated S_{be} profiles based on brine expulsion as the only mechanism for salt redistribution.

A temperature profile was obtained for each time that a S_b profile was determined. Since the generation of each S_{be} profile requires that the initial and final temperature profiles to be known, there are only four S_{be} profiles for the five S_b profiles shown. Each S_{be} profile is between the two time consecutive S_b profiles. Generally, the initial S_b profile is on the right and the final S_b profile is on the left. The closer the S_{be} profile is to the initial S_b profile the less the indication that brine expulsion can account for the observed amount of salt redistribution. Consequently, the closer the S_{be} profile is

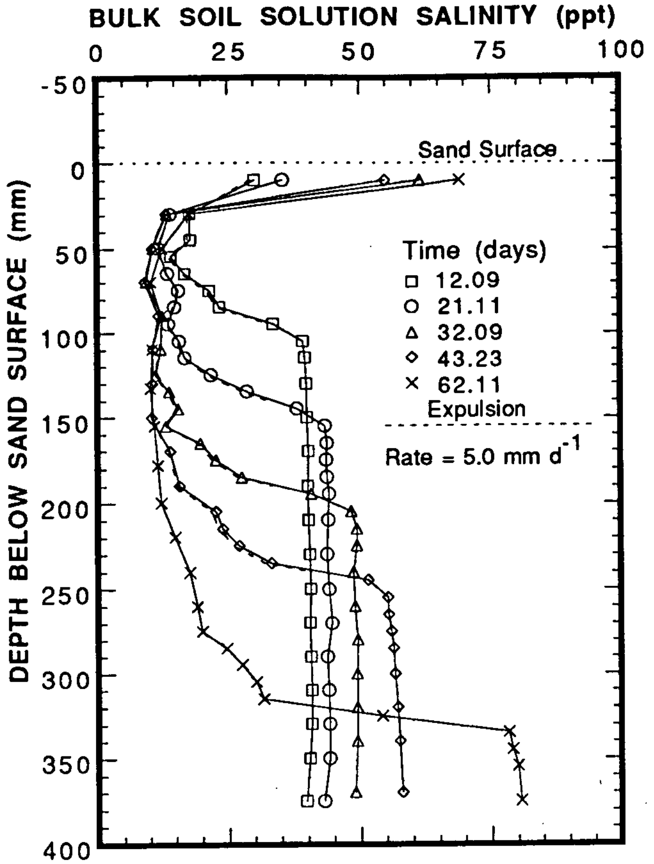

Figure 2. A comparison between the bulk soil solution salinity profiles and the predicted bulk soil solution salinity profiles with only brine expulsion occurring as the mechanism for salt redistribution.

to the final S_b profile the greater the indication that brine expulsion accounts for the observed amount of salt redistribution.

From Fig. 2 it is clear that brine expulsion accounts for very little of the observed salt redistribution since the S_{be} profiles are very close to the initial S_b profiles (nearly identical and difficult to differentiate from the initial S_b profiles). This result was similar for every run of the model based on each pair of time consecutive temperature profiles and initial S_b profile. Also, the same results were obtained for the other tests at different freezing rates.

The percentage of salinity change due to brine expulsion, ΔS_e, was determined for each pair of consecutive S_b profiles. ΔS_e was defined as (Cox and Weeks, 1975):

$$\Delta S_e = \left[\frac{S_{be} - S_i}{S_f - S_i}\right] \times 100 \qquad (1)$$

where S_i is the initial salinity and S_f is the final salinity.

Table I gives the values of ΔS_e for each pair of time consecutive S_b profiles for test FT-2. These values agree very closely with those of Cox and Weeks (1975) for the freezing of pure sodium chloride solutions of nearly the same initial concentration (34.7 ppt). The results of these tests suggest that another mechanism for salt movement, other than brine expulsion, must be occurring in order to account for the observed salt redistribution between S_b profiles. One such mechanism may be gravity drainage, possibly by salt fingering (Baker and Osterkamp, 1988).

Table I.
Effect of brine expulsion on bulk soil solution salinity profiles. Percent brine expulsion calculated from (1).

Depth (mm)	ΔS_e Percent Expulsion			
	Time (days)			
	12.1 - 21.1	21.1 - 32.1	32.1 - 43.2	43.2 - 62.1
10	-13.10	-0.34	0.76	-2.33
20	-76.92	-0.70	1.40	-2.64
30	13.20	12.47	12.95	-2.58
40	10.21	9.37	17.51	-3.25
50	10.88	7.81	24.51	-4.89
60	17.75	4.19	18.52	-6.02
70	11.55	3.29	15.49	-7.50
80	8.84	5.01	12.82	-12.54
90	5.13	14.41	12.52	-26.58
100		12.16	9.12	-63.37
110		8.99	7.81	164.51
120		6.44	15.33	74.28
130		5.57	9.52	50.62
140		4.48	6.00	210.79
150			7.43	-57.16
160			8.79	18.78
170			7.83	11.02
180			6.30	10.71
190			4.34	11.07
200				7.69
210				7.86
220				8.33
230				7.98
240				6.05

In order to examine gravity drainage as a possible mechanism for brine movement, the unexplained salinity difference between the measured profile and that predicted by the brine expulsion model was assumed to be attributed to gravity drainage. For each pair of consecutive S_b profiles, values for the change in bulk soil solution salinity with time due to gravity drainage, $\Delta S/\Delta t$ were determined at several depths. In addition, the average brine content (ppt by volume), V_u, and the average vertical temperature gradient, $\Delta T/\Delta z$, in units of °C mm^{-1}, were also determined. Table II lists these values for the two consecutive S_b profiles at 21.11 and 32.09 days. These values for $\Delta S/\Delta t$, V_u, and $\Delta T/\Delta z$ were typical for each run of the model on every pair of consecutive S_b profiles.

Generally, the values for $\Delta S/\Delta t$ were negative indicating a reduction in S_b values with time. For clarity, it is convenient to refer to the term $-\Delta S/\Delta t$ because an *increase* in the rate of salt removal corresponds to an *increase* in the value for $-\Delta S/\Delta t$ since:

$$\frac{\Delta S}{\Delta t} = \frac{S_f - S_i}{t_f - t_i} \qquad (2)$$

where t_i and t_f are the initial and final times, respectively. It would be expected that if gravity drainage was occurring that values for $-\Delta S/\Delta t$ would increase with increasing permeability. The permeability of the frozen sandy matrix was not determined, however, permeability should increase with increasing V_u values. Consequently, an increase of $-\Delta S/\Delta t$ values with increasing V_u values would indicate possible salt movement by gravity drainage. In addition, because of the dependency of the unfrozen soil solution salinity, S_u, and hence density on temperature, there should also be an increase in $-\Delta S/\Delta t$ with $\Delta T/\Delta z$ values. In other words, an increase in the temperature gradient (warmer with depth) corresponds to an increase in the density gradient (less dense with depth), and hence, a greater driving force for gravity drainage.

Fig. 3 is a graph of $-\Delta S/\Delta t$ versus V_u and $\Delta T/\Delta z$ for all pairs of time consecutive S_b profiles for test FT-2. The results indicate values for $-\Delta S/\Delta t$ increased with increases in V_u or $\Delta T/\Delta z$ values. These results were typical of the other tests with different freezing rates. For test Ft-2, values for $-\Delta S/\Delta t$ appear to increase almost linearly with V_u values for $\Delta T/\Delta z > 0.05$ °C mm^{-1}. A least squares curve fit of this data gave:

$$-\Delta S/\Delta t = 0.07\ V_u - 2.36 \qquad (3)$$

where $\Delta S/\Delta t$ has units of ppt s^{-1} X 10^6 and the correlation coefficient was 0.92480. For $\Delta T/\Delta z < 0.05$ °C mm^{-1}, a linear relation between $\Delta S/\Delta t$ and V_u was not as well defined, nor was it well defined for other tests at different freezing rates.

Table II.
Change in salinity with time due to gravity drainage for test FT-2 from 21.11 to 32.09 days. Average brine content and temperature gradient values were determined by averaging the initial and final values at the specified depth.

Depth (mm)	$\Delta S/\Delta t$ X 10^6 (ppt s^{-1})	Average Brine Content (ppt)	Average Temperature Gradient (°C mm^{-1})
10	27.48	232.28	0.019
20	13.51	147.32	0.019
30	-0.49	64.71	0.025
40	-0.79	59.97	0.031
50	-1.08	55.08	0.033
60	-2.85	57.92	0.036
70	-5.16	62.78	0.047
80	-4.19	71.40	0.053
90	-1.47	75.88	0.061
100	-2.10	82.07	0.068
110	-3.86	94.69	0.079
120	-7.61	116.61	0.079
130	-12.65	165.62	0.078
140	18.87	249.55	0.083

All tests clearly showed increasing values for $-\Delta S/\Delta t$ with increases in V_u or $\Delta T/\Delta z$. This further suggests that gravity drainage may be a major mechanism for brine movement in unidirectional freezing of saline sands under the experimental conditions used herein.

SIMULATED NATURAL FREEZING EXPERIMENT

The preceding discussion presented results of freezing experiments in which the freezing rate was constant and the temperature gradient near the interface was very large. However, when soils freeze naturally, the freezing rate is often proportional to the square root of time and the gradient near the interface is small. In an effort to improve our understanding of the processes that occur when a soil freezes, a new freezing apparatus was built to conduct experiments for examining the distribution of solutes in freezing soils with conditions that approximate those that occur during natural freezing.

The freezing apparatus consisted of a sand filled box, insulated on the four vertical sides and open on the top. The box was placed on top of an aluminum radiator that controlled the temperature at the base of the box. Seven vertical sand columns, arranged in a hexagonal pattern, were placed within the box and attached to the base.

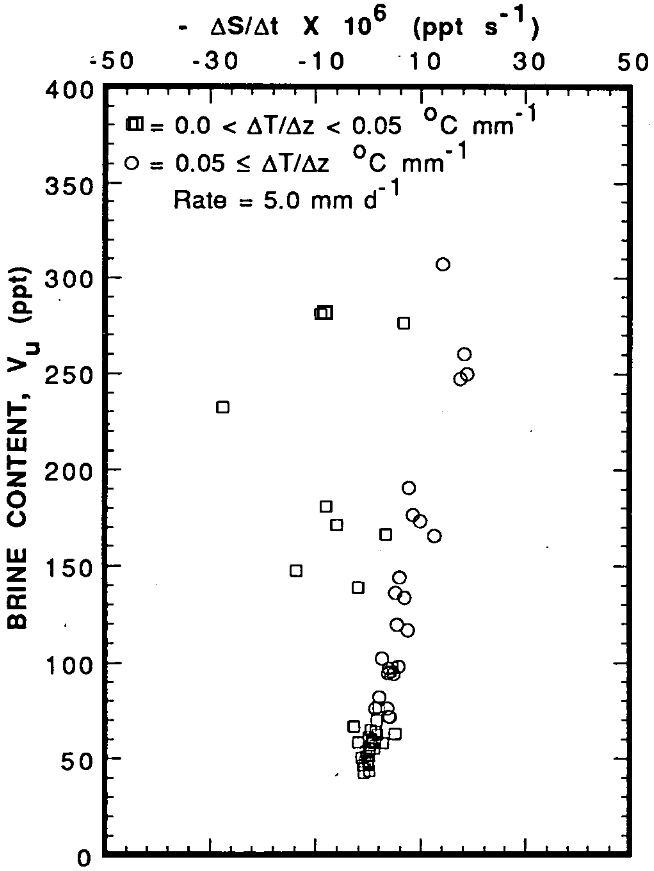

Figure 3. Change in salinity with time due to gravity drainage as a function of brine content by volume for different temperature gradients.

The sand columns were installed so that they could be removed during the experiment for sampling without disturbing the surrounding sand within the box. Soil solution salinity and sand type was similar to that described above for the experiments with constant freezing rates. In addition, sampling and analyses procedures were also similar and are described by Baker (1987) and Baker and Osterkamp (1989).

Vertical temperature profiles were obtained at several locations within the box and along the side of one of the columns. Each column was connected through its base to a soil solution reservoir. The entire freezing apparatus was placed in a temperature controlled chamber. Two of the columns were drained to field capacity to a depth of 300 mm below the surface and a third column was open at the top to allow air exchange. The other four columns were saturated and capped at the top. Prior to the start of the freezing experiment, the temperature of the sand filled box was reduced to -1.4 °C±0.1°C. Freezing was initiated by lowering the temperature of the chamber to - 6.0 °C which marked the start of the experiment.

Fig. 4 shows the S_b profiles for one of the tests. Only those data for three of the capped columns are presented for clarity. The data indicates that during the first three days, when the freezing rate was largest, only slight salt redistribution was observed. By the end of the experiment, substantial salt redistribution had occurred similar to that observed with the constant freezing rate experiments. However, the salt redistribution occurred primarily in the region near the freezing interface where the brine content was determined to be relatively large (greater than 50% by volume of pore space). Additional experiments are currently being conducted to identify the influence of varying initial soil solution concentration, temperature gradient, soil type, and unfrozen water content on salt redistribution during this type of freezing.

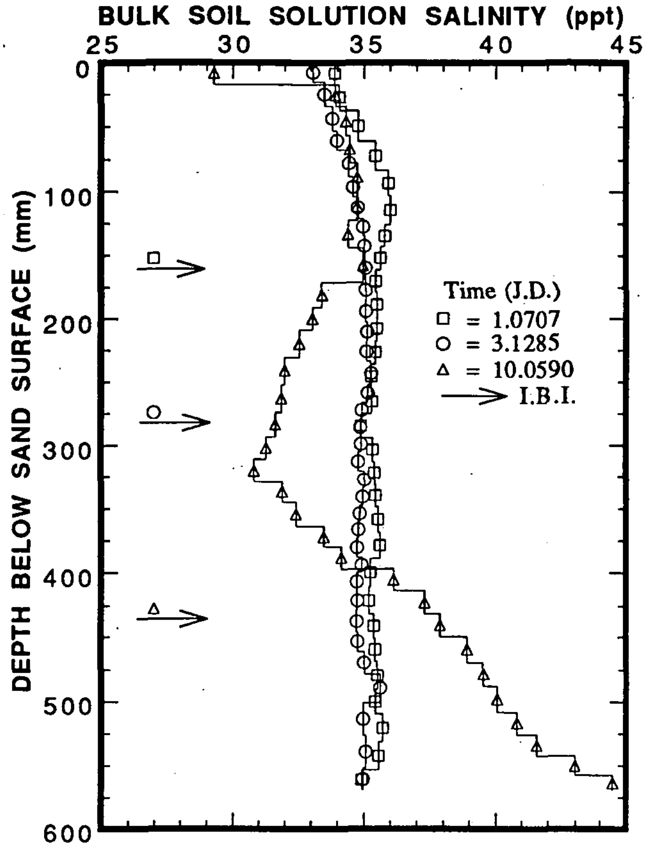

Figure 4. Bulk soil solution salinity profiles for simulated natural freezing experiment with marked locations of the ice-bonded interface (I.B.I.).

Summary

Downward freezing of saline sand columns was conducted at several freezing rates ranging from 1 to 19.3 mm d^{-1}. A finite difference numerical model developed by Cox and Weeks (1975) for determining brine expulsion during the freezing of pure sodium chloride solutions was used to predict brine expulsion in freezing sand columns saturated with a sodium chloride solution. The results suggest that brine expulsion accounts for only a small percentage of brine movement. They suggest further that gravity drainage may be the primary mechanism for brine movement in freezing saline sands. Initial results from ongoing simulated natural freezing experiments show both similarities and differences in salt redistribution characteristics near the freezing interface compared to experiments with constant freezing rates.

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