Non-Steady-State Moisture, Temperature, and Soil Air Pressure Approximation With an Electric Simulator

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ABSTRACT

An electric simulator was used to approximate the non-steady-state, one-dimensional solution of several moisture, temperature, and air pressure problems in soil. The simulator consists of a resistance-capacitance network with accessory units for setting initial conditions and recording or indicating the simulated variable with time and depth. Time and distance can be scaled to convenient magnitudes. Provision for changing the simulated diffusivity with distance and time allows for the approximate solution of several types of moisture problems. An example of absorption, redistribution after absorption, and evaporation from Yolo light clay is given. The absorption solution compares favorably with the mathematical solutions of Klute and Philip.

Comparison of mathematical and simulated solution of temperature distribution in a soil with constant diffusivity and temperature varying sinusoidally at the surface shows excellent agreement. The soil temperature (fluctuating with time) between two measured depths is estimated. The solution agrees reasonably with actual field measurements. The solution of the problem of air pressure fluctuation within the soil due to fluctuation at the surface is given where an impermeable layer exists at a specified depth.

The flow of moisture, heat, and air in soils can be represented by differential equations that are similar in form as has been pointed out by Ingersoll et al. (5), Scheidegger (15), and Kirkham (6). Resistance-capacitance networks have been used by Paschkis and Baker (13) and others (2), to investigate many problems of nonsteady-state heat transfer that had applications to engineering. Morris (11) has also discussed the use of a resistance-capacitance simulator to study non-steady-state fluid flow problems of interest to the petroleum industry. This paper describes a resistance-capacitance network which has been developed to simulate some non-steady-state moisture, heat, and airflow problems in soils.

A comparison of the moisture, heat, and airflow equations in one dimension are shown in table 1. The "electric charge flow" equation as derived by Paschkis and Baker (13) for a resistance-capacitance network is also shown. The similarity in form of the various flow equations is evident as well as the analogous components. The moisture flow equation is different from the others in that the moisture diffusivity is not a constant but will vary both with time and distance since it is a function of moisture content.

Many problems of non-steady-state heat and airflow in soils may be approximated by considering the diffusivity as a constant, but the moisture diffusivity varies over such a wide range that it cannot be considered constant even for a very approximate solution. To apply to moisture flow, the electric simulator must be adapted to account for a diffusivity that varies both with time and distance. Paschkis and Baker (13) used an electric simulator to approximate the solution of a problem involving a non-uniform diffusivity that was steady in time. It is the purpose of this paper to describe a resistance-capacitance network similar to that of Paschkis and Baker (13), that has been modified to allow for varying the diffusivity both with time and distance.

Electric simulation offers several advantages over other methods now available. Many problems involving complicated boundary conditions which have limited mathematical solutions are readily solved. The possibility of varying diffusivity with time and distance allows for the

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Table 1—Comparison of moisture, heat, air, and electric charge flow equations in one dimension for a homogeneous material with gravity influences neglected.

Moisture	$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}(D \frac{\partial \theta}{\partial x})$	Moisture content (by volume) θ	Moisture diffusivity $D = k \frac{\partial \psi}{\partial \theta}$*	Capillary conductivity k	Specific moisture capacity $\frac{\partial \theta}{\partial \psi}$
Heat	$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$	Temperature T	Thermal diffusivity $\alpha = \frac{k}{c}$	Thermal conductivity k	Specific heat capacity c
Air	$\frac{\partial p}{\partial t} = \alpha \frac{\partial^2 p}{\partial x^2}$	Pressure p†	Air diffusivity $\alpha = (\frac{kp_a}{\eta f})$‡	Air conductivity $\frac{k}{\eta}$	Specific air capacity $\frac{f}{p_a}$
Electric charge	$\frac{\partial E}{\partial t} = \alpha \frac{\partial^2 E}{\partial x^2}$	Electric potential E	Electric diffusivity $\alpha = \frac{1}{rc}$	Electrical conductivity $\frac{1}{r}$	Electric capacity c

* ψ is pressure potential.
† Pressure is measured with reference to atmospheric and must be small in comparison with atmospheric pressure for the equation to apply.
‡ p_a is atmospheric pressure, η is air viscosity, f is the ratio of the air-filled pore volume to the bulk volume of the soil, and k is intrinsic permeability.

approximate solution of several problems, such as those involving non-steady-state evaporation and redistribution of moisture, which are not presently soluble by other methods. The main disadvantage of the method is the inaccuracy of the results caused by using components of finite size instead of infinitely small components. Like all finite difference solutions (9) the accuracy could be improved by increasing the number of units and making them smaller. A compromise must then be made between the accuracy desired and the resources available. The "leakage" of charge stored in the capacitors introduces another source of error, but it is negligible if good quality capacitors are used and the time of operation of the simulator is relatively small (less than ½ hour).

THEORY OF THE METHOD

A qualitative explanation of the function of the apparatus (figure 1) would probably aid in understanding how the simulator works. The simulator consists basically of a "chain" of resistances in series alternating with capacitors in parallel. The chain is broken at one end, called the surface, and could continue on indefinitely in the other direction but for practical reasons is of arbitrary length. The boundary conditions at the surface determine the components to be attached there. For example, assume that it is desired to determine the electric potential with time and distance if the initial potential across all of the capacitors is zero and the potential at the surface is maintained constant for all time greater than zero. The electric potential is maintained constant by closing the battery switch "B" at zero time. Current will flow from the battery at x = 0 to x = h (h is the length of one unit) through resistor, $R_{h/2}$, in accordance with Ohm's law. The current arriving at the distance, x = h, will charge up the capacitor, C_h, causing a potential to develop across C_h. If the magnitude of $R_{h/2}$ does not change, the potential developed at C_h will decrease the potential gradient across $R_{h/2}$ which in turn decreases current flow from the surface and causes current to flow through $R_{3h/2}$ into C_{2h}. The flow of charges from C_h through $R_{3h/2}$ would tend to decrease the potential across C_h if additional current were not arriving from the supply at the surface. The time rate of potential buildup is dependent upon the magnitudes of $R_{h/2}$, C_h, as well as $R_{3h/2}$, C_{2h}, etc. The potential will change both with time and distance and can be measured as a function of these two variables. In the case of moisture flow, the above example simulates water absorption into a soil of uniform initial moisture content. The potential across C_h will simulate the moisture content at 1-cm. distance from the

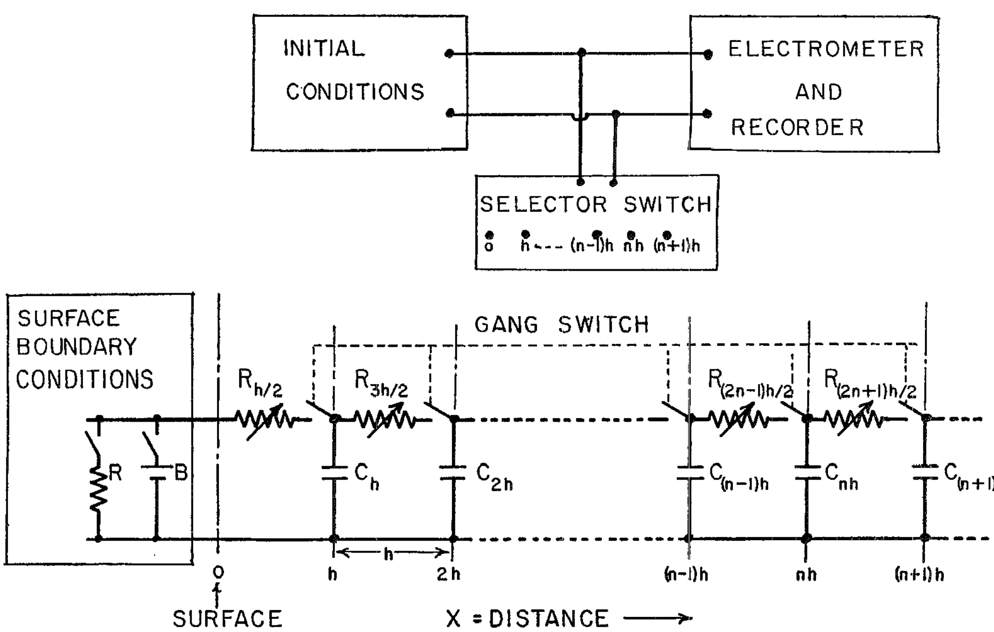

Figure 1—Schematic diagram of simulator.

surface if the resistance, $R_{h/2}$, is proportional to the moisture resistance per centimeter and if the capacitance, C_h, is proportional to the specific moisture capacity per centimeter. The result will be approximately correct because the simulator has units of finite size whereas the soil can be considered as having a large number of very small units. The precision of the approximation could be increased by using a large number of very small units. This method is actually a finite difference type solution of the equation employing electrical components. A numerical solution employing the same method may be possible, especially since high speed computers are now available to perform the tedious calculations.

An approximate equation similar in form to the moisture flow equation can be derived for the simulator network of figure 1. For convenience, assume that current is flowing from left to right. If electrical charge is conserved, the difference between the current flowing through resistor $R_{(2n-1)h/2}$ and $R_{(2n+1)h/2}$ at time, t, must be the current flowing to the capacitor. The current to the capacitor is

$$\frac{\partial Q_{nh,t}}{\partial t} = i_{(2n-1)h/2,t} - i_{(2n+1)h/2,t} \quad [1]$$

where i is electrical current, Q is electrical charge, and the subscripts $(2n-1)h/2$ and $(2n+1)h/2$ indicate the distance the particular unit is from the "surface." For convenience let the subscripts: $(n-1)h,t$; $(2n-1)h/2,t$; $(2n+1)h/2,t$; and $(n+1)h,t$ be designated by a, b, c, d, and e, respectively. Equation [1] then becomes

$$\frac{\partial Q_c}{\partial t} = i_b - i_d \quad [2]$$

The current is related to the resistance and electrical potential difference by Ohm's law so that

$$\frac{\partial Q_c}{\partial t} = \frac{E_a - E_c}{R_b} - \frac{E_c - E_e}{R_d} \quad [3]$$

If the electrical charge, Q, and resistance, R, are replaced by their respective values per unit length, $\bar{Q}$ and $\bar{R}$, times the length of one simulator unit, h, equation [3] becomes

$$\frac{\partial \bar{Q}_c}{\partial t} = \frac{E_a - E_c}{h^2 \bar{R}_b} - \frac{E_c - E_e}{h^2 \bar{R}_d} \quad [4]$$

Equation [4] can also be written

$$\frac{\partial \bar{Q}_c}{\partial t} = \frac{(\bar{R}_b + \bar{R}_d)(E_a - 2E_c + E_e) + (\bar{R}_d - \bar{R}_b)(E_a - E_e)}{2h^2 \bar{R}_b \bar{R}_d}. \quad [5]$$

The right hand side of equation [5] is a finite difference equation (9) which will be shown to be approximately equal to

$$\frac{\partial}{\partial x}\left(\frac{1}{\bar{R}_c}\frac{\partial E_c}{\partial x}\right) = \frac{1}{\bar{R}_c}\frac{\partial^2 E_c}{\partial x^2} + \frac{\partial E_c}{\partial x}\frac{\partial}{\partial x}\left(\frac{1}{\bar{R}_c}\right). \quad [6]$$

Since

$$\frac{1}{\bar{R}_c} \approx \frac{1}{2}\left(\frac{1}{\bar{R}_b} + \frac{1}{\bar{R}_d}\right); \quad \frac{\partial^2 E_c}{\partial x^2} \approx \frac{(E_a - 2E_c + E_e)}{h^2} \quad [7]$$

$$\frac{\partial E_c}{\partial x} \approx \frac{E_a - E_c}{2h}; \quad \frac{\partial}{\partial x}\left(\frac{1}{\bar{R}_c}\right) \approx \frac{1}{h}\left(\frac{1}{\bar{R}_b} - \frac{1}{\bar{R}_d}\right)$$

equation [6] then becomes

$$\frac{\partial}{\partial x}\left(\frac{1}{\bar{R}_c}\frac{\partial E_c}{\partial x}\right)$$

$$\approx \frac{1}{2}\left(\frac{1}{\bar{R}_b} + \frac{1}{\bar{R}_d}\right)\left(\frac{E_a - 2E_c + E_e}{h^2}\right) + \frac{1}{h}\left(\frac{1}{\bar{R}_b} - \frac{1}{\bar{R}_d}\right)\left(\frac{E_a - E_e}{2h}\right)$$

$$\approx \frac{(\bar{R}_b + \bar{R}_d)(E_a - 2E_c + E_e) + (\bar{R}_d - \bar{R}_b)(E_a - E_e)}{2h^2 \bar{R}_b \bar{R}_d} \quad [8]$$

which is identical with the right hand side of equation [5].

Combining equations [8] and [5] gives

$$\frac{\partial \bar{Q}_c}{\partial t} \approx \frac{\partial}{\partial x}\left(\frac{1}{\bar{R}_c}\frac{\partial E_c}{\partial x}\right) \quad [9]$$

If the electric capacitance per unit length, $\bar{C}$, does not change with time or distance, equation [9] can be written as follows by reverting back to the original subscript notation and noting that $E_{nh,t} = \bar{Q}_{nh,t}/\bar{C}$

$$\frac{\partial \bar{Q}_{nh,t}}{\partial t} \approx \frac{\partial}{\partial x}\left(\frac{1}{\bar{C}\bar{R}_{nh,t}}\frac{\partial \bar{Q}_{nh,t}}{\partial x}\right) \approx \frac{\partial}{\partial x}\left(D_{nh,t}\frac{\partial \bar{Q}_{nh,t}}{\partial x}\right) \quad [10]$$

or

$$\frac{\partial E_{nh,t}}{\partial t} \approx \frac{\partial}{\partial x}\left(\frac{1}{\bar{C}\bar{R}_{nh,t}}\frac{\partial E_{nh,t}}{\partial x}\right) \approx \frac{\partial}{\partial x}\left(D_{nh,t}\frac{\partial E_{nh,t}}{\partial x}\right) \quad [11]$$

where $D_{nh,t} = 1/\bar{C}\bar{R}_{nh,t}$. Both equations [10] and [11] are similar in form to the moisture flow equation. The electric potential, or charge, at any time or space depends upon the boundary conditions and the electric diffusivity, $D_{nh,t}$, which can be varied by changing $\bar{R}_{nh,t}$. It should be emphasized that holding the electric capacitance constant in time and distance is for convenience of simulation only. This departure from analogy limits the simulation of moisture flow to homogeneous soils. If the resistance were uniform, equation [11] would be similar in form to the heat and airflow equations shown in table 1.

The simulator allows for flexible scaling of time and distance. The scale is determined basically by the magnitude of the diffusivity. The following equation, deduced from Paschkis and Baker (13), gives the relation of the time and distance scale of the simulator, s, to the prototype, p,

$$\frac{tp}{ts} = \frac{Ds}{Dp}\frac{{h_p}^2}{{h_s}^2}.$$

The quantity h_s is the length represented by one unit (usually 1 cm.). For the moisture flow problems the value of the simulator diffusivity used was about 500 times greater than of the prototype. If each basic unit of the prototype is desired to be of 1-cm. length, the ratio of $tp/ts = 500$. If each unit is desired to represent 10 cm. ($h_p = 10$) then the ratio $tp/ts = 50{,}000$. If the capacitance is in μf. per cm. and the resistance is in megohms per cm., the electrical diffusivity is in cm.^{2} per sec.

DESCRIPTION OF SIMULATOR

Figure 1 shows the details of the simulator. The capacitors used were variable from 1 to 10 μf. in steps of 1 μf. The type used employed "Mylar" (Dupont polyester film) dielectric and were commercial grade of about 10% tolerance. The resistor in each unit consisted of two subunits, a 1-megohm variable resistor in series with a decade resistance switch of 1-megohm increments. The resistance could therefore be varied from 0 to 11 megohms with an accuracy of about 15%.

The simulator consisted arbitrarily of 15 units. Some important features of the apparatus were a gang switch, an initial conditions unit, and a measuring unit. The gang switch (3 position, 15 pole) allowed for simultaneous opening or closing of the circuit connecting one unit to the adjacent unit. The initial conditions unit contained a d.c. voltage source (battery B), a voltage divider, and a multiple switch. By setting the multiple switch at the "n" position the voltage at distance, nh, could be set at any value. The measuring unit consisted of an electrometer or recorder. The electrometer has very low current drain which allows the measurement to be made without appreciable influence on the quantity measured.

METHOD OF SIMULATION

The information needed to approximate the solution of non-steady-state flow problems is (*a*) the moisture diffusivity relationship for the soil, (*b*) the boundary conditions for the particular problem, and (*c*) the scale factors to be used.

Moisture.—The diffusivity-moisture content relationship given by Moore (10) for Yolo light clay was used for the moisture flow studies. For the absorption problem the boundary condition, $\Theta_0 = 1$ for all $t > 0$, was simulated by connecting the battery, B, of the surface conditions unit into the circuit at zero time. The boundary condition, $\Theta = 0$ at $t = 0$ for all $x > 0$, was imposed by discharging all of the capacitors at the start. Because the unit was of finite length, there was no flow out of the network—imposing an additional boundary condition, $\partial\Theta/\partial x = 0$ for all t at $x = 15h$. The scaled diffusivity was then adjusted according to the diffusivity-moisture content relationship by varying the resistors at the appropriate distance so the product, $\bar{R}\bar{C}$, was equal to 1/Ds. The resistance was varied according to the mean of the potentials on either side of the resistor because the resistor is midway between the potentials.

The gang switch was turned from the open to closed position at $t = 0$ simultaneously connecting all of the units together. A timer was also started. After a short time (determined largely by experience) the switch was returned to the neutral position and the timer stopped. The electric potential was measured and recorded across each capacitor. The diffusivities of the different units were adjusted, if necessary, according to the diffusivity-moisture content relationship. The elapsed time was recorded. The process was then repeated as many times as desired.

The surface boundary condition for the redistribution problem ($\partial\Theta/\partial x$ at $x = 0$ for all $t > 0$) was attained by disconnecting the battery, B, and the resistor, R, of the surface conditions unit. Thus, there was no flow of current in or out of the simulator at either end but only redistribution within. The initial potential-distance function at the start of redistribution was taken from the measured values 40×10^3 seconds after absorption began. The remainder of the procedure was the same as outlined for absorption.

The surface boundary condition for the evaporation problem (R at the surface equivalent to 10 megohms electrical resistance for all $t > 0$) was attained by switching resistor, R, of the surface conditions unit into the circuit at zero time. The potential-distance function at the start of evaporation was taken from the measured values 22.6×10^3 seconds after redistribution was started. The remainder of the procedure was the same as outlined for absorption.

Heat.—The two heat flow problems simulated were considerably simpler in that diffusivity was constant with time and distance. The problem involved heat conduction only, with heat of vaporization, etc., neglected. The first problem was to determine the soil temperature of a semi-infinite soil with sinusoidal fluctuation of soil temperature at the surface. This boundary condition at the surface was attained with an apparatus consisting of a d.c. source of power, a special type voltage divider, and a synchronous motor. The shaft of the voltage divider was turned at a constant speed through the synchronous motor shaft. With the d.c. source connected to the proper terminals of the voltage divider, a voltage which fluctuated sinusoidally with time with a period simulating 1 day was produced. This was imposed on the simulator at the surface. After setting the diffusivities of the various units, the process was started without regard to the initial potential (simulating temperature) of any of the units. The operation was carried out for several cycles until the voltage fluctuation with time was identical from one cycle to the next. The problem then was considered solved. The recording of the data was simplified greatly by attaching a recording potentiometer to the electrometer. For this problem "h_p" was taken as 10 cm. Since there was no change in temperature beyond the tenth unit, the solution would apply for a semi-infinite soil.

The second heat transfer problem involved the estimation of a temperature at a given depth in the soil. The temperature as a function of time both above and below the estimated depth was known and constituted the boundary conditions. For simplicity the diffusivity was considered a constant and was computed from the ratio of the temperature amplitudes of the two known depths (14). The boundary conditions were imposed by manually adjusting a voltage divider d.c. source accessory unit in a step-wise fashion, i.e., the boundary potential was held constant over a small time interval. To do this it was necessary to stop the flow after a given predetermined time by turning the gang switch to the neutral position. The new voltage corresponding to the new time was adjusted, the boundary conditions imposed and the process repeated. The initial temperatures at $t = 0$ were approximated by assuming that the temperature change with depth was uniform.

Air.—The airflow problem was very similar to the theoretical heat flow problem and was simulated by the same method. The different periods were obtained by adjusting the rotary velocity of the synchronous motor. The boundary condition of an impervious layer at a given depth was attained by permanently disconnecting the units beyond the specified depth.

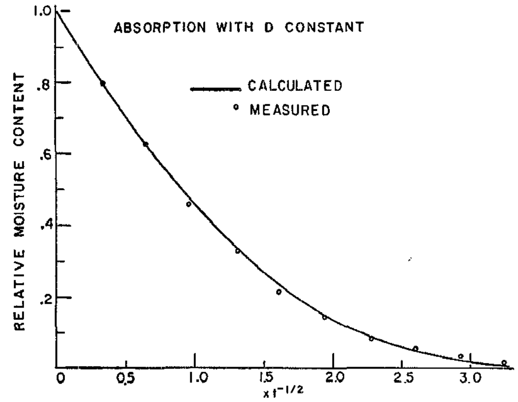

Figure 2—Comparison of calculated and simulated values with constant diffusivity.

RESULTS AND DISCUSSION

Moisture.—A comparison of simulated and calculated values of relative moisture content for absorption with diffusivity a constant is shown in figure 2. The results show excellent agreement. This problem is of little practical importance but provides a convenient method where simulated and calculated values can be compared. The relative moisture content is defined as the ratio $(\theta - \theta_n)/(\theta_0 - \theta_n)$ where θ is the moisture content at any time or distance, θ_n is the initial moisture content at $x \geqslant 0$ and $t = 0$, and θ_0 is the moisture content at $x = 0$ and $t > 0$.

Simulated absorption into Yolo light clay is shown in figure 3. The mathematical solution by the method of Philip (12) and the solution reported by Klute (7) are also shown. The simulated curve lies slightly to the left of the curve calculated by the method of Philip (12), but the shape of the curves is almost identical. The data indicate that the simulated solution is approximately correct and may be sufficiently precise for many uses. The curve calculated by Klute (7) is somewhat different in shape which may be due to a different interpretation of the basic data.

An additional advantage of the simulator is not only the relative ease with which the boundary conditions are established but also the possibility of scale reduction. For example, the prototype time for the total of the three processes shown in figure 4 was 1766.7 minutes, whereas

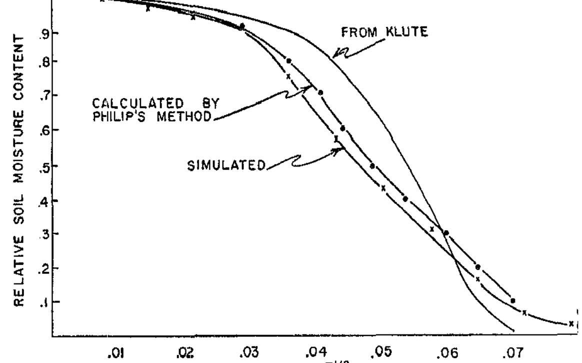

Figure 3—Absorption into Yolo light clay as simulated and calculated by two methods. Data of Moore (10).

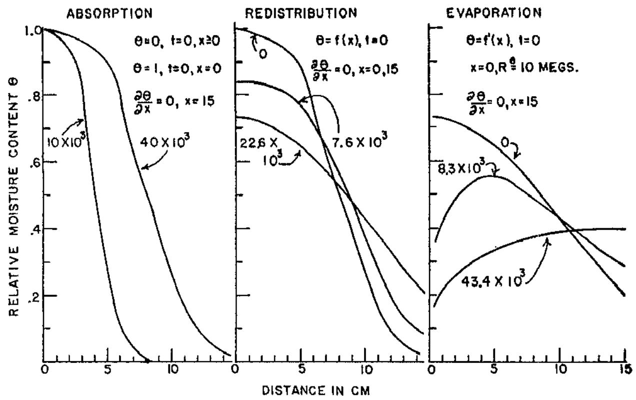

Figure 4—Simulated absorption, redistribution, and evaporation in Yolo light clay with an impervious layer at 15 cm. Numbers refer to the time in seconds. Initial moisture content for redistribution was taken as the moisture distribution 40×10^3 sec. after absorption began. Initial moisture content for evaporation was taken as 22.6×10^3 sec. after redistribution began.

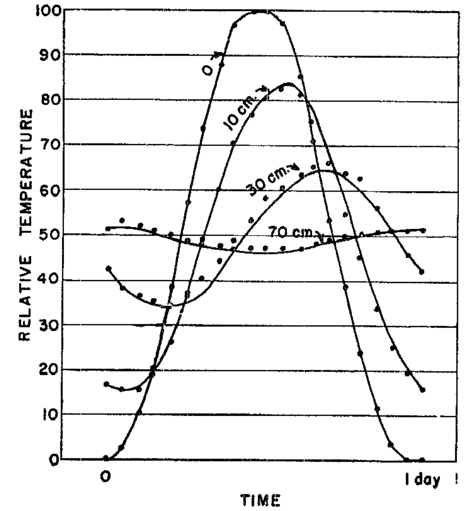

Figure 5—Comparison of calculated (solid line) and simulated (points) values of soil temperature for a semi-infinite soil with uniform diffusivity and the temperature fluctuating at the surface sinusoidally.

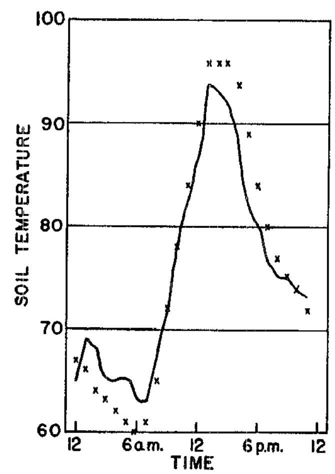

Figure 6—Comparison of simulated (solid line) and measured (points) soil temperature at 4-cm. depth for Geary silty clay loam at Manhattan, Kansas, on August 26, 1958.

the simulator time was 3.5 minutes. The total time necessary to simulate the three problems was about 90 minutes (3.5 minutes simulation, 86.5 minutes "shut down" time for adjusting variables). It is also probable that the simulator can be used where the soil is not homogeneous. This will require modification of simulator to allow for variation of capacitance as well as resistance. The authors are presently investigating this possibility. A disadvantage of the simulator, at present, is that the gravitational term in the general flow equation cannot be included. Thus studies are limited to horizontal flow.

The simulator would be of questionable value if the solution to problems were limited to those already soluble by presently known mathematical means. The great advantage of the simulator is that boundary conditions are easily established for a wide variety of conditions. Such boundary conditions as an impervious layer at any given depth and varying conditions at the surface of the soil are easily established. Figure 4 is an example of a problem simulated involving absorption, redistribution, and evaporation from Yolo light clay. The solutions appear to be reasonable. For the absorption case a definite wetting front is evident and becomes less distinct with time. For the redistribution case the moisture content of the wet zone decreases quickly with time and the moisture content of the dry zone increases comparatively slowly. For the evaporation example the moisture content decreases rapidly at the evaporating surface and increases slowly at the opposite end.

It should be emphasized that the moisture flow data were simulated assuming that moisture diffusivity was a unique function of moisture content. This departs from the true condition where hysteresis is well known to complicate the picture. Approximation by electrical simulation could be quite easily accomplished if these hysteresis effects were well known. There is a very great need for improved methods for characterizing soil moisture properties before this or other methods will give precise solution to actual problems.

Heat.—The simulator is also useful to measure heat flow in soils. It should be emphasized that the heat flow equation considers only heat conduction and does not take into account heat of vaporization or vapor transfer of heat. Figure 5 is a comparison of simulated and calculated values of soil temperature where the thermal diffusivity is constant with the temperature at the soil surface fluctuating sinusoidally. The data indicate excellent agreement between the simulated and calculated values. Figure 6 shows another temperature problem worked on the simulator. The boundary conditions were taken from measured temperatures at 1- and 16-cm. depth on a Geary silty clay loam at Manhattan, Kansas, on August 26, 1958. Measurements were also made at the 4-cm. depth and are compared with the approximated values from the simulator. In general the measured and simulated data agree. The differences may be due to an inaccurate knowledge of the thermal diffusivity or to heat of vaporization, etc. The thermal diffusivity used was computed from the ratio of the amplitudes of the temperature at 1 and 16 cm. assuming sinusoidal fluctuation. This method at best gives only approximate values.

Air.—Pressure fluctuations within a soil caused by wind fluctuations at the surface have been considered by Fukuda (1) and Hanks and Woodruff (4). For sinusoidal fluctuation at the surface and a semi-infinite uniform soil the problem was soluble by classical Fourier methods. However, where a boundary layer existed at some depth or where the diffusivity was some function of depth, the problems was very difficult by classical methods. The simulator described herein was very useful for the solution of these

Table 2—Comparison of maximum pressure of soil air as influenced by depth, frequency, and presence of an impermeable layer with pressure fluctuating at the soil surface. IL = impermeable layer at 41.8-cm. data from simulator. NIL = no impermeable layer, data calculated.

Depth in soil, cm.	Silt loam D = 1056						Sand D = 9153 1 sec. period	
	1 sec. period		10 sec. period		30 sec. period			
	IL	NIL	IL	NIL	IL	NIL	IL	NIL
	100	100	100	100	100	100	100	100
4.2	83	80	99	93	100	96	96	96
8.4	62	63	96	87	100	92	95	86
12.5	52	51	95	80	99	87	93	79
16.7	40	40	93	75	99	84	92	73
20.9	31	32	91	70	99	81	91	68
25.1	28	25	90	65	99	78	90	63
29.3	22	20	90	61	99	75	90	58
33.4	20	16	90	56	99	72	89	54
37.6	19	13	89	52	98	69	89	50
41.8	18	10	89	49	97	66	89	46

problems. As an example, table 2 shows the maximum pressure fluctuation at various depths with different periods with and without a boundary layer for the two soils considered earlier by Hanks and Woodruff (4). Where no boundary layer existed the data was calculated from classical theory (5). The data demonstrate the great influence of the impermeable layer on the amplitude of the pressure fluctuations. This influence was, of course, greater as the frequency decreased and as the diffusivity increased. For the silt loam and the 1-second period, the impervious layer had no influence on the amplitude above 20.9 cm. For the remainder of the data the impervious layer influenced all depths measured.

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