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INFLUENCE OF GRAVEL LAYERS ON SOIL MOISTURE CONTENT AND FLOW

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INFLUENCE OF GRAVEL LAYERS ON SOIL MOISTURE CONTENT AND FLOW

by

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ABSTRACT

Calculations and experimental measurements indicated gravel lenses are unsuitable for diverting water around large burial trenches. The calculations suggest that leaching of radionuclides from the interior of process equipment is unlikely until the soil is saturated near the equipment.

CONTENTS

	Page
LIST OF FIGURES	4
INTRODUCTION	5
SUMMARY	6
DISCUSSION	6
Experimental	6
Infiltration, Drainage, and Rewetting	6
Flow Paths Around a Triangular Gravel Lens	8
Soil-Water Pressure Near Gravel Lenses	9
Theoretical Studies	9
Computer Program	9
Calculated Soil-Water Pressures Near Gravel Lenses	11
Results	12
Infiltration, Drainage, and Rewetting	12
Flow Paths Around a Triangular Gravel Lens	15
Measured Soil-Water Pressures Near Gravel Lenses	16
Calculated Soil-Water Pressures Near Gravel Lenses	16
CONCLUSIONS	21
REFERENCES	23

LIST OF FIGURES

Figure		Page
1	Soil Column Used for Infiltration, Drainage, and Rewetting Experiments	7
2	Infiltration of 2-cm Increments of Rain	13
3	Drainage of Water	13
4	Rewetting with 2-cm Increments of Rain	14
5	Unsaturated Water Movement Around a Triangular Gravel Lens	15
6	Observed Soil-Water Pressure Distributions in a Laboratory-Scale Experiment	17
7	Predicted Soil-Water Pressure Distributions in a Laboratory-Scale Experiment	17
8	Predicted Soil-Water Pressure Distributions for Three Sizes of Flow Barriers at a Tension of 50 cm of Water	18
9	Predicted Soil-Water Pressure Distributions around an 8 x 3 Meter Flow Barrier	19

INTRODUCTION

Nearly all radioactive waste management research has been directed toward ground disposal of low-level liquid waste and the storage of high-level liquid waste. Very little research has been directed toward protecting buried solid waste from leaching by percolating rainwater. This solid waste, including obsolete process equipment, spent ion exchange resins, reactor fuel tube housings, and fragments of experimental fuel elements, is routinely buried with no provision to prevent leaching. Hawkins and Horton[1] have proposed capping burial areas with bentonite, which effectively seals soils. This report evaluates an alternative protection method: diverting water around burial trenches with an overlying layer of gravel (gravel lens).

Water will not flow from unsaturated soil to gravel; the soil above the water table is normally unsaturated. Alway and McDole[2] found that soil held more water above a sand layer than without the sand layer. Eagleman and Jamison[3] investigated saturated soil columns that contained layers of silt and sand with the surface of the column sealed and the bottom open for drainage and evaporation. The water content of the sand, when above the silt loam layer, decreased from 0.15 g/cm^3 one day after the experiment began to 0.02 g/cm^3 after 19 days. The water content of the silt loam layer, when above the sand layer, decreased only from 0.44 to 0.40 g/cm^3 during the same period. Similar studies have been published elsewhere.[4,5]

Three experiments were used to determine the influence of a gravel lens on soil water near the lens and the flow paths taken by the water. The first experiment determined the water distribution in a vertical soil column during 1) infiltration of water into a dry soil overlying a gravel lens, 2) drainage of the soil above the gravel, and 3) rewetting of the drained soil. In the second experiment, dyes were used to trace the flow paths around a triangular lens in a laboratory model. The third experiment measured water pressures throughout a soil slab containing an impermeable layer that represented the gravel layer effect during unsaturated water movement.

The first two experiments were to determine whether a gravel lens can serve as an absolute barrier to water flow. The third experiment was to determine whether all flow can be diverted a sufficient distance to prevent leaching in burial trenches.

SUMMARY

Calculations showed that gravel lenses cannot divert percolating rainwater two meters during periods of prolonged rain. Four-meter diversions would be required to protect solid radioactive waste contained in large burial trenches.

However, the existence of diversion suggests that the contaminated interiors of individual pipes and vessels in such trenches are immune to leaching. The small openings in this equipment permit the diversion of percolating water around the vessel as long as the interior of the vessel remains free of soil.

Laboratory studies of infiltration, drainage, and rewetting confirmed that sandy loam and sandy clay soil have a greater capacity to hold water when they are above a gravel layer. After drainage, 85 cm of soil can retain water equal to or greater than the precipitation that infiltrates during an average rain.

DISCUSSION

EXPERIMENTAL

Infiltration, Drainage, and Rewetting

Infiltration, drainage, and rewetting experiments were conducted in clear plastic boxes 15-centimeters square and 161-centimeters high (Figure 1). A 10-cm layer of gravel was placed at the bottom of the box and another 10-cm layer was placed halfway up the box. A sandy loam soil (75% sand, 15% silt, and 10% clay) or a sandy clay soil (54% sand, 8% silt, and 38% clay) that had passed through a sieve with 2-mm holes filled the remainder

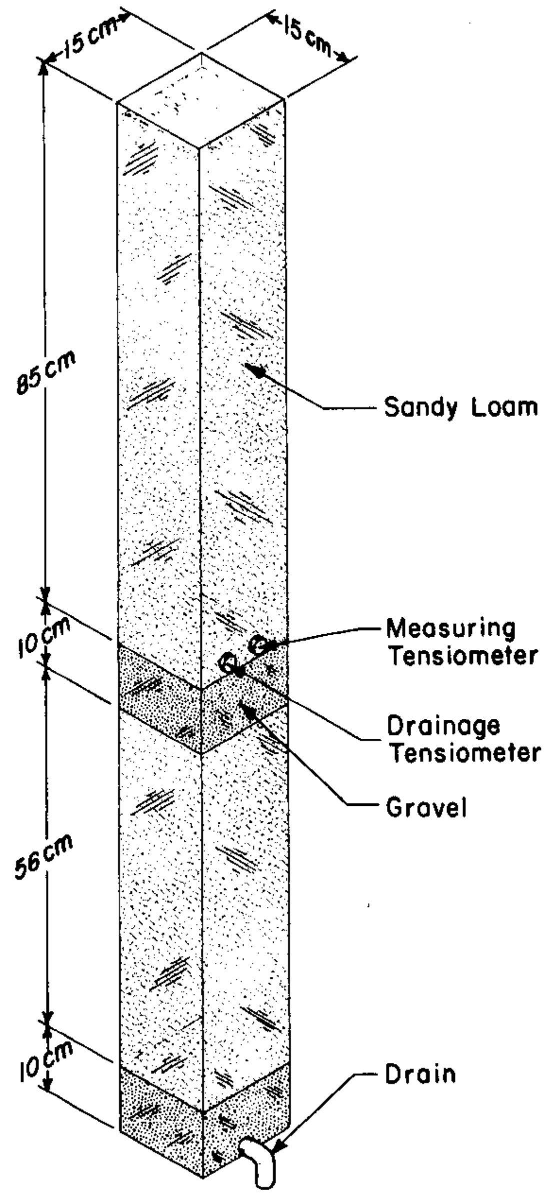


FIG. 1 SOIL COLUMN USED FOR INFILTRATION, DRAINAGE, AND REWETTING EXPERIMENTS

of the column. The gravel layer in the bottom of the box served only as a drain for the column. Two methods, both satisfactory, were used to prevent the filtering down of soil into the gravel: (1) a thin layer of moistened sandy loam was carefully packed above the gravel, or (2) a graded sand acted as a barrier for the sandy clay.

Two tensiometers were positioned 2 cm above the gravel layer located midway down the column. One tensiometer was used to measure the pressure of water in the soil at this location, the other was used to drain water from the column at controlled tensions (subatmospheric pressures). Water content was measured by gamma attenuation.[6] In the infiltration phase of this study, 450 ml of water (equivalent to 2 cm of rain) was added to each column daily until the soil in the entire column was wet. Evaporation was prevented throughout the study. The distribution of the added water was determined prior to the next addition. The columns were allowed to drain for 5 days following the infiltration study, with the soil water at atmospheric pressure at the drainage tensiometer. After this 5-day period, small increments of tension were applied to the drainage tensiometer by lengthening the hanging water column attached to the tensiometer cup. The water released at each tension was recorded, and the water distribution in the soil column was determined before the tension was increased. After the drainage study, the drained soil was rewet by daily additions of 2 cm of water.

Flow Paths Around a Triangular Gravel Lens

Actual flow paths in the vicinity of a triangular gravel lens were observed in a clear plastic box 122 cm long, 61 cm high, and 5 cm thick packed with air-dried, sieved, sandy clay soil. The triangular gravel lens was 55 cm long and 21 cm high. The base of this isosceles triangle was 41 cm below the soil surface. A triangular lens was studied rather than a rectangular one because sloping barriers will divert water better than flat barriers. Cotton swabs with Erio Floxine 2 G Supra (Reference 7, No. 18050) were inserted 2 cm below the soil surface. Water was added through capillaries to the surface of the box at the rate of 1.2 cm per hour. The dye traced the flow paths from the soil surface to the drains at the base of the box.

Soil-Water Pressure Near Gravel Lenses

The influence of a simulated gravel lens on the water pressure in the soil during steady-state infiltration was measured in a plastic box 100 cm wide, 100 cm high, and 7.6 cm thick. The box was filled with sandy clay except at one end where a sloping plastic barrier 40 cm wide and 30 cm high was positioned. The base of this lens was 60 cm from the soil surface. The plastic barrier was inserted rather than a gravel lens because of easier installation. From the dye study, such a substitution was satisfactory because no water flows through the lens during unsaturated flow.

Water entered the box through long fritted cylinders at the soil surface. These cylinders supplied water to the box at a tension of 20 cm of water for the first experiment and 50 cm for the second. The fritted cylinders were supplied with water from constant head bottles. Fritted-glass tensiometers along the face of the box were connected to water manometers. At steady state, the tension at each tensiometer was recorded. If all pressures in the vicinity of the gravel were less than atmospheric, water could not flow through the gravel.

THEORETICAL STUDIES

Computer Program

The flow of water through saturated and unsaturated soil is described by Darcy's law

$$V_i = -k \nabla \phi \qquad (1)$$

where $V_i = \frac{Q}{At}$ = velocity in the ith direction where i = x, y, z

Q = quantity of water moving

A = cross-sectional area of the soil column

t = time

k = the hydraulic conductivity

$\nabla\phi$ = the hydraulic gradient, the space rate of change of hydraulic head in the direction of flow

From Darcy's law

$$V_x = -k \frac{\partial\phi}{\partial x}$$

$$V_y = -k \frac{\partial\phi}{\partial y}$$

$$V_z = -k \frac{\partial\phi}{\partial z}$$

Substituting these values into the equation of continuity

$$-\left(\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y} + \frac{\partial V_z}{\partial z}\right) = \frac{\partial\theta}{\partial t} \qquad (2)$$

where θ is the water content of an element of soil gives

$$\frac{\partial}{\partial x}\left(k\frac{\partial\phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial\phi}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial\phi}{\partial z}\right) = \frac{\partial\theta}{\partial t} \qquad (3)$$

There is no known solution for this transient equation at the present time.

Reisenauer, Nelson, and Knudsen[8] used finite difference techniques to reduce the steady state form of Equation 3 (i.e., $\frac{\partial\theta}{\partial t} = 0$) along with the relationships between ϕ and θ and k and θ to a system of simultaneous equations. They used a computer to solve the resulting system of equations. Their computer program can solve one-, two-, or three-dimensional problems with up to 8000 grid points and can handle as many as 15 different soils in any one problem. The only information needed to solve Equation 3 for a particular set of boundary conditions and soils is the geometry of the system and the relative capillary conductivity as a unique (i.e., no hysteresis) function of the pressure head. Although the program was prepared for an IBM 7090 using FORTRAN and FAP languages, the equation could be solved using an IBM 360 operating on the emulator mode. One drawback of the program is its inability to handle the boundary condition with a specified flux across the boundary. The less flexible boundary condition of a fixed potential must be used. Also, steady-state flow had to be assumed because no transient solution is available. However, the assumption of steady state is not inappropriate because flow approaches steady state during periods of extended rainfall.

Calculated Soil-Water Pressures Near Gravel Lenses

Boundary values identical to those in the laboratory model used to measure soil-water pressures were inserted into the computer program to determine whether the computer program could predict water pressures actually found in the soil. The plastic barrier or gravel lens was represented in the computer program by a very impermeable soil because the laboratory model would not let water flow through the lens. The water supply to the surface of the box was maintained at a tension of 20 cm of water in the first calculated solution and at a tension of 50 cm of water in the second solution while the bottom of the box was maintained at a tension of 0 cm of water (the water table). The left and right sides of this two-dimensional problem were boundaries across which there was no flow. The observed and the predicted values were compared.

After the computer program was tested on laboratory-scale models of gravel lenses, the program was used to predict the water pressures that would be observed near larger gravel lenses. Again the gravel lens was represented mathematically by an impermeable soil so that no water could flow through the gravel. Such representation permits water pressures greater than atmospheric to build up in the soil, and where such pressures exist there would be flow through the gravel. The computer program was used to predict the water pressure in the vicinity of three flow barriers: 2 meters wide and 1 meter high, 4 meters wide and 2 meters high, and 8 meters wide and 3 meters high. In the calculations, the distance from the soil surface to the water table was assumed to be 10 meters and the peak of the barrier to be 3 meters from the soil surface. The mathematical model assumed that the soil was 20 meters wide and that no flow occurred across the vertical boundaries. Water pressures around the three barriers were calculated for the cases in which water was introduced to the soil surface at 20 and 50 cm of tension.

RESULTS

Infiltration, Drainage, and Rewetting

The columns of sandy loam and sandy clay soils wet progressively deeper as each additional 2 cm increment of water was added. The water distribution with depth, determined using the gamma apparatus, for the sandy loam is shown in Figure 2a and for the sandy clay is shown in Figure 2b after each water addition. When water reached the gravel, further increments of water increased the water content in the soil above the gravel, but water did not penetrate the gravel until 18 cm of water had been added to the sandy loam soil and 28 cm of water had been added to the sandy clay soil. When water moved into the gravel lens, the tensiometer above the gravel lens indicated that the soil was saturated.

The water content of the sandy loam and sandy clay soils was reduced throughout the region above the gravel lens when known tensions were applied to the drainage tensiometer. The water distributions after drainage at tensions of 0, 18, 38, and 54 cm of water are shown in Figure 3a for the column of sandy loam soil. The water distributions for the column of sandy clay soil are given in Figure 3b after drainage at tensions of 0, 20, 43, 55.5, and 89 cm of water. The volumes of water drained at these tensions were equivalent to 0.8, 3.0, and 5.2 cm of water from the sandy loam soil and 1.2, 4.2, 6.1, and 7.4 cm from the sandy clay.

The water content of the soil increased throughout the entire column with each 2-cm increment of water added during rewetting of the drained column. The water distribution 16 hours after each 2-cm increment of water added to the sandy loam and sandy clay are

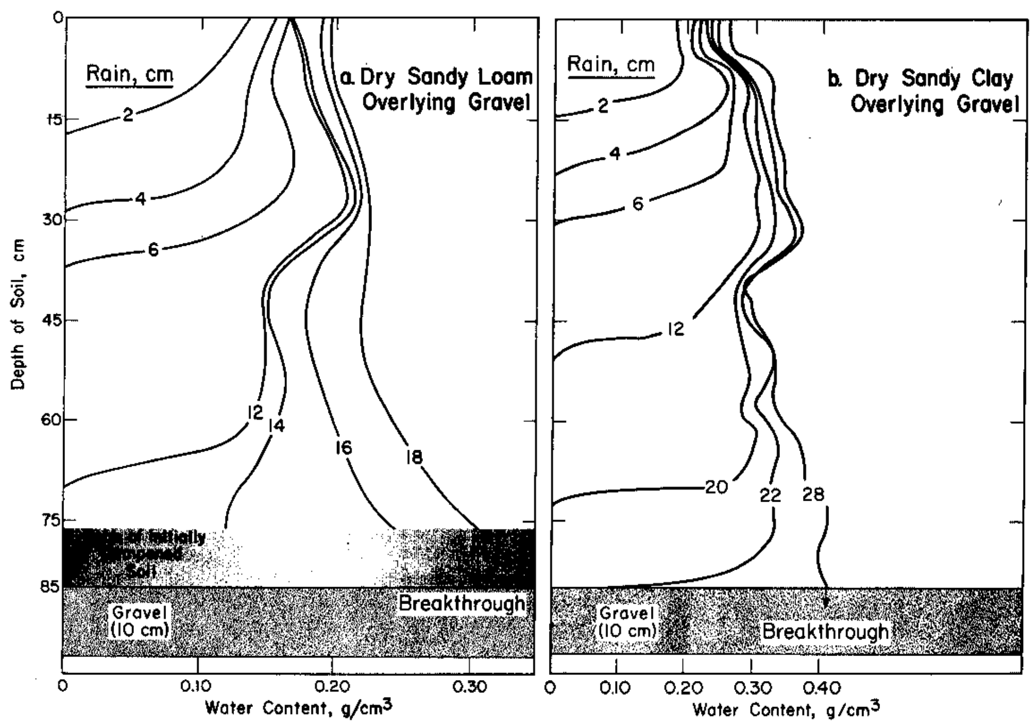


FIG. 2 INFILTRATION OF 2-cm INCREMENTS OF RAIN

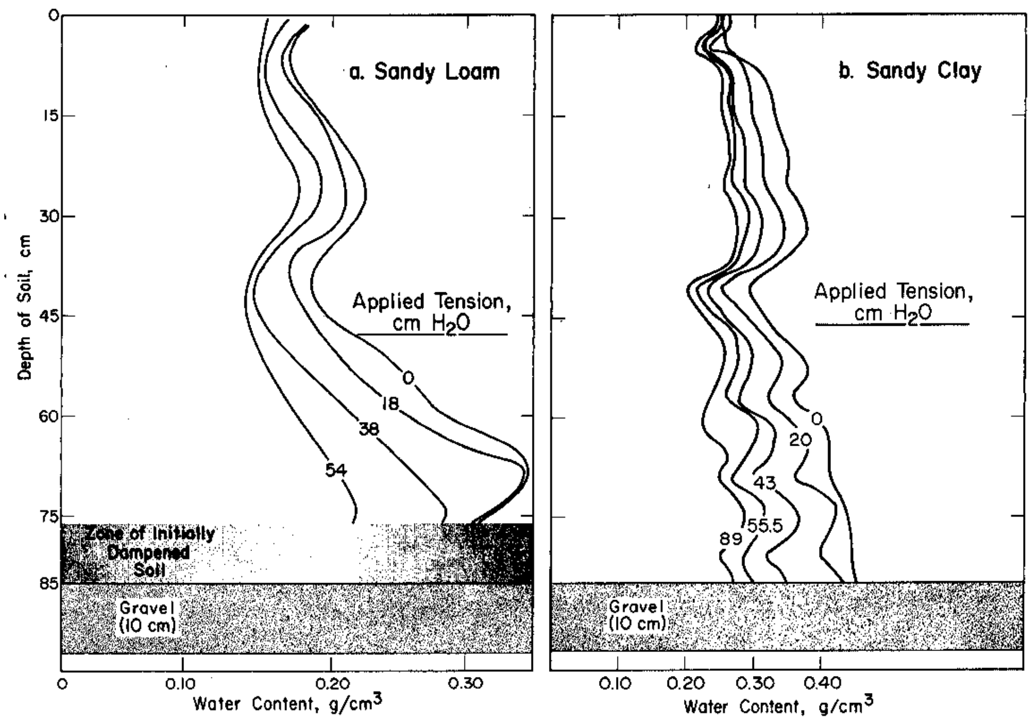


FIG. 3 DRAINAGE OF WATER

shown in Figures 4a and 4b. Water began to flow from the soil into the gravel during the third increment of water to the sandy loam soil and during the fourth increment (not shown in figure) of water to the sandy clay. Water content changes in the column were greatest close to the gravel lens.

These results show that gravel is a barrier to soil moisture flow as long as the overlying soil remains water unsaturated. Also, after drainage the soils in this study are capable of containing, without becoming saturated, amounts of water equal to or greater than the amounts that would be expected to infiltrate during most individual rains.

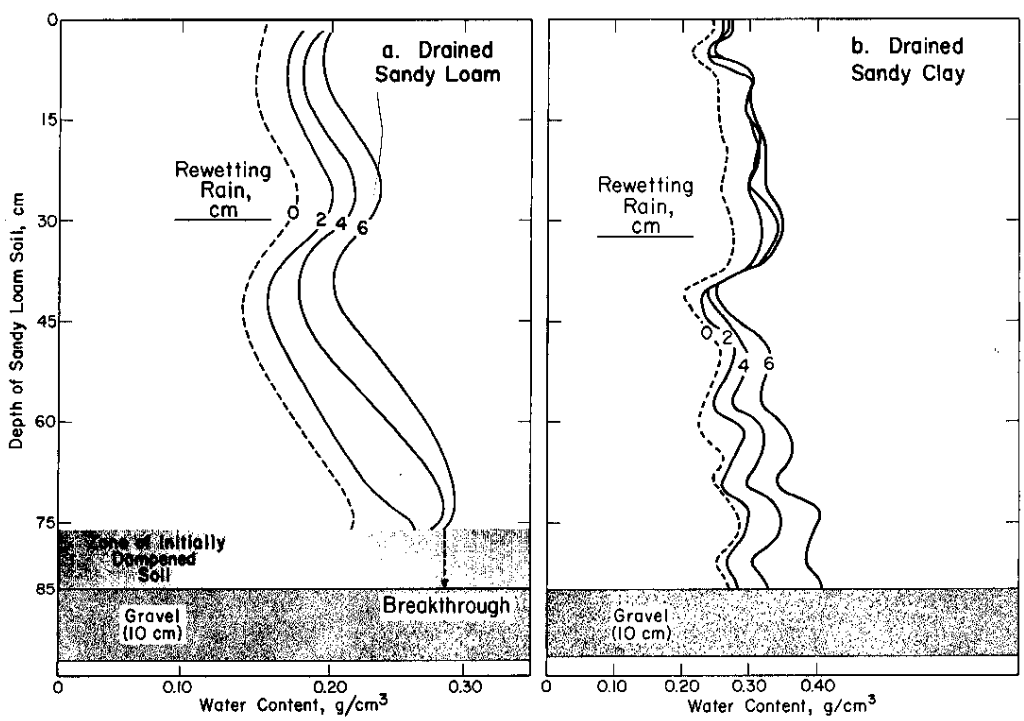


FIG. 4 REWETTING WITH 2-cm INCREMENTS OF RAIN

Flow Paths Around a Triangular Gravel Lens

Flow lines obtained when dye was used to trace movement of water through a container having soil in which there was a triangular gravel lens are shown in Figure 5. The streamlines show that gravel lenses can divert percolating water around them when the overlying soil is unsaturated. Even at a considerable distance from the gravel lens, the dye traces are deflected by the alteration in flow paths resulting from the barrier to flow.

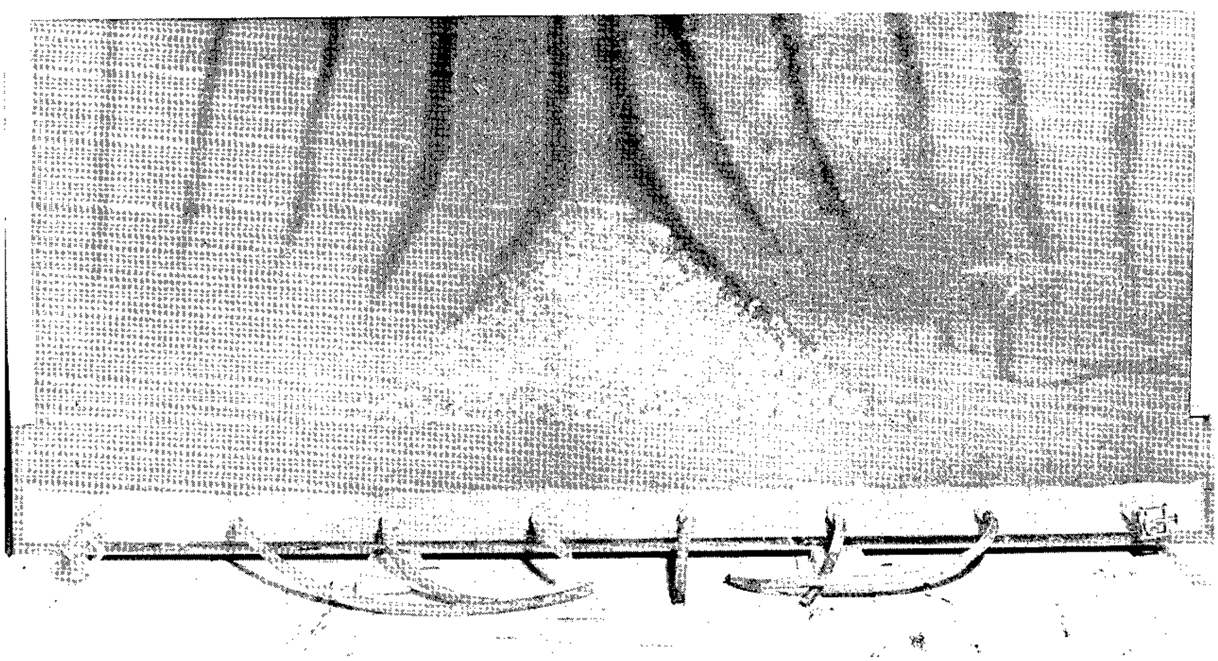


FIG. 5 UNSATURATED WATER MOVEMENT AROUND A TRIANGULAR GRAVEL LENS

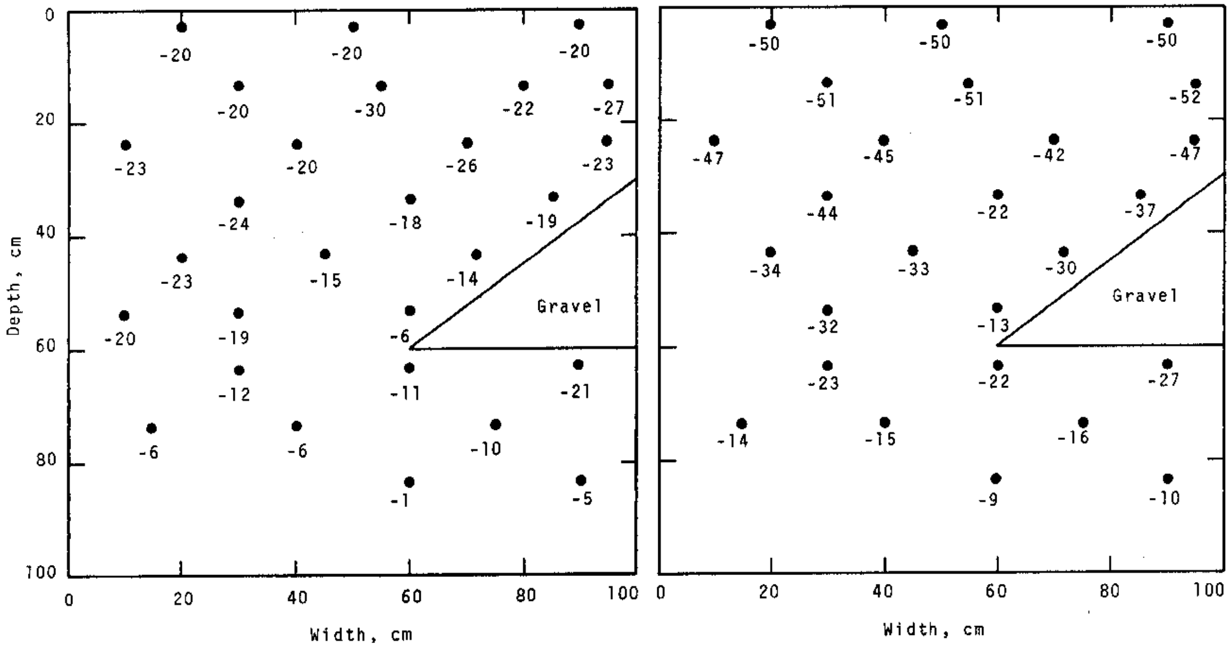
Measured Soil-Water Pressures Near Gravel Lenses

The tensiometer readings for the laboratory study on water pressure in the vicinity of a gravel lens are shown for tensions of 20 and 50 cm in Figure 6 after steady-state conditions were reached. Because all pressures were less than atmospheric, no water flowed through the gravel. The regions of lowest tension (highest water content) are at the bottom tip of the gravel lens. There are some values that are illogical. These values are attributed to heterogeneous packing and settling of the soil.

Calculated Soil-Water Pressures Near Gravel Lenses

The calculated pressure distribution for the laboratory-scale model is shown in Figure 7. A comparison of the values in Figures 6 and 7 indicates that the observed values generally correspond with the predicted values. The discrepancies between observed and predicted values are attributed to nonuniform packing. Even greater discrepancies would be expected in tests of larger gravel lenses.

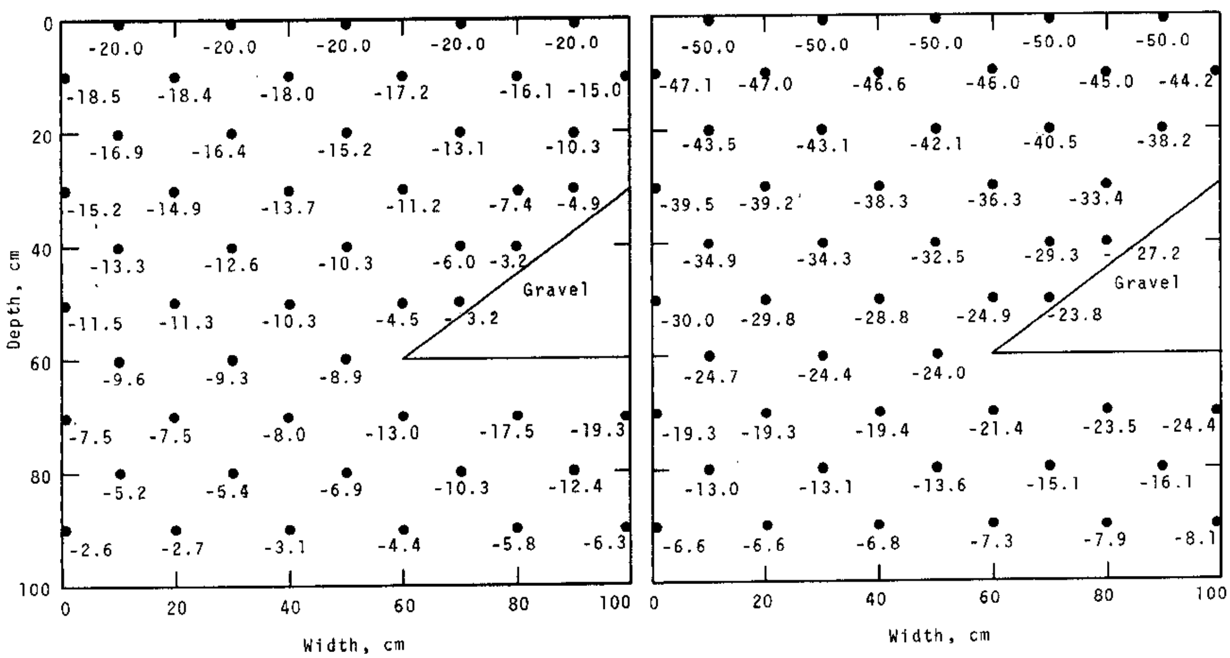
In contrast to the smaller lenses where the soil remained unsaturated, the calculated pressure distributions for barriers larger than the laboratory model (Figures 8 and 9) show that zones of water saturated soil can be expected in the vicinity of triangular gravel lenses whose base is at least two meters wide when water is added to the soil surface continuously at 20 or 50 cm of tension. The saturated region was at the peak of these large lenses; the wettest soil close to the small lenses (those remaining unsaturated) was near the corner of the lens. In actual tests, positive pressures would not develop above the gravel because water would flow through the gravel.



a. Tension of 20 cm of Water

b. Tension of 50 cm of Water

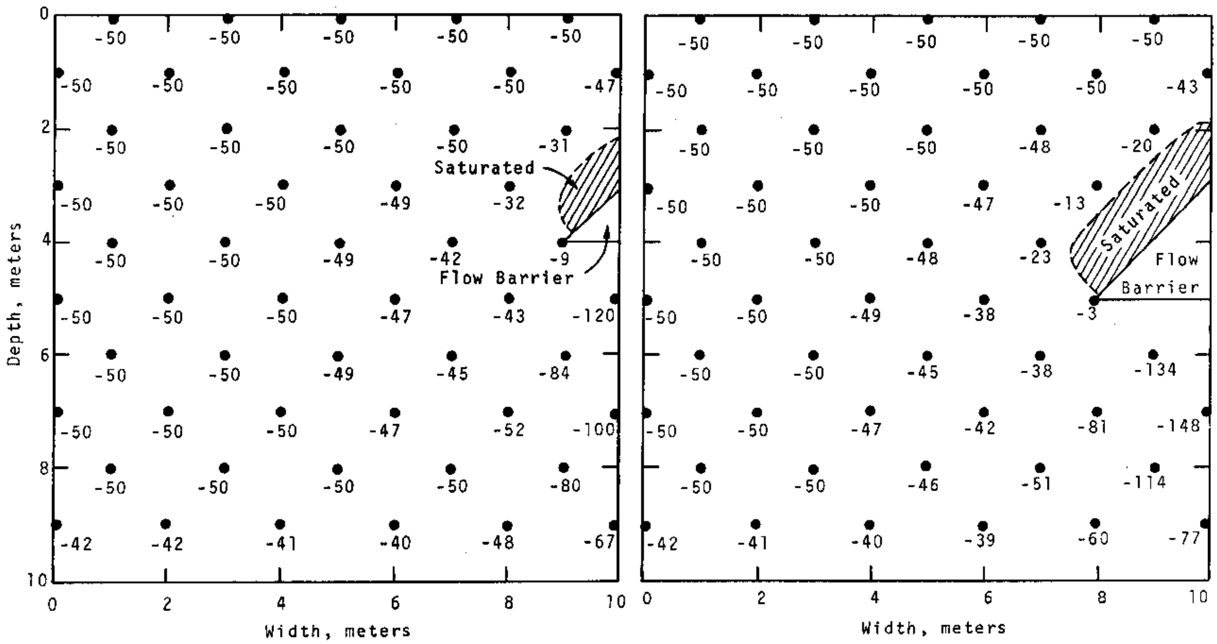
FIG. 6 OBSERVED SOIL-WATER PRESSURE DISTRIBUTIONS IN A LABORATORY-SCALE EXPERIMENT



a. Tension of 20 cm of Water

b. Tension of 50 cm of Water

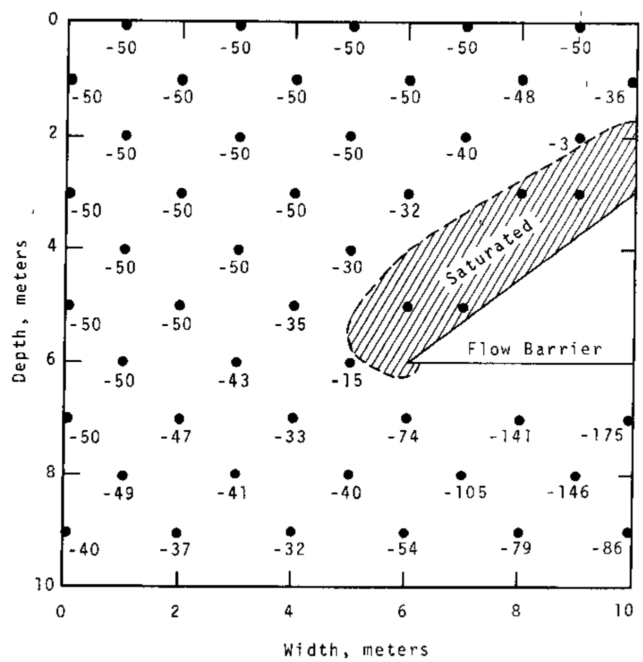
FIG. 7 PREDICTED SOIL-WATER PRESSURE DISTRIBUTIONS IN A LABORATORY-SCALE EXPERIMENT



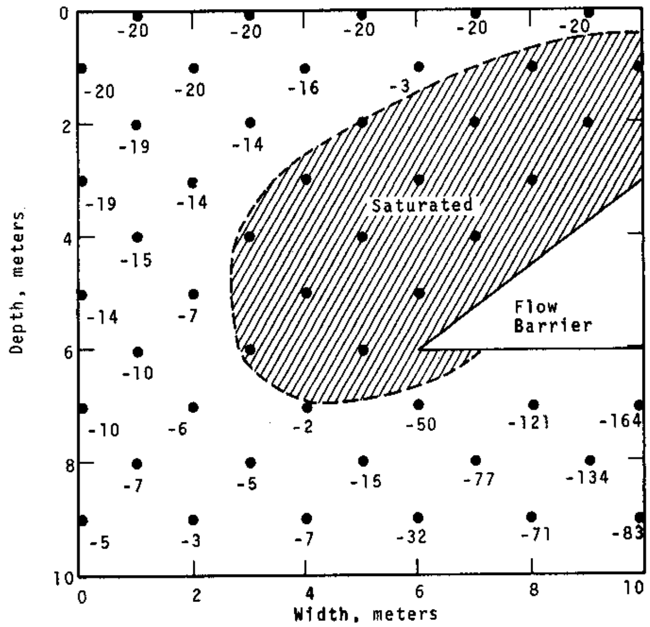
a. 2 x 1 meters

b. 4 x 2 meters

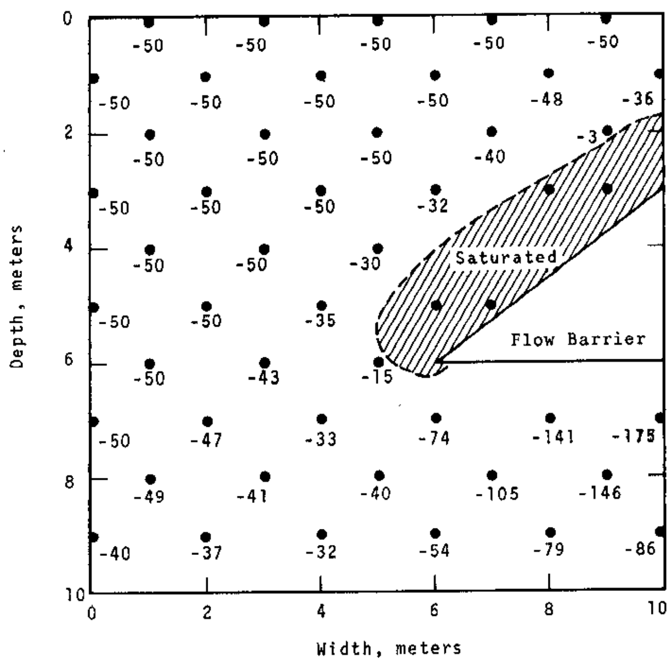
FIG. 8 PREDICTED SOIL-WATER PRESSURE DISTRIBUTIONS FOR THREE SIZES OF FLOW BARRIERS AT A TENSION OF 50 cm OF WATER



c. 8 x 3 meters



a. Tension of 20 cm of Water



b. Tension of 50 cm of Water

FIG. 9 PREDICTED SOIL-WATER PRESSURE DISTRIBUTIONS AROUND AN 8 x 3 METER FLOW BARRIER

CONCLUSIONS

The infiltration, drainage, and rewetting studies with sandy loam and sandy clay soil show that a gravel layer 85 cm below the soil surface can significantly increase the water holding capacity of the soil and that water does not flow through the gravel until the soil in contact with the gravel becomes saturated. After the sandy loam soil had been drained until the tension on the water in soil in contact with the gravel was 54 cm, the soil could store 5 cm of infiltrating rain before water flowed into the gravel. After drainage to a tension of 89 cm, the sandy clay could store 7 cm.

Under field conditions where tensions greater than 300 cm are common due to vertical drainage and tensions greater than 15 atmospheres are common at the soil surface due to evaporation, the temporary storage capacity will be even greater. These quantities of temporarily stored water exceed the amounts of infiltrating rain which would be expected during most individual rains; for gravel to prevent all leaching of radioactive waste buried beneath or in the gravel, this temporarily stored water must drain around the gravel between rains.

During periods of prolonged rain, flow around the gravel must be adequate to prevent saturation of the soil above the gravel. The theoretical calculations showed that the latter objective cannot be obtained with gravel lenses as small as two meters and in actual practice heterogeneous packing of the overlying soil would probably further reduce the effective size of the gravel lens. A 2-meter lens is too small to protect burial trenches of a satisfactory width in humid regions. A large gravel lens may have some practical value as a secondary barrier below a low permeability clay, because flow is governed by the least permeable layer.[9,10] In this case, the clay layer need only restrict flow to the rate at which it can be diverted by the gravel. In regions where the quantity of rain percolating to the water table is very low and where prolonged rainfall does not occur, gravel lenses would be effective barriers.

This study indicates that much of the buried solid radioactive waste is immune to leaching, because a large percentage of the buried radioactive material is inside vessels, pipes, and other process equipment. Openings in this equipment are usually smaller than the gravel lens used in the laboratory studies. If the interior of the equipment is not filled with soil, the same phenomena which diverts water around gravel will prevent leaching of the interior of this equipment.

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