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THE INFLUENCE OF VADOSE ZONE CONDITIONS ON GROUNDWATER POLLUTION

PART I: BASIC PRINCIPLES AND STATIC CONDITIONS

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Summary

The significance of the vadose soil zone (i.e., above a water table) is of the utmost importance in groundwater pollution problems. Much of this zone is unsaturated, such that fluid movement and contaminant attenuation conditions are favorable for mitigation of aquifer pollution. In this paper, the basic principles of moisture retention and the implications for leachate control are described in a state-of-the-art format.

To illustrate the use of these concepts six generalized examples are presented. They cover a wide range of practical situations, including:

- vadose zone storage
- land treatment of wastewater and sludges
- waste dewatering
- hydrocarbon spill storage
- capillary break situations
- air and water drainage under liners

Since this paper treats only the static condition, a companion paper will be offered shortly dealing with leachate flow and seepage in a wide range of applications.

Introduction

Much of the study of groundwater pollution has focused on contaminant movement in saturated aquifers [1]. However, in many cases, seepage from surface facilities must first pass through the vadose zone, which is that portion of the geologic profile above the water table. Much of this zone is unsaturated, and contains air and other gases entrained in the pores. This complicates the movement of leachate through soil because the permeability of the vadose zone varies with the degree of saturation. The hydraulic gradient driving the flow may have a component that is a function of capillarity. Darcy's Law, the basic description of macroscopic fluid flow in porous media, can be used to describe flow in such unsaturated materials. The rate of leachate seepage into a water table equals the rate that can pass through the vadose zone.

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Groundwater pollution is mitigated in soil by several physical, chemical and biological processes which retard or transform either the dissolved contaminants or the liquids carrying them [2—4]. Dilution due to mechanical dispersion and molecular diffusion also reduces waste concentrations, but does not change pollutant mass [1,4]. Those contaminant attenuation processes which require oxygen, venting of decomposition gases or vaporization of volatile fractions require an unsaturated condition. The ability of the vadose zone to support wastewater reactions is evident by the success of millions of domestic and commercial septic systems. Failure of such systems is often associated with submergence, overloading or other conditions which raise the degree of saturation [5].

Physical and other chemical retardation processes may also be very efficient in the vadose zone. For instance, the leachate concentration is highest in the soil directly under the source. Consequently, reactions that vary with pollution concentration may occur most intensively as the degree of saturation is reduced. Therefore, conditions are favorable for adsorption and cation exchange on clay particles in the vadose zone. The low water content of unsaturated soil also reduces the mass of dissolved and mobile contaminants during reactions involving solubility limits.

Porous materials retain water under tension as a function of soil structure, ambient fluid pressures and other factors. Moisture deficiencies in soil occur when the moisture content is below that at equilibrium. In this case, seepage liquid as well as the dissolved materials conveyed in it are retained in the soil. The retained leachate is temporarily or permanently prevented from percolating down to an aquifer.

It is necessary to estimate the rate of seepage and the degree of saturation within the vadose zone as a first step in the evaluation of potential impacts of contaminated seepage impact. The purpose of this paper is to present an overview of the hydraulic principles of fluid flow and moisture retention in the vadose zone. With these principles well in hand, data on the hydraulic loading to a facility and the subsurface soil properties can be used to assess leachate mobility. Both hydrologic and geochemical information is necessary to complete an estimate of the total impact of seepage on groundwater resources.

This paper is presented in two parts, of which this is Part I. Included in this portion are descriptions of the zones of soil moisture, the basic principles of capillary conditions in soil, methods of evaluating moisture distribution in soil, and examples of how unsaturated conditions can affect moisture movement in static or quasi-static situations. Part II presents the principles of flow in the vadose zone and several general examples of seepage analysis. Both steady-state and transient conditions are considered. These two papers show how vadose zone conditions and soil properties can be useful in the analysis of groundwater pollution, and in the design of mitigating procedures.

Static distribution of soil moisture

An understanding of the subdivisions of the groundwater regime under static conditions is required to deal with problems involving the vadose zone. Under static conditions, this zone can be divided into three subdivisions as shown on Fig. 1 [7].

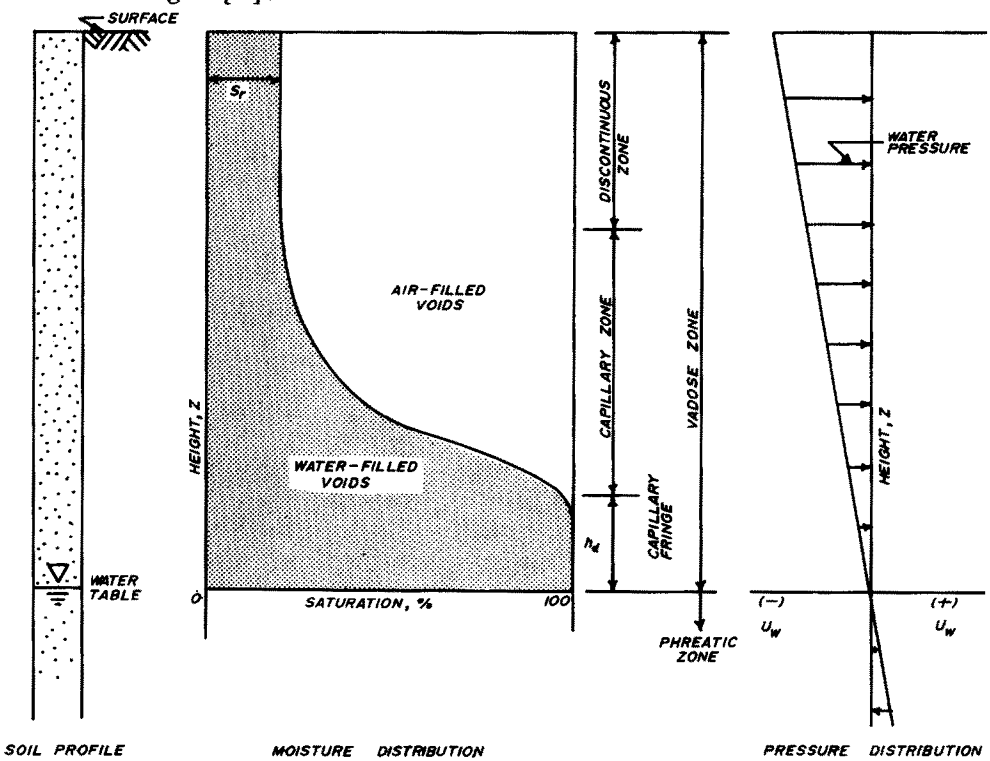

Fig. 1. Hydrostatic pressure and zones of soil moisture above a water table.

Before discussing the definitions and features on each subdivision, it is useful to note some of the conventions employed in groundwater analysis. The pore water pressure, u_w, is one of the controlling variables in all hydraulic problems. It is customary to consider compressive water pressures as positive, thus the tensile stresses that exist above the water table are negative. Hence, it can be seen from Fig. 1 that the water table, at atmospheric or zero gage pressure, is the basic division between the phreatic zone of positive pressure and the vadose zone.

It is often convenient to convert water pressure, which has the units F/L^2 to a water pressure head, h_p, as expressed in units of length:

$$h_p = \frac{u_w}{\rho_w g} = \frac{u_w}{\gamma_w} \tag{1}$$

where the terms ρ_w and γ_w are the mass density and unit weight of water, respectively. The values of h_p and u_w vary linearly with the distance above the water table under static conditions. Consequently:

$$h_p = -z \tag{2}$$

The water table is also called the phreatic surface, below which all soil voids are usually saturated. The water table elevation can be determined in the field by installation of observation wells that penetrate an aquifer. However, accurate measurement of the water table in wells requires pipe casing of sufficient diameter to prevent a capillary rise (e.g., over 0.5 inch diameter). Water will freely enter such a well through screens, and samples for the analysis of water quality can be recovered by pumping or bailing.

Soil water in the vadose zone is under tension, so that water will not enter an observation well completed in the vadose zone. It is necessary to use tensiometers to measure the water pressure and lysimeters to obtain samples [8].

The three static divisions of the vadose zone are differentiated by the relationship between moisture content and water pressure in each level:

a. Capillary fringe

The capillary fringe is the zone of essentially complete saturation under negative pressure that extends for some distance above the water table. The capillary fringe can be observed in trenches that penetrate to the water table. The thickness of the capillary fringe, h_d, can be approximated by:

$$h_d = \frac{4T_s}{\gamma_w d_{50}} \tag{3}$$

where T_s = surface tension (F/L); d_{50} = average pore diameter (L); and γ_w = unit weight of water (F/L^3).

It can be seen from eqns. (1) and (2) that the top of the capillary fringe represents a specific negative water pressure. The height of the capillary fringe in soil is analogous to that of capillary rise in a tube of a specific diameter. The capillary rise in a soil is inversely proportional to the mean pore diameter, which is primarily a function of the soil texture, or gradation, but is also dependent upon porosity and other factors. Consequently, h_d is higher in fine-grained soils than in coarse materials. This is illustrated in Fig. 2, and some typical values of h_d are given in Table 1 [6].

b. Capillary zone

As shown on Fig. 1, the soil profile is unsaturated above the capillary fringe. The unsaturated capillary zone is the interval of the unsaturated zone where air and water each occupy a portion of the pores and each fluid portion is interconnected in tortuous channels. The radius of each interface between air and water is a function of the difference between the two fluid pressures, the capillary pressure. In general, interfaces are located in a void where the interface and pore radii are similar, as shown on Fig. 3. Smaller pores contain water, larger pores contain air.

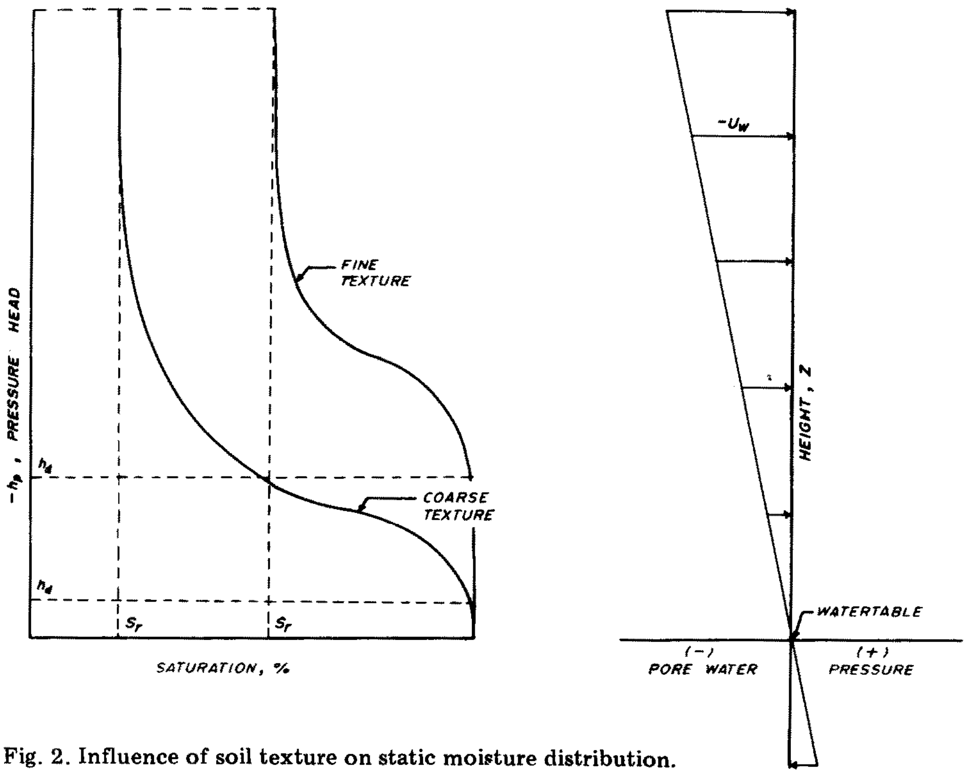

Fig. 2. Influence of soil texture on static moisture distribution.

TABLE 1

Typical values of capillary rise, h_d, in various soils, after Lambe and Whitman [6]

Description	d_{10}[a] (mm)	e[b]	h_d (cm)
coarse gravel	0.82	0.27	5.4
sandy gravel	0.20	0.45	28.4
silty gravel	0.06	0.45	106.0
fine sand	0.03	0.36	165.5
silt	0.006	0.95	359.2
clay	–	–	>500

[a] d_{10} = effective soil size, i.e., particle size at which 10% of the soil mass is finer than the balance.
[b] e = void ratio, i.e., volume of voids/volume of solids.

In a porous medium, one of the fluids present preferentially wets, or is adsorbed on particle surfaces. In most soils, water is the wetting fluid, while air, hydrocarbons and other immiscible fluids are the non-wetting fluids [7]. In an air—water system, the capillary pressure is:

$$p_c = u_a - u_w \tag{4}$$

where p_c = capillary pressure (F/L^2); u_a = air pressure (gage); and u_w = water pressure (gage).

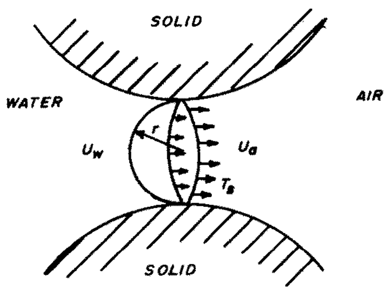

Fig. 3. Curved air—water interfaces in porous media.

Under conditions of zero air pressure and negative water pressure it can be seen that p_c is a positive value, equal and opposite to the water pressure. Capillary pressure can also be expressed as a pressure head, h_c, by dividing p_c by the unit weight of water. Therefore, h_c increases with height above a water table if the water pressure distribution is hydrostatic. The height of the capillary fringe is numerically equal to a specific value of h_c. In static cases, the ordinate of Fig. 1 can be labeled z, $-h_p$, or h_c, as required. This is not true when there is vertical movement of water.

Surface tension maintains equilibrium on the air—water interfaces as shown on Fig. 3. The radius, r, of the interface is defined with the Kelvin capillary model [9]:

$$r = \frac{2T_s}{p_c} = \frac{2T_s}{h_c/\gamma_w} \tag{5}$$

The interface radius decreases with height above a water table as p_c and h_c become larger. As the interfaces retreat into smaller pores, the moisture content also decreases. It can be seen from Fig. 2 that coarse-grained soils with few small pores are free draining, or decrease in moisture content more rapidly as the distance above the water table increases. Fine-grained soils retain high moisture contents at considerable distances above the water table.

c. Discontinuous moisture zone

The degree of saturation reaches a limiting value in each soil at some height above the water table, as shown on Figs. 1 and 2. The discontinuous moisture zone is the portion of the vadose region above this level. The water retained in the soil is strongly sorbed on the surface of solid particles, and is not displaced by air as the capillary pressure increases. However, this strongly attracted moisture can be removed by evaporation and plant transpiration (evapotranspiration). Equation (5) does not apply in this zone. The water film does not comprise a channel capable of transporting water [10].

The minimum saturation under hydrostatic conditions is called the residual displacement saturation, S_r. Its value is a function of specific surface (area per unit volume) of the soil, shape of the pores, and interactions between the solids and the soil water. Low values of S_r (5—15%) are observed in granular (coarse) soils, since they are generally inert and have a low specific surface. High values of S_r occur with fine-grained or well-graded soils, due not only to their high specific surface, but also as a result of solid particle attractions for water.

Retention curves

The relationships between saturation and capillary pressure that are shown on Figs. 1 and 2 are called capillary retention, suction, or pressure—saturation curves. Such curves are characteristic of a particular geologic formation suggesting that retention is a property of the soil material and its structure.

The most obvious value of a retention curve is as an indicator of drainability [9]. An initially saturated soil or waste material will drain to a moisture distribution shown by its retention curve. An index of such drainage is the specific yield, the ratio of the volume of water that a soil will yield by gravity drainage to the total volume of the soil.

The distribution of moisture with depth that is shown on Figs. 1 and 2 is a function of the microscopic pore geometry (eqn. 5). The moisture content and the soil structure also govern the resistance of the soil to flow of fluids. Two properties used in the analysis of fluid movement have already been discussed, h_d and S_r. Parameters which are similar in value to the capillary pressure at h_d include the air entry, displacement pressure and bubbling pressure [7]. For the purposes of preliminary analysis all of these parameters can be treated as being equivalent. Various mathematical functions can also be used to derive an index of the pore-size distribution from suction curves [10]. The relative amount of water retention, or drainability, is also an index of permeability. Low values of S_r and h_d indicate a high ability to transmit water when the soil is saturated. The use of these properties in flow analysis will be discussed in Part II.

The retention curve of a geologic formation can be obtained by measuring the moisture content at intervals of a soil core sample. A graph of the moisture versus depth represents hydrostatic conditions, provided that a sufficient time has elapsed since a recharge event, such as rainfall or irrigation. Figure 4 shows such a curve for a stratified soil formation, such that the two soils shown on Fig. 2 are interbedded. Figure 4 includes sections of the retention curves of each material over the appropriate pressure or height intervals. Also shown on Fig. 4 is a shallow drying zone that may be encountered in the field. This zone of moisture deficiency is the result of evaporation and plant transpiration [11]. When the moisture content is below S_r, as is common near the surface, eqn. (2) does not apply.

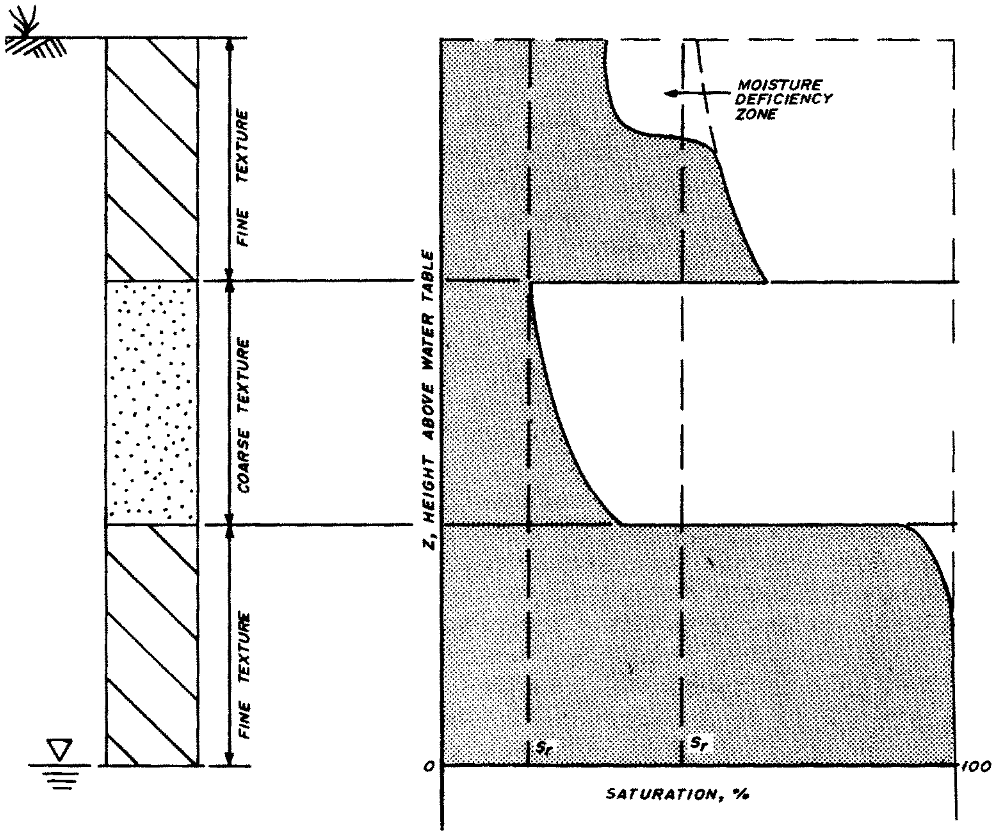

Fig. 4. Influence of stratification and evapotranspiration on field moisture retention.

Retention curves can also be generated in the laboratory using representative field samples or samples of materials to be placed in a project, such as wastes and compacted clay liners. These curves can be developed either on a desaturation or an imbibition cycle [12]. Various experimental methods are discussed in Refs. [7] and [13], while the physics of desaturation is examined in Ref. [14].

In the laboratory, the sensitivity of moisture retention to various influences can be assessed. As noted previously, the major influence on the retention curve is the soil gradation [15]. However, the other physical and chemical properties and conditions are also important. Densifying a soil reduces its porosity and the average pore diameter. Therefore, a given soil in a dense condition will have higher values of S_r and h_d than if it is in a loose state [16]. Changes in these properties will occur if the site subgrade compresses, or if a waste is compacted [17].

The fabric, or arrangement of soil particles, also influences the unsaturated hydraulic properties. Clays which have a flocculated fabric (random particle orientation) have higher average pore radii than do clays which have a dispersed, or aligned structure. Therefore, a particular clay soil in a dispersed fabric will tend to retain more moisture than the same soil that is in a dispersed structure [18,19]. Natural sediments tend to have a flocculated structure, whereas compacted soils tend to have a higher degree of particle dispersion.

Soil water retention is also affected by the chemical properties of the solids and fluids. These conditions vary with the amount and type of groundwater contamination. Chemical conditions are especially critical in clay soils,

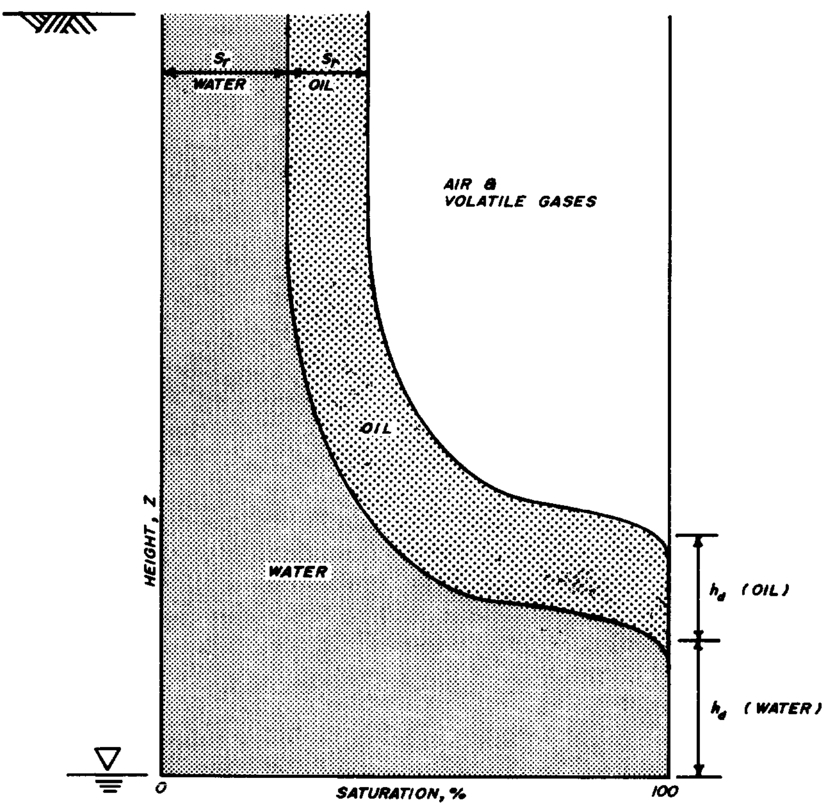

Fig. 5. Retention of multiple immiscible fluids in the vadose zone (homogeneous soil).

which have special significance due to their low permeability and value in contaminant sorption and cation exchange. The geometry of the air—water interface in clay soils is not completely defined by eqn. (5), but is the resultant of adsorptive and osmotic forces in addition to surface tension [20, 21]. The diffuse ionic double layer theory is often used to describe water sorption by clay minerals [22]. It has also been shown that permeation of clays with certain hazardous organic materials increases the saturated permeability of clay materials due to reduction in the thickness of the adsorbed water layer [23,24].

When other immiscible fluids are present in soil in addition to water and air, an order of "wetness" is established. For instance, petroleum-based hydrocarbons are less attracted to solid surfaces than is water, but more so than air. Hence, an immiscible hydrocarbon that is lighter in density than water forms a retention curve atop that of the water, as shown on Fig. 5 [7]. Residual saturations of petroleum products range from 10% for light hydrocarbons such as gasoline to 20% or more for heavy lubricating oils [25]. Thus, it is not possible to remove all of an oil spill from soil by pumping [26].

Applications

In this section, the use of unsaturated soils to control leachate generation and movement is discussed by way of six generalized examples. The implications for gas movement and groundwater pollution mitigation processes are also discussed.

Example 1: Vadose zone storage

The upper part of the vadose zone is subject to water loss by evapotranspiration. The results of this process were shown on Fig. 4. When the near-surface moisture content is below the residual saturation, the negative water pressures are extremely high, and the soil has a high suction capacity. Therefore, water will be sorbed up to the equilibrium retention if it is made available.

The depth of the moisture deficiency zone can be considerable in arid or semi-arid areas. The natural cycle of rainfall wetting and subsequent evapotranspiration may be confined to the upper few meters, so that a deep dried zone is often a permanent natural feature. Hence, it appears feasible to use this zone to isolate containers of toxic wastes [27]. Leakage from such buried containers would be retained in the immediate area due to sorption of moisture in the soil or rock.

The concept of vadose zone storage is also employed at mine tailings ponds to prevent seepage from reaching the water table [28]. The seepage initially travels as an advancing wetting front, as shown on Fig. 6. The wetting front moves downward under a hydraulic gradient including both gravity potential and pressure difference components. It can be seen from Fig. 6 that the degree of saturation in the zone of moisture deficiency in advance of the wetting front is lower than the residual saturation at the trailing end. Hence, water is retained, and the wetting front tends to dissipate. If the residual saturation, the existing saturation, S_o, and the soil porosity are known, then the amount of adsorption potential in a unit volume of soil is:

$$\text{Potential storage} = (S_r - S_o)\, n \tag{6}$$

The volume of seepage contacting the water table is less than that escaping the impoundment by the amount stored in accordance with eqn. (6). The final moisture distribution will approximate the hydrostatic distribution (see Fig. 2) insofar as liquid is available to fill such a moisture profile.

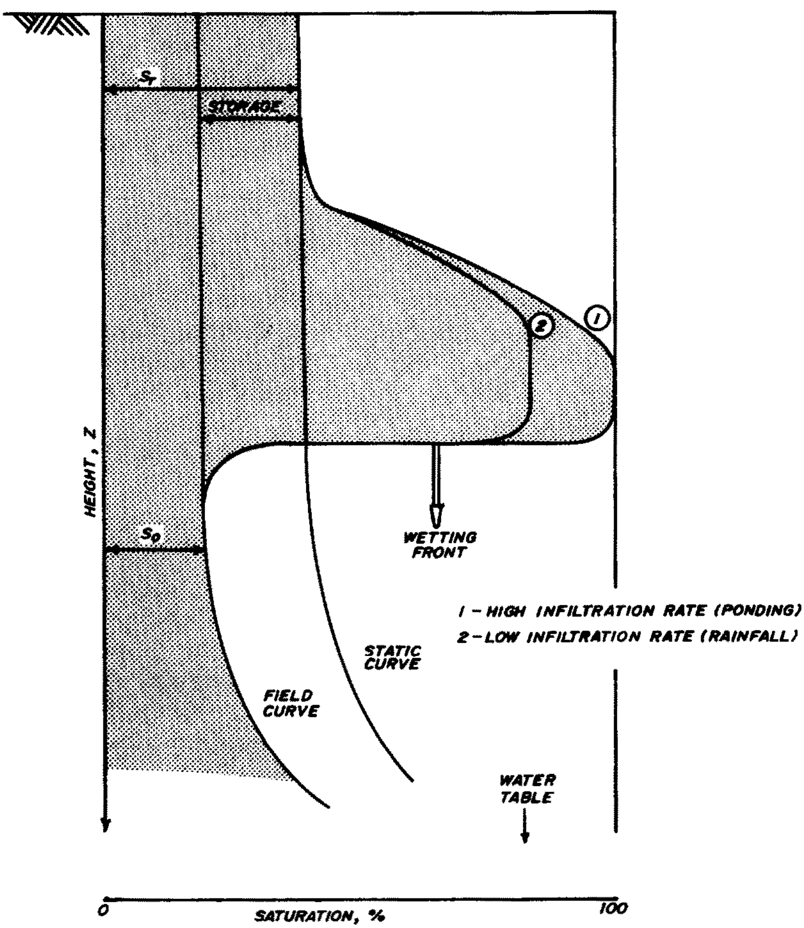

Fig. 6. Storage seepage liquid in zones of moisture deficiency.

The initial storage capacity can only be used once, unless the adsorbed fluid evaporates. This will not normally occur under a waste impoundment. Rather, subsequent wetting fronts that arise from continued leachate seepage or rainfall recharge will tend to displace rather than bypass previously adsorbed leachate [29]. However, the more gradual release of contaminants allows dilution in the underlying flowing aquifers. A change in the quality of the seepage may also re-mobilize materials which have been converted to solid form [30]. For example, a drop in pH may redissolve contaminants which have precipitated due to neutralization of the initial wetting fluid. Therefore, a dependence on moisture adsorption by design is most viable when the rainfall recharge is low, a discreet volume of leachate is available to leak from a given site, and the moisture deficiency zone is deep.

The concept of vadose zone storage can also be used in humid areas even if the natural moisture deficiency zone is not very deep. Fills that are placed under liners to establish the design grade, and compacted clay liners themselves may also form a moisture deficiency zone. Therefore, some leakage through landfill and lagoon liners will be retarded in the subgrade. Grading the surface of a landfill, and installation of an impermeable cover will reduce infiltration. With these measures, the mobility of the leachate is lessened and an element of redundancy is added to the design.

Example 2: Land treatment of wastewaters and sludges

The capacity of the drying zone that occurs between rainfall events and the ease of gas circulation may be useful parameters in the design and operation of land treatment facilities for waste liquids. Neither covers nor liners can be installed, so it is essential to limit the initial depth of penetration of each sludge or wastewater dosage [23].

The purpose of most land treatment systems is to purify wastes by a variety of physical, chemical and biological processes. Eventual seepage of applied liquids to the water table is not a serious problem if the dissolved or suspended contaminants have been stabilized in the soil. Waste treatment in soil is more efficient if aerobic conditions can be maintained [32]. Consequently, land treatment of wastes depends primarily on irreversible purification processes that do not result in the accumulation of soluble evaporites. This is a particular concern if these solids are toxic and can be adsorbed by plants [33]. Over-application of wastewater or submergence during high rainfall causes anaerobic conditions. Consequently, the treatment zone clogs with an increased biomasss and an accumulation of incomplete decomposition products [34].

It is critical that the amount of rainfall infiltration be minimized by the use of proper surface drainage. This will prevent premature vertical displacement of incompletely treated wastewater to deep zones of low oxygen availability. Moisture deficiency conditions are restored by evapotranspiration as the soil dries after a sludge application. During this period, oxygen is replenished, decomposition gases are vented, and larger proportions of the soil liquid are in intimate contact with the solid surfaces and scavenging biomass [32]. Excess rainfall infiltration delays the drying process, reduces air circulation, and thus extends the dosing interval.

With all other things being equal, layered soils offer the most opportunities for contaminant treatment [35]. For example, a coarse, free-draining material near the surface provides a matrix for biomass anchorage in aerated conditions. If that soil is underlain by another with some clay content, seepage penetration is restricted and cation exchange capacity may exist for solutes not stabilized biologically.

Example 3: Waste dewatering

Dewatering solid or semi-solid wastes before deposition in a disposal site reduces the required impoundment capacity and also decreases the initial volume of leachate that will drain. The residual moisture content and the moisture content that is optimum for compaction are about the same in some bulk process wastes [16]. In this case, dewatering can result in both a reduction of leachate volume and the most favorable conditions for compaction.

However, if the dewatered waste is placed at a moisture content below its residual value, some of the rainfall that infiltrates through a landfill cover will be adsorbed. By itself, this condition reduces the mobility of leachate that may be produced. It will be shown in Part II that the depth of liquid accumulated on a liner significantly influences the rate of seepage [28].

Example 4: Hydrocarbon storage

The concept of underground adsorption of liquids is particularly useful in estimating the impact of an oil product spill or leak on the groundwater. As noted in a previous section, hydrocarbons that are less dense then water are retained in soil up to a residual saturation [25]. A previously uncontaminated soil has the full amount of potential storage indicated by eqn. (6), such that there is a zero value of S_o for the oil product. Therefore, hydrocarbons that penetrate the ground surface might not reach a deep water table.

However, oil retention in a soil does not provide a panacea for aquifer pollution. The lighter fractions of an oil product retained in the soil tend to dissolve with time in percolating water produced by rainfall [26]. The severity of the spill impact on groundwater is lessened due to the dilution so provided. Microbial treatment processes for subsurface oil product decomposition have been developed [36]. Such decomposition requires air, however, and thus, unsaturated conditions.

Example 5: Capillary break

Water does not readily move into an unsaturated coarse material from a fine-grained soil unless the moisture content of the latter material is quite high [37]. This is the concept of the capillary break, which can be employed to reduce infiltration through landfill covers. In particular design arrangements, such a break can also provide gas venting and promote surficial plant growth at landfills. Figure 7 illustrates the concept.

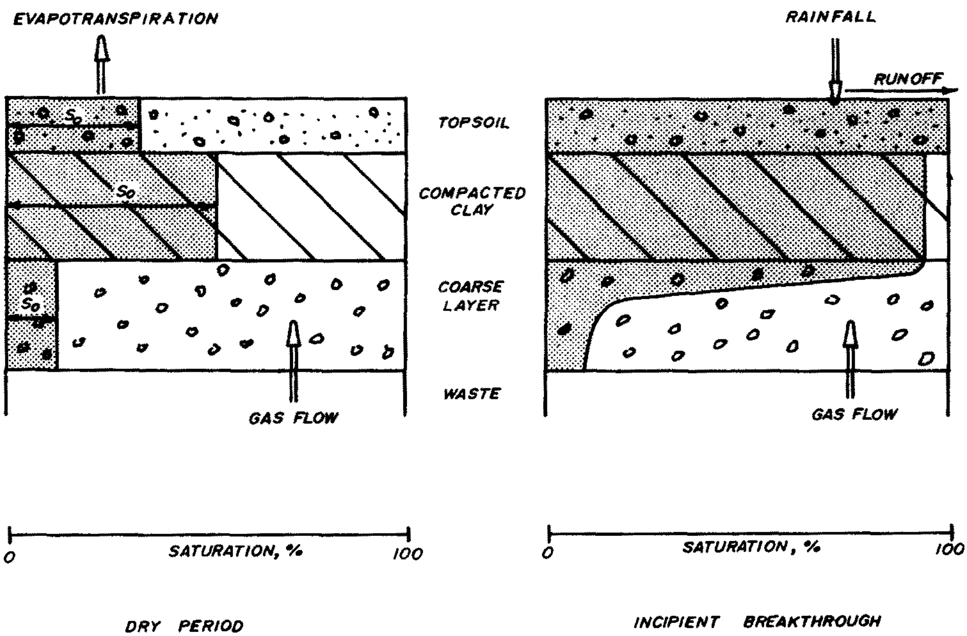

Fig. 7. Retardation and near-surface storage of rainfall infiltration by a capillary break.

The basic mechanism of the capillary break is that the capillary pressure head in the upper layer, h_c, must decrease to a value similar to the displacement pressure head, h_d, of the underlying material before breakthrough occurs [18]. A delay in this breakthrough is provided by using the highest textural contrast between layers that is possible, such as the use of a compacted clay cover over a coarse gravel. The upper layer will tend to retain more of the surface infiltration than it would if the cover were homegeneous, since downward transmission is delayed. However, provisions to prevent internal erosion when a breakthrough occurs must be considered [38]. If the time frame of the breakthrough delay exceeds that of the rainfall event, little or no water passes into the coarse layer, and hence, into the waste pile. The moisture retained in the upper layer is near the surface, and will thus be eventually removed by evapotranspiration [29].

Several other benefits accrue from the construction of a capillary break in a landfill cover system. The higher moisture in the upper layer improves the environment for plant growth, and thus erosion and cracking are reduced. The coarse layer forms a porous reservoir in which methane and other gases rising from the landfill are accumulated. Such gases can either be channeled to collection points or vented at intervals through the cover. Within the landfill, the process of waste decomposition produces gases that require room for expansion or escape, or else high pressures result. Soils and membranes which do not readily transmit liquids also tend to act as gas barriers and thus may force the gas to migrate laterally, into the soil around the fill. Explosion of volatile gases and migration of methane to nearby basements are serious problems [39]. Provision for gas escape routes makes it feasible to install a impermeable clay or geomembrane cover without undue concern that high gas pressures will cause unwanted side effects.

A capillary break is not likely to perform well under a liner as a means to prevent movement of seepage. The existence of a positive pressure on the liner at the point of a leak will force rapid saturation, and a breakthrough would occur quickly.

Example 6: Sub-liner drainage

It is often advisable, or even required, that a drain be placed under a liner in order to intercept and retrieve seepage. Such a drain will also protect a liner from rupture or flotation due to high gas pressure in the subgrade. As a seasonal water table rises, the air in the voids is displaced. Such displacement is difficult under a very wide liner over a shallow water table, so that high subliner air pressures can result. Leachate that is subjected to biological activity in the subgrade after leakage from a lagoon will also produce decomposition gases. "Whaling", or floatation of flexible membrane liners is a problem in shallow lagoons [38]. The overburden pressure restraining the liner is often low, because flexible membrane liners (geomembranes) are of negligible weight. Only about 0.8 psi of air pressure is necessary to lift a liner holding two feet of wastewater. Drains under liners provide both a means for air drainage and a passage for liquid retrieval.

Summary and conclusions

It can be seen from the preceeding discussions that the static distribution of moisture in a soil profile is primarily dependent upon the following factors:

- soil texture and structure
- fluid and solid surface chemistry
- fluid pressures
- evapotranspiration

If there is no evaporation, and the soil moisture has reached a static condition, then the moisture profile is the capillary retention curve. Examples of these curves have been presented. The in-situ moisture profile can be computed with data which are normally acquired in a site investigation. Laboratory tests can be used to indicate the variations in the moisture retention and other properties that would result from physical and chemical changes due to impoundment construction and seepage.

The use of such moisture profiles or retention curves include the following.

- basic site characterization
- depth of aeration
- volume of available moisture storage
- opportunities for leachate dilution before water table impact
- values of parameters used to analyze unsaturated flow, such as S_r and h_d
- general indication of permeability or ease of drainage

Six illustrative examples were provided in the paper.

Taking the described principles as a whole, one can appreciate the complexity of the unsaturated zone and the problems and challenges that lie therein with application to waste disposal problems. With sufficient insight, however, design and modeling can be more realistic, and emphasis can be placed on areas where more research might be directed. For example, there is a wealth of numerical data available in the agricultural literature regarding the influences on the properties of unsaturated natural soils. However, it is difficult to confidently do more than discuss trends in the variations of unsaturated soil properties that result from seepage of industrial solvents. Therefore, even preliminary design may require extensive laboratory or large-scale simulation work on an individual project. Similarly, the ranges of effectiveness for various materials combinations that might be used in capillary break formation are not extensively published, nor are data on oxygen transfer deep in the soil.

The concentration in this part is primarily on static conditions. Descriptions of flow in the vadose zone, also illustrated by examples, will form the second part of this effort.

Acknowledgements

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List of symbols

d_{10}	effective soil particle size
d_{50}	average soil particle size
e	void ratio
g	gravitational constant
h_c	capillary pressure head
h_d	height of capillary fringe; displacement pressure head

h_p fluid pressure head
p_c capillary pressure
r radius of air—water interface
S degree of saturation (water)
S_o field saturation
S_r residual displacement saturation
T_s surface tension
u_a air pressure (gage)
u_w water pressure (gage)
z height above the water table
γ_w unit weight of water
ρ_w mass density of water

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