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Project Summary

Effect of Capillarity and Soil Structure on Flow in Low Permeability Saturated Soils at Disposal Facilities

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Some permit applications propose to place hazardous waste land-disposal facilities in saturated zones of low-permeability (low-K) soils. Naturally occurring soils of this type are frequently anisotropic and heterogeneous. Heterogeneities may be of lower or higher permeability than the surrounding soils, and may range from small, isolated-pockets to large, interconnected zones. Low-K heterogeneities, particularly those extending long distances perpendicular to the flow direction, can retard flow. High-K heterogeneities, particularly those extending long distances horizontally or vertically to a location in or near the underlying aquifer, can result in rapid migration of any pollutants reaching these zones. Anisotropies in hydraulic conductivity can range across several orders of magnitude, resulting in rapid migration of facility releases.

The final report addresses the movement of the leachate after release from the facility and does not consider those factors relating to the containment afforded by the facility proper. Discussions include (1) soil characteristics and the influence soil-forming mechanisms have on the types of heterogeneities and anisotropies to be expected in low-K soil; (2) the roles played by the tension-saturated zone, anisotropies, and heterogeneities in subsurface leachate movement; and (3) the advantages and disadvantages of various available computer models to simulate leachate movement in the saturated, low-K anisotropic, and heterogeneous cases.

This Project Summary was developed by EPA's Hazardous Waste Engineering Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The EPA draft guidance document prepared to accompany the July 26, 1982, regulations for hazardous waste management recommends that liner systems be constructed wholly above the seasonal high water table, that is, in the unsaturated soil. The document further states that "a case-by-case demonstration of containment will be necessary for landfills located wholly or partially in the saturated zone." In all likelihood, permit applications will be received which propose to locate hazardous waste disposal facilities in a saturated zone of low permeability (low-K) soil.

The objective of this project was to assess the effects of heterogeneities, anisotropies, and the tension-saturated zone with respect to movement of subsurface leachate releases in saturated low-K soils. Soil characteristics and the influence of soil-forming mechanisms on the types of heterogeneities and anisotropies to be expected in low-K soils are discussed. The advantages and disadvantages of generic types of computer models for application to leachate movement in saturated, low-K soils are addressed. The basic requirements for adequate modeling and the data input needed to solve the models are identified and described. Two available computer programs are used to obtain sample model simulations and to generally demonstrate the usability of these and other codes based on similar computational techniques for prediction of contaminant migration in low-K soils. These models, however, do not consider the tension-saturated zone. Also, heterogeneities considered in the simulations are assumed to be continuous rather than localized.

The role played by the tension-saturated zone in subsurface leachate movement was approached by formulating the hydrodynamics as a modification of classical free surface techniques. The equations of motion of ground-water flow in the vicinity of an excavation were formulated to permit analytical determination of the free surface (i.e., the shape of the top of the capillary fringe) and the effects of capillarity on this shape and on the entire flow network.

Approach

Modeling of Leachate Migration in Saturated Low-K Soils

In general, contaminants that are soluble in ground water migrate by miscible transport processes. Transport mechanisms such as convective transport, mechanical dispersion, and molecular diffusion as well as physicochemical interactions between the soil and the contaminant species are important in determining the quality of ground water. The interactions include adsorption/desorption of the contaminant species on soil particles as well as chemical reactions between soil chemicals and contaminants (e.g., ion exchange). Aqueous leachates generated by land disposal of liquid and solid wastes migrate by such miscible transport mechanisms and form a large class of typical ground-water contamination problems. Liquid contaminants that are insoluble in ground water are transported by immiscible (or multiphase) transport processes. The present discussion is limited to miscible contaminant transport processes.

In saturated environments, ground-water flow generally obeys Darcy's law, which states that flow velocity is proportional to both the hydraulic gradient and hydraulic conductivity of the soil. Complications arise from the heterogeneous and anisotropic nature of soils because the hydraulic conductivity is usually variable in space and also dependent on the flow direction. The dispersion and diffusion of the contaminant species are expressed by Fick's law, which, when combined with convective flux, give the net migration flux of the contaminant species. The governing conservation equations, when combined with flux relations, reduce to a set of coupled, nonlinear, second-order partial differential equations—one describing the ground-water and flow and the other characterizing the migration of chemical species.

These equations are then solved using appropriate initial and boundary conditions and system parameters to obtain flow and concentration profiles. The boundary conditions are usually of two types: (1) specified functional values (e.g., head or concentration values at specified locations); and (2) specified flux values (e.g., water flow rate or mass flux of solute). To solve the transient equations, initial functional values of head or concentration over the entire region are also required. For dilute solutions, the ground-water density may be assumed to be constant and independent of solute concentration, thus uncoupling the flow and transport equations.

Available computer simulation codes are based on either analytical or numerical solutions to the above equations in one-, two-, three-dimensional form. The level of complexity is a function of geometry, heterogeneity of the porous matrix, anisotropy, and transport mechanisms represented. Generally, the energy transport equation is ignored, although it may be significant in a few special cases. The flow and solute transport equation are generally assumed to be uncoupled, and most chemical transport models assume a binary system (i.e., one contaminant of importance in ground water).

The accuracy of any solution depends on the accuracy of various parameters incorporated into the equations. For flow problems, the critical parameters are soil hydraulic conductivity and porosity. To account for heterogeneities and anisotropies, vertical and horizontal components of the hydraulic conductivity need to be provided over the entire flow region. Compressibility of the soil and fluid are combined in a single parameter, specific storage. The critical parameters in solu transport problems are the hydrodynam dispersivities and molecular diffusi coefficients for the solute species interest. The hydrodynamic dispersivi is essentially a property of the flu velocity and the porous matrix, and it often dependent on flow direction. addition, the attenuation mechanism such as adsorption and chemical rea tions, if important, need to be expresse by suitable attenuation coefficients. all these parameters, the attenuati coefficients are the most difficult obtain. However, this problem may avoided by considering the worst ca of no attenuation. This is applicable the conservative specie that is expect to migrate the farthest.

Most computer simulations treat th dispersion coefficient the same as th diffusion coefficient. Although the diff sion and dispersion terms are added obtain overall dispersion coefficient there is a significant difference betwee them. Diffusion is a molecular phenom enon and allows the flow of contam nants against the direction of groun water flow. Mechanical or hydrodynam dispersion arises from the uneven flo and division of flow of water as it move through soil particles. The dispersio depends on flow velocity and soil matri and may mathematically be expressed diffusion-type equations. But unlik molecular diffusion, the mechanic dispersion does not allow flow of co taminants against the ground-wat flow. This problem is less significant f convection-dominant solute transpo processes. For dispersion-dominate cases, any prediction of contamina migration against the ground-water flo direction should by viewed with cautio

In low-K soils, where flow velocitie are low, molecular diffusion may becom a dominant solute transport mechanism Theoretically, the hydrodynami dispersion coefficient is proportional the flow velocity, the proportionalit constant being called dispersivity, a. (I a simple form, the longitudin hydrodynamic-dispersion coefficient, D = a_L $|V|$, and the transverse hydro dynamic-dispersion coefficient, D_T = a $|V|$.) Thus, at sufficiently low velocitie the molecular diffusion coefficient ma become greater than D_L and D_T.

Special Considerations

The primary concern in modeling the flow and solute transport in saturated low-K soils is the presence of heterogeneities in these soils. Because of the high resistance of low-K soils to ground-water flow, the effects of nonuniformities such as stratified permeable sand layers, fractures, and fissures become very important as these provide the low-resistance path to leachate flow. For very low-K soils with hydraulic conductivity less than 10^{-9} cm/sec, almost all the flow may be expected through such nonuniformities.

Any applicable model must be able to represent these nonuniformities adequately. Finite element models offer an advantage in this respect, as they can better accommodate uneven distribution of heterogeneities. Simulation of fractures present special problems as these represent extreme discontinuity in the soils with porosity equal to unity, and the ground-water flow equation may not be strictly applicable in such a case.

A second important consideration in low-K soils is the contribution of the molecular diffusion process to solute transport. For very low flow velocities, such as 10^{-9} cm/sec (e.g., with $K = 10^{-7}$ cm/sec and hydraulic gradient = 0.01), the hydrodynamic dispersion coefficient may become smaller than the molecular diffusion coefficient which is usually in the range of 10^{-5} to 10^{-6} cm^2/sec. In such cases, molecular diffusion may represent a dominant transport mechanism over advection and hydrodynamic dispersion. Applicable models should, therefore, include a molecular diffusion term in the solute transport equation, along with advection and hydrodynamic dispersion contributions. Also, the hydrodynamic dispersivity data for low-K soils are generally not available, and data on other soils may indicate higher values. Based on laboratory experiments, low values of dispersivities may be expected for uniform low-K soils.

Another aspect of simulations of low-K soils is the large time increment and time scales involved. Long time periods may be required for significant advancement of the concentration front. Over such long periods, the boundary conditions may become variable and time-dependent. Examples of these boundary conditions are the concentration and flux of solute species at the source and the prevailing hydraulic gradients in the flow region. In such situations, models incorporating variable, time-dependent boundary conditions may be desirable.

Sample Model Simulations

Two available computer programs were used to obtain sample model simulations and to demonstrate generally the usability of these and other codes based on similar computational techniques for predicting contaminant migration in low-K, saturated soils:

1. SEFTRAN—Simple and Efficient Flow and Transport—code developed by Huyakorn of Geotrans, Inc. *This model is based on finite element techniques and can allow rectangular or triangular elements for flexible geometry.*

2. Two-dimensional U.S. Geological Survey Model developed by Konikow and Bredehoeft of USGS. *This model is based on finite difference techniques and uses the method of characteristics to solve the solute transport equation.*

Both programs provided analyses of two-dimensional fluid flow and contaminant transport in areal/cross-sectional configuration of saturated heterogeneous and anisotropic media. The solute transport part can take into account convection, hydrodynamic dispersion, equilibrium adsorption, and first-order decay processes. *The SEFTRAN model takes into account molecular diffusion, whereas this term is ignored in the USGS-2D model.*

Contaminant migration through low-K soils may be described as a two-step process. In the first step, the contaminant migrates vertically through saturated low-K soils to an underlying aquifer or a more permeable zone. In the second step, the contaminant entering the more permeable zone or aquifer is transported horizontally away from the source. These two steps were simulated with the above mentioned codes.

The first sample model simulation studied vertical migration of a contaminant from a hazardous waste land disposal facility to an underlying aquifer through saturated low-K soil. The SEFTRAN code was used for this case, and the effects of heterogeneity and anisotropy of the soil were examined in this simulation. The heterogeneity was simulated by introducing a thin, highly permeable, continuous sand layer in an otherwise homogeneous low-K soil. Also simulated was the case of very low-K of soils with and without molecular diffusion.

In the second sample model simulation, horizontal migration of contaminants from the landfill site through an underlying aquifer was simulated using the USGS2D model. Here also the effects of heterogeneity and anisotropy of the permeable aquifer were studied.

Conformal Mapping

As stated previously, of particular interest is that situation where a landfill, surface impoundment, or waste pile would be located in saturated low-K soil. A facility so located would tend to influence local flow dynamics, including the water table and the capillary fringe (tension-saturated zone).

The problem to be addressed is a disposal facility sited such that its lower surface is beneath the normal water table. As in a well, there is a tendency for ground water to flow into the excavation. A complicating factor, however, is capillary attraction, which draws fluid into the soil interstices and creates a zone of negative pressure, the capillary fringe or tension-saturated zone.

In the capillary fringe, the region between the water table and free surface, the physical picture is that of individual granules whose interstices contain no significant vapor bubbles. This zone is normally referred to as the tension-saturated zone or the negative pressure zone. Within this zone the pressure ranges from atmospheric ($P = 0$) at the water table to some negative value ($P = -H_c$) at the free surface, where

P = Manometer pressure in head units, L

H_c = Equilibrium capillary rise, L.

Above the top of the capillary fringe, the physical appearance is that of individual granules whose interstices are filled primarily with vapor or gas bubbles. This region is referred to as the unsaturated zone and its moisture content normally decreases with elevation or increases with depth. Fluid motion in the unsaturated zone is not addressed in this report.

In order to assess the effects of the capillary fringe on the fluid flow patterns in the neighborhood of the excavation, the equations of motion for the flow field are formulated and solved with the capillary pressure, H_c, as an adjustable parameter. Comparative analysis of the solutions for various values of the capillarity reveal and quantify its effects.

Classical potential theory, which applies here, in which the flow is proportional to the gradient of some potential, provides a relatively easily visualizable and familiar representation of the flow field in the form of the flow net. This net is comprised of lines of constant potential and orthogonal, or perpendicular, lines of constant stream function. The lines of constant stream function, or stream lines, represent particle tracks in steady flow; hence no fluid flows across these lines. Any two such lines form a stream tube, through which the total flow is constant.

Imagine that the lines of constant potential and flow lines are drawn on an infinitely stretchable thin sheet of rubber. Imagine moreover that this rectangular piece of rubber is positioned and deformed so that the lateral edges correspond to the centerline of the excavation, the bottom of the pit, and the free surface. If this stretching is done in such a way that angles are preserved, e.g., conformally, then the resulting curvilinear network comprising the (now deformed) lines of constant potential and constant stream function represents a new flow field, the one sought in this study.

Conformal mapping is a mathematical formalism for accomplishing this stretching. In a typical application, a simple flow configuration (a rectangle) is mapped onto a more complicated geometry (the disposal facility) in such a way that the important mathematical features of the flow net are preserved and the resulting curvilinear flow net is a theoretically accurate representation of the flow field in the more complex geometry. The mathematical formalisms are developed and solutions presented from which the behavior at various values of the capillarity can be compared.

A simple mathematical transformation converts the isotropic solution to an anisotropic one through coordinate stretching. The effects of anisotropy are examined. Heterogeneities can also influence flow. A local heterogeneity can be of two types, either more or less conducting than the adjacent soil structure. Conformal mapping techniques are used in this project to examine flow paths in the neighborhood of both types of structure.

Findings

1. Soils frequently exhibit anisotropic flow behavior in that the horizontal hydraulic conductivity is greater than the vertical. This phenomenon can increase the net flow substantially at a given hydraulic gradient as a result of the more open horizontal flow path for liquid motion. For example, a fourfold full force increase in horizontal conductivity can increase the net flow at a given hydraulic gradient by approximately fourfold over the isotropic situation.

2. Heterogeneities and anisotropy are common in naturally occurring low-K soils. The heterogeneities can range from small, isolated pockets to large, continuous or connected regions with high hydraulic conductivities.

3. Since interconnected secondary porosity can significantly increase the average hydraulic conductivity of a low-K soil, these zones must be mapped if subsurface leachate migration is to be adequately modeled or a landfill sited with any assurance of contaminant containment by the natural low-K soil (in the event of a failure in the primary liner).

4. Several ground-water transport models applicable to movement of leachate releases in saturated low-K soils that are heterogeneous and/or anisotropic are available. Numerical models that employ finite element and/or method of characteristics are the most applicable. None of the models have been verified for this case by comparison to actual field conditions.

5. The analysis shows that the effect of capillarity is to draw fluid vertically into the soil interstices and thence to open the area through which fluid can flow into the excavation. Capillarity thus causes the flow into an excavation to increase over the no capillarity case; the magnitude of the increase can be on the order of 10 to 20 percent of the total flow and is higher for higher hydraulic gradients.

6. Heterogeneities, such as joints, fissures, animal and root holes, and silt and sand seams can occur in a soil and can cause an increase several orders of magnitude in t average hydraulic conductivity of low-K soil. Heterogeneities wi high hydraulic conductivity, e. sand lenses, root holes and fissure are of most significance when th extend for a large distance, allowi rapid migration of pollutants th reach the heterogeneity. Heterog neities with low hydraulic condu tivities, e.g., rocks, are of mo significance when they extend for large distance perpendicular to t direction of flow. In this configur tion, migration is retarded.

7. Conformal mapping is capable providing the details of the flow fiel e.g., the velocities at all locatio surrounding the disposal facilit This velocity field can be used conjunction with other numeric models in the analysis of oth phenomena of interest; namel diffusional transport superimpose upon the convective flow fiel adsorptive and desorptive intera tion of contaminants in the grour water with local soils, reacti degradation of possible contam nants catalyzed by mineral matt within the soil or otherwise, ar contaminant transport times fro the disposal facility to the surface to adjacent bodies of water.

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The complete report entitled "Effect of Capillarity and Soil Structure on Flow in Low Permeability Saturated Soils at Disposal Facilities," (Order No. PB 87-180 576/AS; Cost: $18.95, subject to change) will be available only from:

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