FIELD DEMONSTRATION AND QUANTIFICATION OF INTERFACIAL MASS TRANSPORT IN LOW PERMEABILITY POROUS MEDIA -- IMPLICATIONS FOR GROUNDWATER PROTECTION

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Presented at: 26th Annual Meeting, Geological Society of America, South Central Section, Houston, Texas. February 23, 1992.

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Emerging studies in groundwater hydrology suggest that the transport along interfaces in porous media is a significant source of contaminant migration. The consequence of such a mechanism is that bulk hydraulic conductivities of natural clays at depth may be higher than previously thought, and aquifers that are overlain by such clays may be more succeptable to contamination than currently believed.

Anderson et al. (1991) reported evidence of horizontal transport in a recent study of compacted clay liners for hazardous waste disposal facilities, Their dye study revealed vertical and horizontal fracture traces and indicated that the rate of horizontal flow at interlifts far exceeded that of vertical flow within a lift. They concluded that minimizing horizontal flow will improve liner performance, and that breakthrough time is primarily a function of <u>horizontal</u> conductivity.

This paper describes the design and implementation of a field scale experiment that is being conducted at the University of Houston Coastal Research Center to demonstrate an interfacial transport mechanism conceptually similar to the interlift transport observed in the engineered soils. Methods to quantify the transport mechanism using interconnected fracture network models are being explored. The tracer study uses adsorbing dye tracers, and conservative tracers to provide additional engineering information on the behavior of contaminants under the interfacial transport hypothesis.

Anderson, D.C., M.J. Lupo, J.A. Rehage, J.O. Sai, R.L. Shiver, R.C. Speake, K.W. Brown, and D. Daniel, 1991. <u>Factors controlling minimum soil liner thickness</u>, Risk Reduction Engineering Laboratory, Cincinatti, Ohio, Report EPA/600/S2-91/008.

Introduction

The transport of contaminants along interfaces in porous media is source of contaminant migration that is overlooked in low permeability porous media. The consequence of such a transport mechanism is that the apparent bulk hydraulic conductivities of naturally occuring clays may be much higher than previously thought and aquifers that are overlain by such clay sediments may be much more susceptible to contamination than previously believed due to rapid migration of contaminants from sewage canals, landfills, agricultural return flow and other sources.

Well Head Protection Areas (WHPA) are based on time of travel of groundwater from contamination sources to public supply wells. Typically, the time of travel estimates are based on continuum hydraulics that use idealized conceptualization of the groundwater flow system. The Theis equation is probably the dominant method of obtaining estimates of hydraulic conductivity, which are then used to estimate time of travel. Under the Theis conceptualization, a typical pumping test would indicate that clayey units have low hydraulic conductivity and would generally be less succeptable to contaminant migration that an equivalently sized sand unit. However, one assumption of the continuum model is that flow occurs relatively uniformly across the pumped interval. In a fractured system, or along a geologic interface, flow can be distributed unequally. The distribution could be such that high volumes at high velocities are discharged across relatively short intervals (fractured media), or small volumes at high velocities are discharged across short intervals (interfacial flow). The pumping tests are designed to relate volumetric flow to conductivity and storage, yet the time of travel concept is inherently velocity related.

The proposed modeling and quantification experiment is designed to provide quantification and modeling tools that will be useful to engineers and researchers conducting investigations in low permeability porous media. These tools will help them quantify the interfacial transport mechanism when designing source area control schemes, and waste containment structures in regions where traditional concepts of hydraulic conductivity are inadequate to describe the flow field.

Literature Review

Vadose zone hydrologists have studied the effect of large pores, and have found that traditional diffusion formulations are inadequate (Gee et al., 1991). Large macropores are thought to be responsible for the rapid water movement under irrigation or intense rainfall. Germann et al. (1986) has described this rapid water movement using a kinematic wave equation to explain subsurface storm flow in forested watersheds. Interestingly, flow equations for fractured media can also be interpreted as kinematic wave equations.

The permeability of fractured rock is important for predicting the movement of fluid in rocks such as granite, however, the permeability of fractured permeable media has special importance in the study of contaminant movement. In a fractured permeable medium, the solid matrix stores the fluid, while the fractures significantly control the flow and direction of transport when a pressure gradient is applied. Interestingly, research involving low permeability materials suggests that fracture type flow occurs quite commonly and has important implications in contaminant transport in these materials.

Transport along fractures has been of increasing interest since the United States first investigated placement of low-level radioactive wastes in the fractured basalts of eastern Washington, and Idaho. Evaluating groundwater flow and solute transport in clay rich aquitards has also received attention in recent years because of the potential use of such aquitards for the containment of hazardous wastes and for the protection of underlying aquifers from other surface sources of contamination.

Grisak and Cherry (1975) evaluated the hydraulic characteristics of fractured clay-rich Quaternary deposits in southeastern Manitoba by monitoring the response of piezometers installed in a clayey aquitard to pumping in an underlying aquifer. Some piezoemeters in the clay responded rapidly to pumping whereas others showed no response. The authors concluded that the fractures controlled the effective bulk hydraulic conductivity of the clay sediments. Keller et al. (1986) investigated clayey glacial till overlying a sand aquifer at a site in west central Saskatchewan. The lower 6m of the 18m thick deposit at this site appeared to be unweathered and no evidence of fractures was observed in core samples. The analysis of pumping tests and piezometer response tests revealed that the effective hydraulic conductivity of the sediments was several orders of magnitude higher than that indicated by core sample consolidation tests. Even though standard field techniques found no evidence of fractures, response of the aquitard to aquifer pumping indicated the presence of a permeable fracture network throughout the aquitard.

Rudolph et al. (1991) recently studied the flow and transport of groundwater in fractured clay near Mexico City. They found that publications pertaining to both aquifer recharge derived from leakage through the clayey aquitard and pore pressure response in the geotechnical behavior of the clay have assumed that the aquitard behaves as a conventional porous medium without specific consideration of the possible influence of fractures.

The majority of the fractures in their study were vertical and filled with fine sand. Mechanisms for the creation of such fractures are seismic activity and clay desiccation caused by extended drought periods. They used geochemical analysis and hydraulic response data to test two conceptual models of the flow and transport system in the region: (1) a model that considers that the clay layers are massive unfractured continuous porous media with solute migration influenced by advection and diffusion, and (2) a model that assumes that the clay layers comprise a network of hydraulically conductive fractures (primarily vertically oriented). They concluded that only the fractured porous medium model accurately reproduced the field data using realistic values for the physical parameters, and furthermore state "This [result] leads to the conclusion that the clay behaves as a fractured porous medium with some portion of the fracture network being continuous throughout the entire thickness of the aquitard."

An important observation to be made, assuming these conclusions are correct, is that the bulk hydraulic conductivities of naturally occuring clays at depth may be much higher than previously thought. An important consequence is that the rate of migration of contaminants from sewage canals, landfills, and other waste sites may be rapid, and therefore aquifers that are overlain by such clay sediments may be much more susceptible to contamination than previously believed.

These studies have primarily been concerned with the vertical transport in clayey soils, the horizontal component has largely been ignored until very recently. Anderson et al. (1991) reported evidence of horizontal transport in a recent study of compacted soil liners for hazardous waste disposal facilities. They have developed a model to determine the minimum thickness of a soil liner that has an in-place hydraulic conductivity smaller than $1 \cdot 10^{-7}$ cm/sec, has sufficient strength to support the waste overburden, and prevents breakthrough of any contaminants for a specified period of time. They stated that while soil liners must restrict flow within a lift and between lifts (interlift flow), defects such as cracks , clods, channels, continuous macropores , and incomplete bonding between lifts can significantly affect the performance of a liner. If such defects are ignored, then liners exhibit permeabilities that are much larger than expected based on typical small scale permeameter tests. In a laboratory study they found that the compaction process is inhomogeneous, and a single lift exhibits differential compaction throughout its depth. The upper portion of a lift is compacted, and continuum permeability descriptions are adequate, while the lower portion still exhibits preferential flow regions. They also performed a field study through three lifts over one-half meter thick (total thickness). Their dye study revealed vertical and horizontal fracture traces and indicated that the rate of horizontal flow at interlifts far exceeded that of vertical flow within a lift. They concluded that (1) hydraulic conductivity is the most important property in determining the thickness required in a soil liner, (2) minimizing horizontal flow will improve the overall performance of the liner, and (3) breakthrough time is primarily a function of horizontal conductivity.

Such evidence of horizontal flow in engineered soils suggests that similar interfacial facilitated transport exists in natural systems and ignoring bedding perpendicular to the hydraulic gradient could lead to surprises.

Practical quantification of fracture type flow is largely based on using "equivalent" hydraulic conductivities in a spirit similar to the equivalent domains in the stochastic theories. The equivalent hydraulic conductivity approach is considered largely adequate for steady discharge, but in transient flows "multiple" porosity effects are observed, and a multicontinuum approach is used (Bear and Bachmat, 1991).

Figure 1 depicts a typical conceptual model of a compressible multi-structure soil medium at two scales (Kemper, et al., 1972). In vertical flow, the principal hydraulic gradient lies perpendicular to the clay platelets. Vertical fractures, have an obvious effect on the hydraulics of the system. At the very least, vertical fractures considerably reduce the tortuous path water must travel to flow. At the interface, the actual pore space available to flow is larger than the pore space in either of the two contiguous media, and transport along this "fracture" could be significant. The significance of this type of transport is evident when one considers the equivalence between the hydraulic conductivity of a fractured medium and a medium that satisfies the continuum hypothesis. Maini and Hocking (1977) studied this equivalence and show, for example, that the flow through a 100 m thick cross section with a hydraulic conductivity of $1 \cdot 10^{-7}$ m/s could also come from a *single fracture* in an otherwise impervious rock matrix with an opening less than 0.2 mm.

When such a mechanism exists in natural systems, breakthrough times of contaminated waters that are isolated from uncontaminated waters by natural aquitards will be much quicker than expected. The protection such aquitards provide to underlying aquifers from surface sources of contamination, may be negligible, and the purpose of the experiment is to demonstrate whether the mechanism is significant in local soils, and to develop quantification tools for describing the phenomenon.

Experiment

The objectives of the experiment are: (1) to develop a three-dimensional model for low permeability soils that incorporates facilitated interfacial transport and sorption-type interactions, (2) to validate the model using conservative and non-conservative inorganic and organic tracers and multi-level soil water sampling devices, and (3) to quantify the transport mechanism(s) as a function of readily observable physical parameters (grain size distribution, soil and water chemistry, drying curve relationships, etc.). The field experiment is being constructed at the University of Houston Coastal Center.

The Center is located upon the Beaumont formation, and the soils are fine-grained clays that were deposited in a "backswamp" environment behind natural levees of major rivers and distributaries. The soils of the Beaumont formation were preconsolidated by desiccation when the level of the Gulf of Mexico was about 100 meters lower than its present level. This process is one of the mechanisms believed to cause fracture networks in Mexico City clays.

The desiccation has produced a soil with fairly consistent values of preconsolidation pressure with depth, and has left the soil with a pattern of generally random and small fissures and slikensides, which are partially healed. Like the Mexico City clays, there is little evidence of major fracture networks.

The piezometric surface at the Center is located about 1 meter below the ground surface, so that soils are saturated. Free water is encountered in thin seams of sand or silt at about 7 meters below ground surface. These thin seams will be used to to test the horizontal facilitated transport mechanism, as they form a geologic interface between clays, and are roughly equivalent to "poorly" bonded landfill lifts.

Figure 2 shows the experimental conceptual design for testing the interfacial transport hypothesis. A forced gradient is used to help maintain hydraulic control of the experiment. The interfacial samplers are located along the interface and within the water bearing unit. If the interfacial mechanism exists, tracer labeled water should appear along the interface sooner than at the sample points within the water bearing unit. Multiple horizontal sample locations are included to help correct for the effect of apparent dispersion, as well as increase the resolving power of the sampling network (Cleveland, 1991).

Figure 3 shows a typical soil profile for the Coastal Center site. The interface between the red clay and the first water bearing unit is very sharp (at least for five borings performed to date). This sharp interface is ideal for testing the interfacial transport mechanism that is described above.

A traditional monitoring well is unsuitable for this research because its placement disturbs the very subsurface structure being studied. A small diameter monitoring point was designed to satisfy the need to minimally disturb the subsurface, yet be placed and completed under monitoring well requirements, and not become clogged with suspended fines during development, yet have less head loss than a suction sampler. Figure 4 shows the proposed sampler design that will be installed in selected locations shortly.

The proposed tracers for the research are Rhodamine WT, sodium fluorescein, and lithium chloride. The lithium chloride tracer is expected to behave as a conservative tracer, and is detectable in the parts per trillion range by atomic absorption analysis. The other tracers are non-conservative organic dyes that are commonly used in flow tracing research. The two organic dyes tend to bracket the arrival of common pesticides when used in time of travel tracer tests (Sabatini and Austin, 1991) and are chosen as surrogates for contaminants of interest.

Status

The current status of the experiment is: (1) Two of three sites have two borings each to locate potential interfaces for the experiment. (2) The fluorometric analytic procedure has been developed by the University of Houston Department of Geosciences who are collaborating on this research. (3) An 8" by 36" laboratory column with multiple sampling ports has been constructed and is awaiting media packing. (4) A interconnected fracture network hydraulic simulator for steady conditions has been constructed and is awaiting testing.

Conclusions

The results of the experiment will determine if interfacial transport is a significant transport mechanism that should be considered in well protection strategies, aquifer restoration design, and source identification programs. The experiment will develop quantification tools that will assist geologic engineers predict contaminant behavior from commonly measurable physical parameters.

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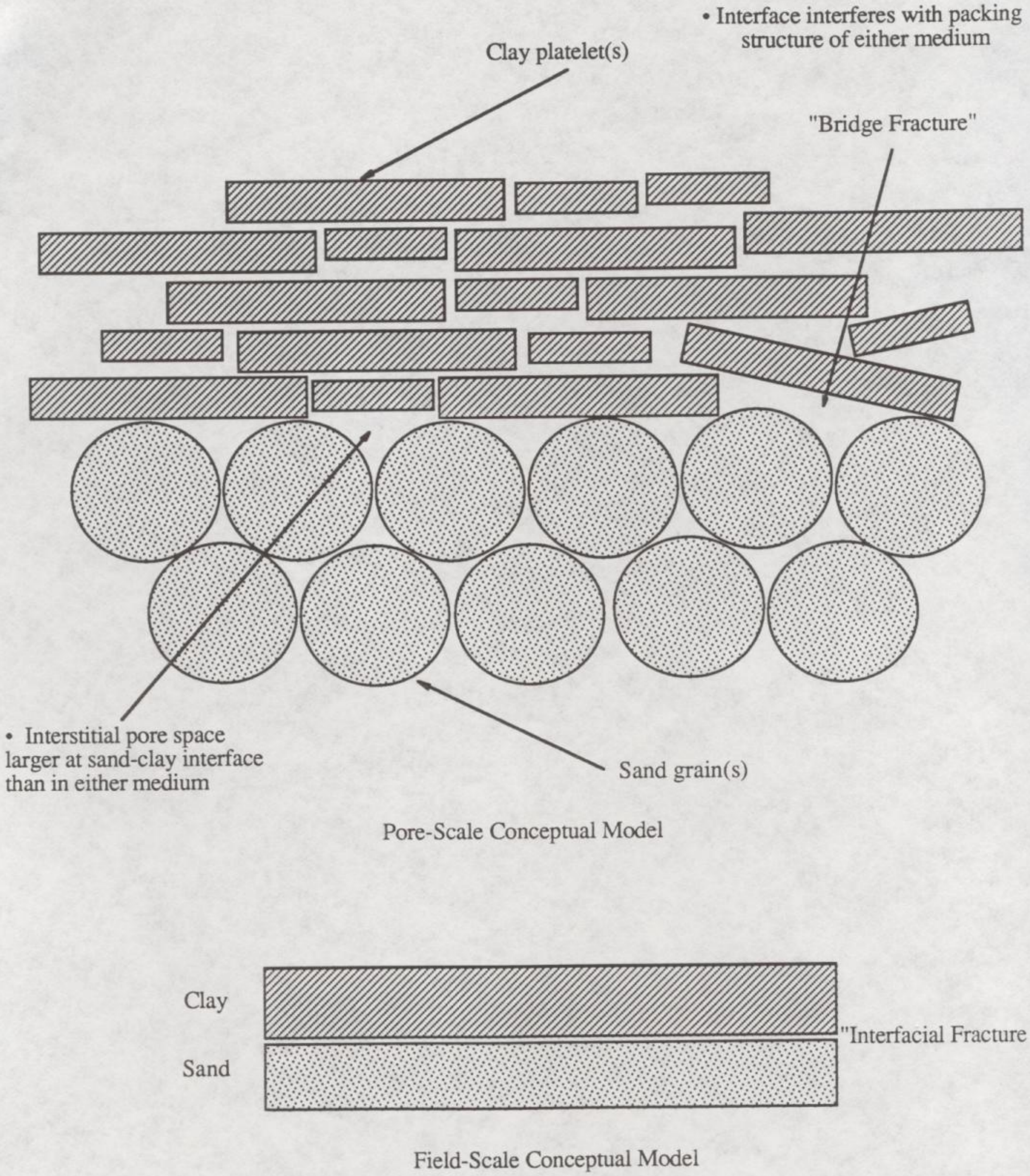
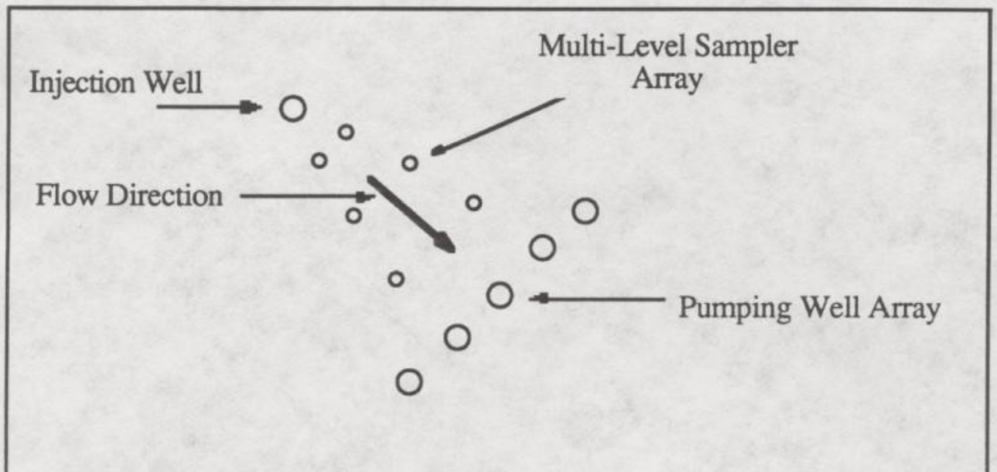
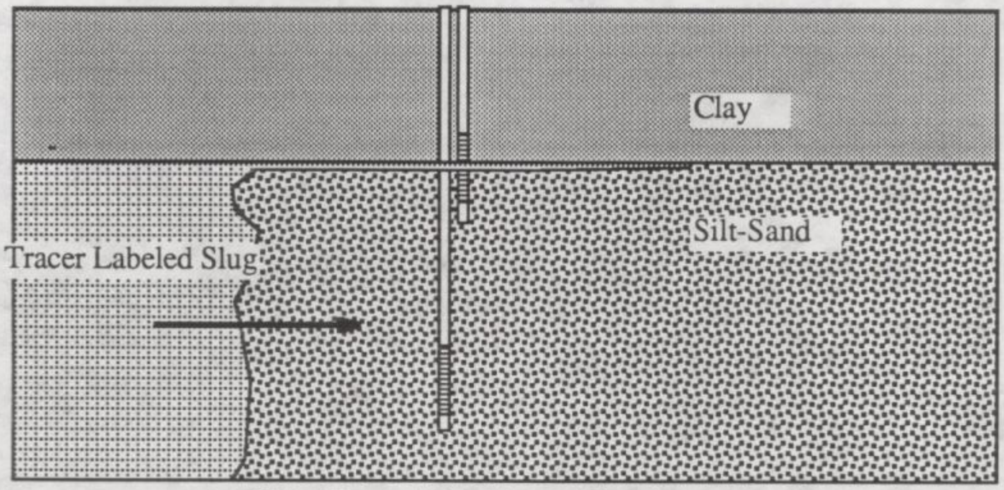


Figure 1. Conceptual Soil Structure



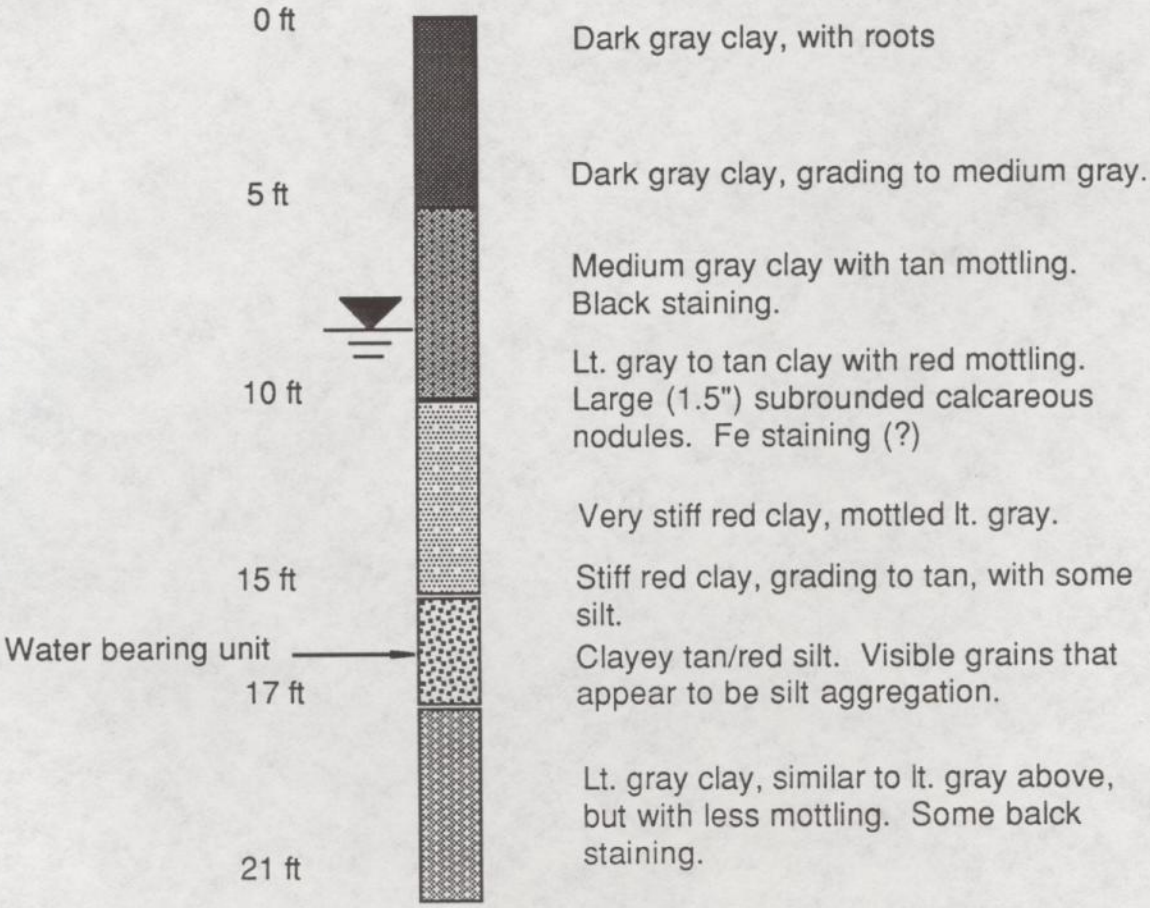
Plan View of Experimental Monitoring Network



Side View of Experiment Showing Multi-Level Samplers, and Interfacial Transport of Tracer Slug

Figure 2. Experiment Conceptual Design

Typical Soil Profile at Proposed Experiment Site



Profile based on logs of MW-1, MW-2,
MW-3. P-1. IS-1. and IS-1B

Figure 3. Tyical Soil Profile at UH Coastal Center

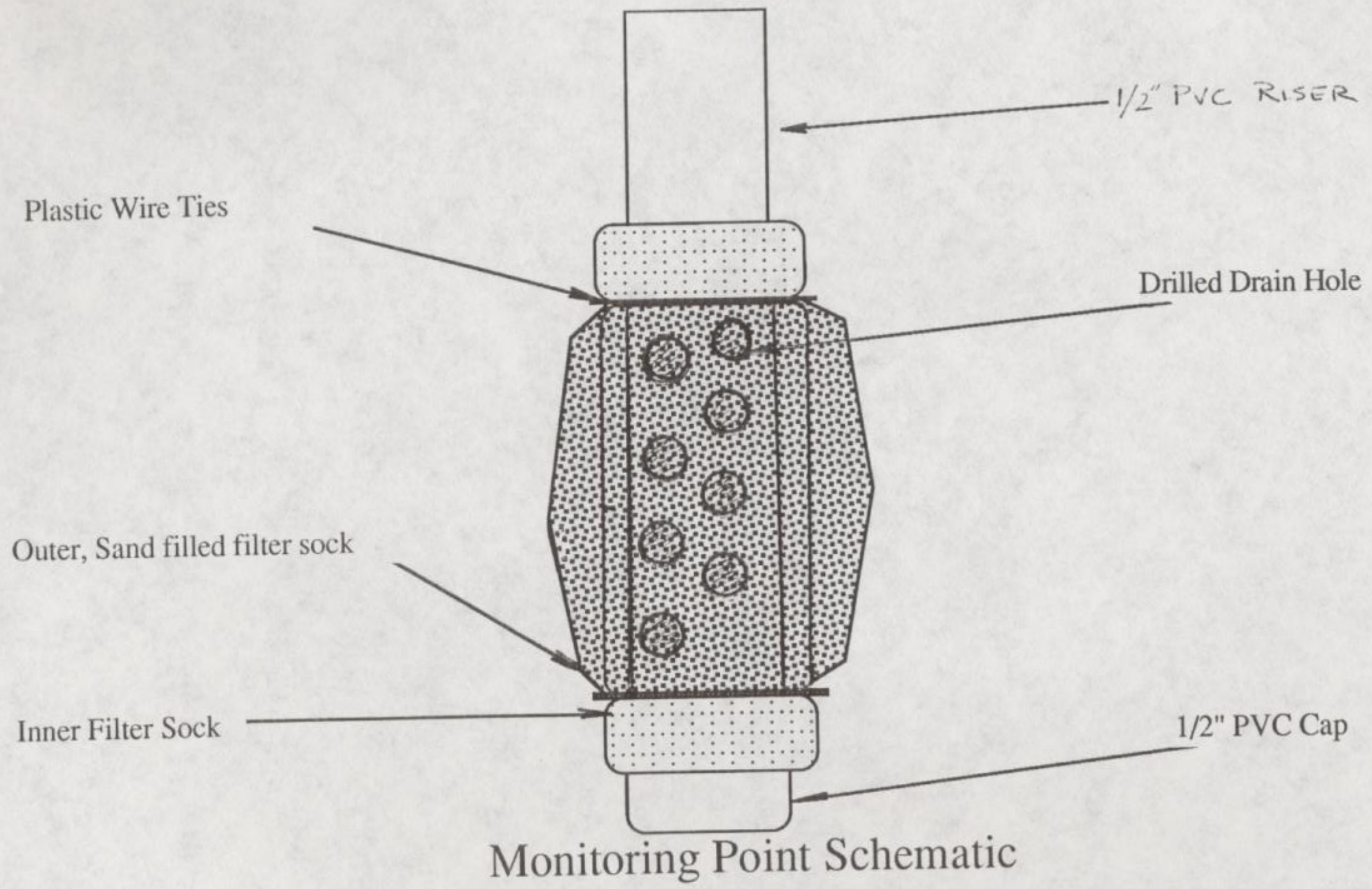


Figure 4. Interfacial Sampler Schematic Design