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VADOSE ZONE MONITORING TECHNIQUES

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INTRODUCTION

Monitoring fluids of the vadose zone has multiple motives, including detecting contaminants, measuring soil properties and water conditions for construction or monitoring geologic hazards, and determinations of water saturation that may be used for optimizing irrigation. Because fluids must move through the vadose zone to reach the water table, monitoring of the vadose zone allows predicting possible sources and processes of groundwater contamination. Geologic hazards such as landslides, rising water tables, or land subsidence can be partially predetermined by monitoring the vadose zone. And in agriculture, monitoring soil water content to irrigate most efficiently has a long history.

Monitoring the temporal and spatial variance in the vadose zone is vitally important to engineers, geologists, meteorologists and other environmental scientists interested in studying water and contaminants. There are many techniques that directly or indirectly assess water content, sorbed mass, gaseous and liquid contaminants, flow direction, and other parameters that may be monitored. The methods discussed here are divided into two categories, direct and indirect monitoring techniques. Direct monitoring techniques require a degree of sampling or large-scale soil disturbances. Conversely, indirect techniques are analogous to remote sensing in which no disturbance to the soil or water is required, although a well may be required in some techniques. This section discusses in short detail some of the attributes and shortfalls of most of the currently used techniques for monitoring the three phases of the vadose zone: liquid, soil, and gas. For a more in-depth understanding, readers are directed to the references listed after each entry.

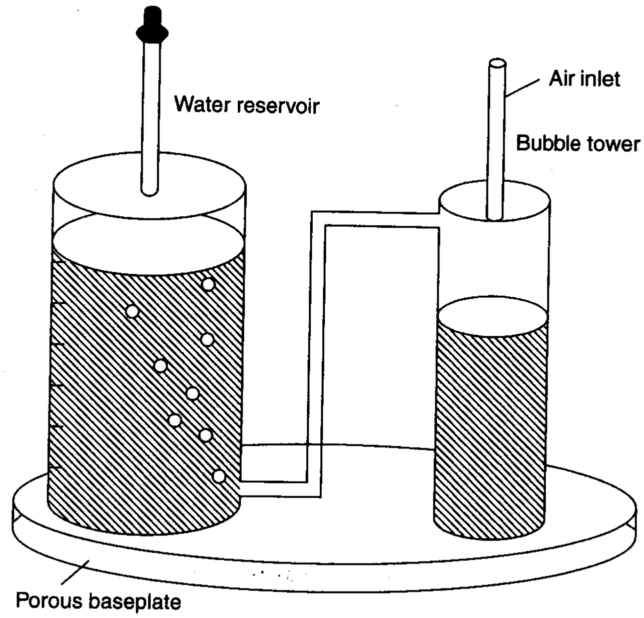

Figure 1. Tension infiltrometer. Tension measurements may be made using a handheld tensiometer on nongraduated models or on the side of graduated models (pictured).

INDIRECT MONITORING METHODS

Indirect methods for monitoring the vadose zone commonly have links to geophysical tools, principles, and techniques. Many vadose zone characteristics such as water content, the presence of contamination, and flow direction, among others may be determined without soil sampling. These techniques may also be used to determine the nature and extent of soil stratification for site delineation.

In practice, these methods are generally nonintrusive and do not require disturbing the soil, but some require well installation. When drilling or augering is necessitated, proper techniques must be ensured so that mud linings, drilling fluids, or other drilling by-products do not affect hydraulic conductivity, which may then affect measurements. It is also important to clean any grease or oil from drilling tools to avoid contamination and to clean tools between use.

Tension Infiltrometers

Tension infiltrometers are used to characterize hydraulic properties of saturated and partially saturated porous media, including saturated and unsaturated hydraulic conductivities. Infiltrometers are commonly used to measure hydraulic conductivity as a function of matrix potential in partially saturated porous media, sorptivity, steady-state volumetric flow rate (Q), and water content (Fig. 1).

There are variations of the disk infiltrometer and multiple methods of measuring hydraulic properties using infiltrometers, but all consist of three basic parts: the bubble tower, the reservoir, and a porous baseplate. The porous base plate lies flat on a wetted soil surface, and both the bubble tower and reservoir are connected perpendicularly to it. The purpose of the baseplate is to establish hydraulic contact between the soil and the reservoir. A thin layer of moist sand may be placed under the baseplate to ensure better hydraulic conductivity between it and the soil. The reservoir supplies water to the baseplate and the bubble tower; the latter consists of a series of tubes that relieve the vacuum in the reservoir when water infiltrates into the soil. Tension measurements correspond to the level of the water in the reservoir. An important point to note is that hydraulic conductivity must exist between the baseplate and the wet porous media for the device to operate.

The main advantage of disk infiltrometers is that *in situ* measurements of vadose zone hydraulic properties are rapid, reliable, and replicable and the devices are inexpensive and easy to operate. There exists, however, a limited range of tensions (generally 0 to 25 cm below the ground surface (BGS) in which the infiltrometers can operate; and measurements can be made only at the soil surface unless trenches are dug to the desired measurement level and the device used (1–3). Ideal soil properties are also assumed (soil is uniform, homogenous, and nonswelling), and pore closure may result from the weight of the device if used on freshly cultivated soils. There are other limitations that may be observed in Hussen and Warrick (4).

Neutron Moisture Probe

Initially designed for the agricultural industry, the neutron moisture probe has been adapted to environmental monitoring to obtain soil moisture levels. It is a nondestructive method of obtaining soil moisture levels when the probe is inserted in a well. The only restriction to depth of use is the length of the well used and the probe cord length.

Once lowered down a well, the probe begins to emit neutrons. The velocity at which neutrons return to the probe is correlative to the substance by which they were reflected. Neutrons reflected by heavy atoms of the soil matrix return with higher velocities compared to those of neutrons reflected by lighter hydrogen atoms. Hydrogen may be found in organic matter or in mineral lattices, but water is the greatest source of hydrogen in the subsurface. Due to this, the counts of reflected low-velocity neutrons are correlative to soil moisture content. A complete moisture stratification along the length of a well may be obtained, given a well-calibrated instrument.

Attributes of the neutron probe include ease of use and high accuracy, given a well-calibrated probe. It may be operated by one person, and soil moisture changes of the order of 1–5 volume % may be measured. Water flow pathways may also be located with the instrument. The largest drawback of the neutron moisture probes lies with calibration difficulties that may be extreme. Improper neutron probe calibration nearly renders the probe useless. Ideally, the probe is calibrated using soils collected in a drum with a known quantity of water from the field site of interest. Another drawback is that neutron probes cannot distinguish between water and other substances with similar hydrogen densities in the subsurface, such as gasoline. Problems of applying single calibrations to multiple media types also arise, which is the case in heterogeneous soils. Inaccuracies may also be result from improper well packing and the presence of certain elements, such as migrating boron or chlorine. Finally, care should be taken to mitigate exposure to the neutron source (5–8).

Psychrometers

Psychrometers represent another tool adapted from the agricultural industry for environmental monitoring. Estimation of the hydraulic gradient using the matric suction, osmotic potential, and water vapor potential are possible.

The generic class of instruments used to measure relative humidity using both wet and dry bulb thermometers are called psychrometers; they may be used for both surface (agriculture) and subsurface (environmental) applications. For the latter, they are placed in a small diameter well and surrounded by silica flour or air-filled packers. A dry bulb thermometer is employed to measure the ambient temperature, and a wet bulb thermometer is then used to measure the temperature decrease resulting from fluid evaporation in the subsurface (evaporative cooling). Liquid-filled thermometers are not accurate enough for the precision required, however, and thus more precise thermocouple thermometers are employed. The junction of two wires, a thermocouple, generates an electrical current that is a function of the junction temperature. The temperature of the thermocouple determines the activity of the water surrounding it, which is then correlated with the evaporation rate.

The direction and magnitude of water and contaminant migration may be observed easily and inexpensively with psychrometers, but regular calibration and monitoring of the thermocouple are necessary as temperature deviations of $\pm 0.001\,^{\circ}\mathrm{C}$ between the thermocouple and the liquid phase can introduce significant errors. Regular calibration is necessary due to corrosion of metals and the accumulation of salts on the thermocouple junction. Also, psychrometer equations assume that water is the first liquid to condense, and, at a site containing volatile liquids, this may not always be true (9,10).

Tensiometry

Tensiometers measure the force which holds water to the soil, or the soil–water potential, at shallow depths (0 to 8 m BGS). Because water moves from areas of high potential energy to low, evaluation of water's energy may be used to estimate the direction of water flow and the direction of contaminant plume migration. Rapid measurements at different locations may be obtained with tensiometers, which may then be plotted to obtain a spatial distribution of water and an estimation of the water flow direction.

A tensiometer measures matric potential using a porous ceramic cup placed in the soil, a connecting tube, and a vacuum gauge. The cup and tube are filled with water to provide hydraulic contact from the tensiometer to the water in the soil. Once placed in the ground, water flows out of the cup and into the soil until equilibrium is reached. Because the device is sealed from the atmosphere, the drop of the water level in the tube creates a vacuum which is measured by a vacuum gauge or pressure transducer from the surface.

Tensiomenters represent a low-cost, simple, and accurate measurement of matric potential (11–13). It is one of the most widely used devices for monitoring soil moisture levels in the vadose zone, though tensiometry values are limited to tension values below 0.85 bar at atmospheric pressures near 1 bar. For field applications, air coming out of solution from water or air trapped in the tube are the major shortcomings. During installation, care must be taken to ensure good hydraulic contact between the cup and the soil.

Time-Domain Reflectometry

Time-domain reflectometry (TDR) allows shallow, rapid, *in situ* measurements of water content and electrical conductivity in porous media (14–17). It is commonly used to locate underground cables. It is a relatively new development in vadose zone monitoring that was first described by Topp et al. (18). Accuracy within 1–2% of volumetric water content is feasible with TDR.

TDR uses a probe that is inserted into the soil equipped with 2 or 3 metallic rods that transmit electromagnetic pulses. The travel time of these pulses across the rods through the soil is used to compute the soil's bulk dielectric constant from which the water content is inferred, which provides an average soil water content over the depth of probe insertion.

The main advantage of TDR is that simple and rapid accumulation of shallow soil moisture content with high volumetric accuracy is possible. Calibration requirements are minimal compared to other indirect monitoring methods, and measurements for spatial and temporal analyses are easily obtained. The drawbacks associated with TDR include temperature-dependent readings and probe insertion in rocky or hard substrates because readings are limited to depth of insertion. Additionally, water molecules bound by interfacial forces in high surface area substances, for example, clays, result in lowered bulk dielectric constant compared to other soils at similar water content.

Ground-Penetrating Radar

Ground-penetrating radar (GPR) is an adaptation of seismic reflection for shallow use that images subsurface features by deploying radar waves. It may be used to image any homogeneity in the vadose zone, including contaminant plumes and soil stratification.

GPR is used to observe the electromagnetic impedance of soils using high-frequency radar waves to measure subsurface properties. It consists of an enclosed wave emitter and antenna unit that is dragged across the ground, generally in a grid pattern. Wave pulses are emitted and when an inhomogeneity is encountered, part of the incident energy is reflected back to the radar antenna within the unit. The reflected signal is amplified and transformed into a viewable image. The data are in visual form, not a quantified form, so results must be interpreted.

Any inhomogeneity in the vadose zone can be imaged with GPR. For vadose zone monitoring, contaminant plumes of both light nonaqueous phase liquids (LNAPLs) and dense nonaqueous phase liquids (DNAPLs), as well as buried utility lines and pipes may be imaged with GPR. Additionally, both underground storage tanks (UST) and leaking underground storage tanks (LUST) may be imaged and discerned. The most obvious drawback to GPR, however, is the fact that all data must be interpreted from visual images. Heterogeneities are viewed as anomalies in imaged data, which must be deciphered according to available information on subsurface conditions. Due to this fact, GPR benefits from use in combination with other vadose zone monitoring techniques to avoid misinterpretations (19,20).

Electrical Resistance Blocks

Electrical resistance blocks have been used in agriculture for more than 50 years to measure soil moisture in dry areas. In the environmental field, they are employed where other methods, including tensiometers, lysimeters, and manometers, are not operable due to low soil–water tension, generally between 0.5 and 15 bars.

The method consists of two or more electrodes that are placed in a porous block, commonly made of gypsum. The block is buried in the soil and allowed to remain until moisture equilibrium with the native soil is achieved. Changes in the electrical properties of the block, measured with the electrodes, reflect changes in the water content, which are measured with a wheatstone bridge resistance meter.

The benefits of this technique include low-cost, extensive historical use in agriculture research, and simplicity of use. It is generally useful for approximate soil moisture level changes. The disadvantages include limited historical use in the environmental industry and measurement and calibration difficulties at wet soil moisture potentials. Standard calibration curves exist, but as in many indirect techniques, soil-specific calibration of the instrument is recommended. Other limitations are associated with dissolution of the gypsum block and salinity changes in vadose zone water.

DIRECT MONITORING METHODS

Direct monitoring methods, in contrast to indirect monitoring methods, employ sampling of the vadose zone for liquid, soil, or gas. Obtaining liquid samples is fairly straightforward, using the most widely practiced method, suction lysimeters, but techniques for soil and gas sample acquisition are generally more complicated. Soil sampling commonly involves trenching or digging of some sort, which may be subject to Occupational Safety and Health Administration (OSHA) guidelines (24). Trenches deeper than 5 feet are subject to OSHA regulations and diggings deeper than 20 feet require the approval of a professional engineer. Soils are also subject to maximum allowable slope protocol, depending on their nature. In addition, certain cases may require confined space, heavy machinery, or decontamination permits. Readers are referred to OSHA literature for proper digging protocol. In gas sampling, problems stem from the nature of the phase being sampled, and, to a lesser extent, safety concerns. Vadose zone gas readily exchanges with any other gas with which it comes in contact, and thus samplers must be fully enclosed. Special safety procedures are required when considering volatile substances, such as methane.

Additionally, direct monitoring methods have a much higher risk of introducing contamination into the aquifer or exposing workers to contamination, and thus proper field procedures are absolutely necessary. In contaminated areas, all equipment must be constructed of nonreactive and low sorbing materials and be decontaminated between each use (25–27).

Direct Liquid Monitoring Techniques

Directly monitoring the liquid phase of the vadose zone involves obtaining a representative sample, whether in the form of water or NAPL. These may be important for soil–water chemistry analyses or contaminant plume delineation, among others. The primary method of collection is by using suction lysimeters placed into unconsolidated soil. As a suction device, lysimeters rely on applying a vacuum greater than the soil–water tension to draw a water sample up to the surface. A porous cup is inserted into the soil or in a shallow well, and a vacuum tube connects it to the surface. Once the vacuum is applied, water is drawn to the surface and a sample is obtained. Outside of lysimeters, other methods involve driving devices into unconsolidated sediment or lowering devices down wells above the water table to acquire liquid samples. Lysimeters have the advantage of being relatively cheap and simple to install. Virtually no maintenance is required, although sample volumes may be small.

Described by Gardner (28), wavelengths of light from gamma to X ray may be used to monitor the water content of the vadose zone by direct soil sampling. In practice, however, only gamma rays are employed. In this method, a sample is collected and a narrow beam of gamma radiation is sent through it. A recorder on the opposite side of the sample records only those rays that passed freely through the sample with no reflection along the way. By this method, the volumetric water content can be measured (29).

Direct Soil Monitoring Techniques

Due to the sorbing nature of many contaminants, soil samples are used to monitor the spatial and temporal distributions of contaminants in the soil. For certain applications, undisturbed samples are desired, in which case special precautions must be taken, and certain sampling tools and techniques must be employed. Generally, soil sampling involves inserting a device into the ground to recover a soil sample, although more intensive methods may be necessary in certain situations. Hand-operated samplers are typically used for shallow sampling and mechanically powered devices for deeper sampling. There are five basic hand-operated samplers, as described by Dorrance et al. (30), that include screw augers, barrel augers, tube samplers, hand-powered augers, and bulk samplers (shovels, etc). Each type has its own pros and cons depending on cost, ease of use, availability, size of matrix grains, degree of sediment cohesiveness, and other factors. Due to these, sampler choice is often site specific. For deeper monitoring applications, mechanically powered tools such as a drill rig must be employed.

Direct Vadose Zone Gas Monitoring

Monitoring the gas phase of the vadose zone is important because many contaminants volatilize to a significant degree. Unlike liquid and soil phases, the gaseous component of the vadose zone is problematic because atmospheric air and foreign vadose zone gases readily exchange and react upon exposure. When sampling, all gaseous vadose zone samples must avoid exposure to foreign air, and all sampling methods must be designed to avoid it. *In situ* sampling and devices with internal liners designed to seal samples from the atmosphere are preferred (31).

Monitoring through sampling the gas phase typically involves hydraulically ramming a specially designed device into the soil where it collects samples via a vacuum and pumps them to the surface for collection. Passive gas sampling by an *in situ* absorbent, such as an activated carbon trap placed in the vadose zone, may be used, but less information is provided by this method. Direct sampling of gases is more desirable, but it is more difficult and costly. An alternative is monitoring gas advection by using groundwater tracers. A tracer that partitions to the gas phase is injected, samples are taken at other sites, typically at wells, and analyzed for the tracer concentration (32–35).

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