CHAPTER 5

HYDROGEOLOGIC SITE INVESTIGATIONS

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5.1 INTRODUCTION

The purpose of hydrogeologic site investigations is to characterize soil and ground water pollution problems in sufficient detail to facilitate design of a cost-effective corrective action program. For this purpose, the site investigation entails measurement of the physical parameters that control subsurface contaminant transport at a given site. Geologic, hydrologic, and chemical data must be acquired and integrated to define the nature and extent of soil and ground water contamination and the potential for migration of contaminants within the natural ground water flow system. To the extent practical, the remedy should be anticipated at the outset of an investigation so that design-basis information necessary for development of the corrective action program is obtained in a timely and cost-effective manner.

The preceding chapters of this book have reviewed the general principles of ground water occurrence and flow within geologic formations and the nature of the most common ground water contaminants. In this chapter, the engineering procedures involved in the acquisition and interpretation of ground water flow and contaminant information will be addressed. The following sections outline a systematic approach to planning and implementing soil and ground water contamination studies and summarize engineering standards for data evaluation and presentation.

.2 DEVELOPMENT OF CONCEPTUAL SITE MODEL

Hydrogeologic processes are, by nature, complex, due to the heterogeneities of geologic formations and the transient effects of aquifer recharge and discharge phenomena. Additional complexity arises from the presence of contaminants that may be irregularly distributed in, and reacting with, subsurface formations and ground water. Consequently, detailed characterization of contaminant distribution and transport patterns throughout every inch of an aquifer system is impractical. From an engineering perspective, our objective is therefore to define subsurface contaminant transport processes to the degree necessary to allow us to design effective measures for control or reversal of these processes, as needed to protect public health and the environment.

Ultimately, protection of drinking water resources may require us to extract or "mine" the contaminated ground water mass from the affected aquifer. Therefore, it is helpful to approach a ground water contaminant delineation study in much the same manner as prospecting for hydrocarbons or precious metals. We do not need to know each twist and turn of every minor "ore" seam, but we do want to know how wide and how deep the play runs and, because our "ore" is a fluid, which way it is moving and how fast.

The hydrogeologic site investigation is the procedure by which we develop our understanding or our "working model" of contaminant plume migration within the ground water flow regime. In all cases, this model of the subsurface environment is constructed of three principal components of information:

1. **Geology**: the physical framework within which subsurface fluids collect and flow;
2. **Hydrology**: the movement of fluids through this physical framework; and
3. **Chemistry**: the nature of the chemical constituents that are entrained in this flow system and the chemical and physical interactions between the contaminants and the subsurface formation and ground water that may be occurring.

We build our model of the site by systematically addressing each of these principal components in turn. First, we must characterize the stratigraphic profile beneath the site and identify those strata serving as potential conduits for fluid flow and the geologic features that may influence the movement and accumulation of nonaqueous phase liquids (NAPLs). Second, we must measure the fluid hydraulic head distribution within the zone of saturation to determine the actual rate and direction of ground water movement through these conduits. Third, water samples are collected and analyzed to map the lateral and vertical extent of contaminant migration within the ground water flow regime.

There is significant overlap in the acquisition of these three classes of data, and in practice, they are collected simultaneously. For example, a soil boring may be drilled to characterize the geology of the site; it provides soil samples for laboratory analysis of contaminant concentration; and it may be converted to a monitoring well to permit collection of ground water samples and hydrologic data. A well designed site investigation will maximize the relevant information collected during each step of the work program. It is then the job of the project engineer or scientist to sort this information into a meaningful and accurate picture of subsurface ground water flow and contaminant transport processes.

5.3 STRATEGY FOR HYDROGEOLOGIC SITE INVESTIGATIONS

5.3.1 Overview and General Considerations

As a practical matter, site investigation workplans usually represent a compromise between the ideal of knowing as much as possible about a site and the realities imposed by a finite budget. For the purpose of economy and efficiency, every field and laboratory measurement conducted during the investigation must contribute to the conceptual model of the site. The key is to design a work program that provides the necessary data by making the maximum use of the available resources.

To achieve project objectives in a cost-effective manner, a clear strategy for mapping the contaminant zones must be established prior to commencement of field or laboratory work. At the outset, all available site information concerning subsurface geology, ground water flow, and the nature, extent, and timing of the contaminant release should be assembled to guide the selection of sampling locations. Data quality objectives and appropriate sampling and testing technologies must be identified to ensure collection of data that meet not only the engineering, but also the regulatory requirements of the project.

As a basis for a site investigation strategy, all subsurface contaminant problems should be viewed as two distinct zones of contamination: (1) contaminant source materials and contaminated soils in the unsaturated soil (or rock) zone; and (2) nonaqueous phase liquids (NAPLs) and/or ground water containing dissolved contaminants within the zone of saturation (Figure 5.1). For practical purposes, we can define the vertical boundary between these two zones as the surface of the uppermost water bearing unit beneath the site (e.g., a water-saturated stratum with hydraulic conductivity, $K \geq 1 \times 10^{-4}$ cm/sec). These two zones differ significantly in terms of their operant mechanisms of contaminant transport and the requisite corrective actions, and therefore should be addressed individually in the course of the hydrogeologic site investigation.

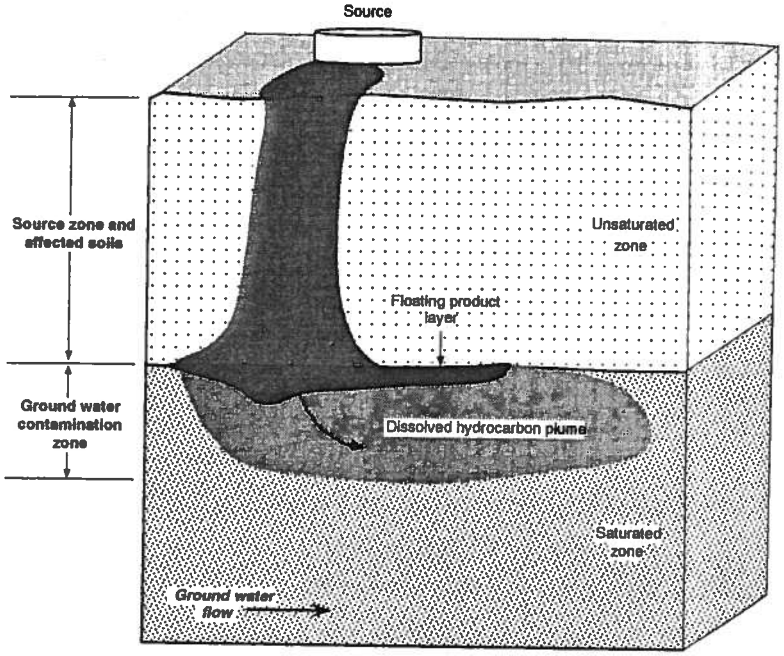


Figure 5.1 Zones of contamination for two-stage site investigation approach.

5.3.2 Unsaturated Source Zone Characteristics

Most incidents of hazardous chemical release to the subsurface environment occur as surface spills of products or wastes or leachate percolation from the base of waste landfills, surface impoundments, or material stockpiles. As the wetting front percolates downward through the unsaturated soil (or rock) zone underlying the source area, a significant portion of the contaminant mass may be retained in the unsaturated soil matrix due to the effects of filtration, sorption, or capillary retention. For many years thereafter, this contaminated soil can serve as a source of continuing contaminant release to stormwater flowing across the site surface or percolating downward through the unsaturated soil zone to the depth of underlying ground water.

Depending on the size and geological characteristics of this residual source zone and the nature and concentration of the contaminants, protection of surface water and ground water resources could involve either complete excavation and removal of the contaminated soils, capping of the site to minimize rainfall contact and precipitation, or contaminant extraction by means of in-situ soil venting or rinsing. To support design of appropriate corrective measures, the hydrogeologic site investigation must therefore address the full lateral and vertical extent of residual contaminants within the unsaturated soil zone and the potential for future release of contaminants to local water resources.

5.3.3 Ground Water Plume Characteristics

Dissolved contaminants contained in waste leachate fluids penetrating to the depth of ground water occurrence will become entrained in the natural ground water flow system and spread laterally and vertically in accordance with local ground water flow gradients (Figure 5.1). Free-phase liquid contaminants may be subject to an additional "density gradient" with light non-aqueous phase liquids (LNAPLs, such as gasoline) floating atop the zone of saturation and collecting in the structural highs of confined water-bearing units. Alternatively, dense non-aqueous phase liquids (DNAPLs) can percolate downward through the water-bearing stratum to perch and spread atop underlying confining units (Chapter 11).

In all cases, ground water contamination problems are fluid problems. The contaminant enters the ground water system as a fluid and can therefore be removed or controlled as a fluid. Unlike contamination within the unsaturated soil zone, excavation and removal of the soil or rock mass from the zone of ground water contamination is neither practical nor necessary. The hydrogeologic site investigation must therefore provide definitive information on the current lateral and vertical extent of dissolved and free-phase contaminants within the ground water, as well as the hydraulic processes controlling contaminant migration.

5.3.4 Two-Stage Site Investigation Approach

In practice then, the hydrogeologic site investigation proceeds as a two-stage process: (1) delineate the unsaturated source zone, comprised of the chemical waste or product mass and the associated contaminated soils within the unsaturated soil column, and (2) investigate the presence and extent of contaminant migration within the underlying ground water system. Step-by-step strategies for implementation of these source zone and ground water contamination delineation studies are outlined below and illustrated on Figures 5.2 – 5.4.

Procedures for Unsaturated Source Zone Characterization. The objectives of the source zone characterization study are to locate the site of the release, identify the contaminants of concern and determine their concentrations, and delineate the source material or unsaturated soil mass that may act as a continuing source of contaminant release to surface water or underlying ground water. The principal steps required for delineation of the source zone are illustrated in Figure 5.2 and listed below.

As shown on the task flowchart, to commence the delineation study, available chemical information regarding the suspected source of the subsurface release (e.g., waste or product spill) must be compiled to provide a basis for design of the laboratory testing program. If

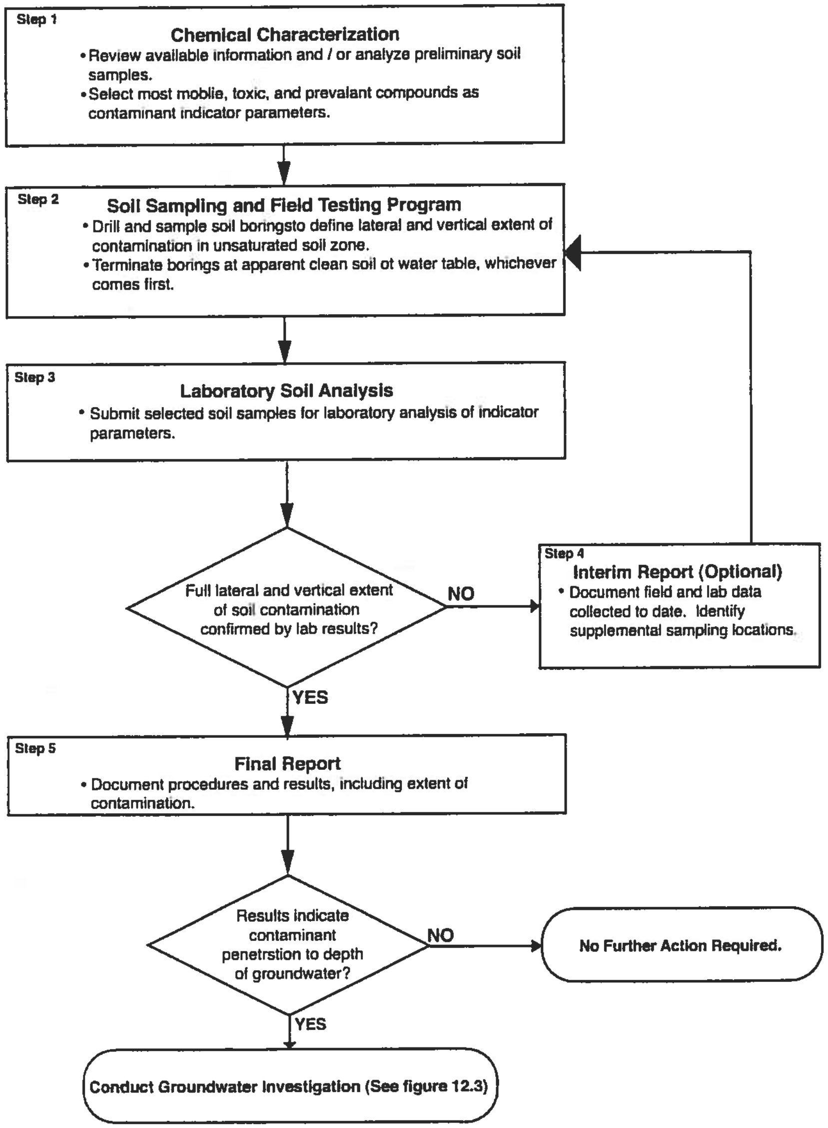


Figure 5.2 Procedures for source zone characterization.

such information is unavailable or inadequate, representative contaminated soil samples should be collected from the release site and analyzed for a broad suite of chemical compounds, as appropriate, to identify the principal contaminants of concern. Appropriate laboratory indicator parameters and field testing procedures should then be selected on the basis of the prevalence, mobility, and toxicity of the principal constituents identified.

In Step 2 of the source delineation, a field sampling and testing program is conducted to define the apparent lateral and vertical extent of contamination within the unsaturated soil zone. At each soil sampling location, sampling and field testing should be conducted continuously with depth until either clean soil or ground water infiltration is encountered. As discussed in Section 5.4, typical field test methods for hydrocarbon contamination include organic vapor headspace analyses and various colorimetric indicator tests.

To confirm the apparent lateral and vertical extent of contamination observed in the field, samples of the uppermost "clean" soils encountered at each sampling location should be submitted for laboratory analysis of indicator parameter content (see Step 3, Figure 5.2). Representative samples from within the contamination zone should also be submitted for analysis of total and leachable contaminant indicator concentrations in order to characterize contaminant mass and mobility.

Delineation of the contaminated soil zone is an iterative process, often requiring two or more field and laboratory cycles for completion. Should the results of the source zone investigation show contaminants to have penetrated to the depth of underlying ground water at concentrations exceeding relevant cleanup standards, a ground water contamination study will also be required.

Procedures for Ground Water Contaminant Plume Delineation. The objective of a ground water contaminant investigation is to determine the presence and extent of dissolved or free-phase contaminants, as well as the likely rate and direction of contaminant migration within the ground water flow system. Principal steps to be followed are shown on Figures 5.3 and 5.4.

As indicated on the task flowchart, the ground water investigation must be preceded by identification and characterization of all potential source zones in the study area. A detection monitoring program, involving installation of 1 to 3 ground water sampling points at each known or suspected source location, should then be completed to identify all sites of hazardous constituent release to ground water.

Ground water plume delineation should be conducted in a step-wise procedure in order to minimize the number of ground water sampling points required. First, based upon the suspected age of the release and the lateral ground water seepage velocity determined during the detection monitoring study, estimate the potential length of the contaminant plume (i.e., seepage rate × time = length) and space sampling points accordingly along the plume axis to locate the actual downgradient boundary. Second, to define the width of the contaminant plume, complete additional sampling points on 1 or 2 lines running transverse to the plume axis. Finally, to determine the vertical limit of contaminant migration, collect and analyze ground water samples from "nested" sampling points (i.e., samples collected in close lateral proximity, e.g., < 10 ft distance, but from different discrete depths within the water-bearing unit).

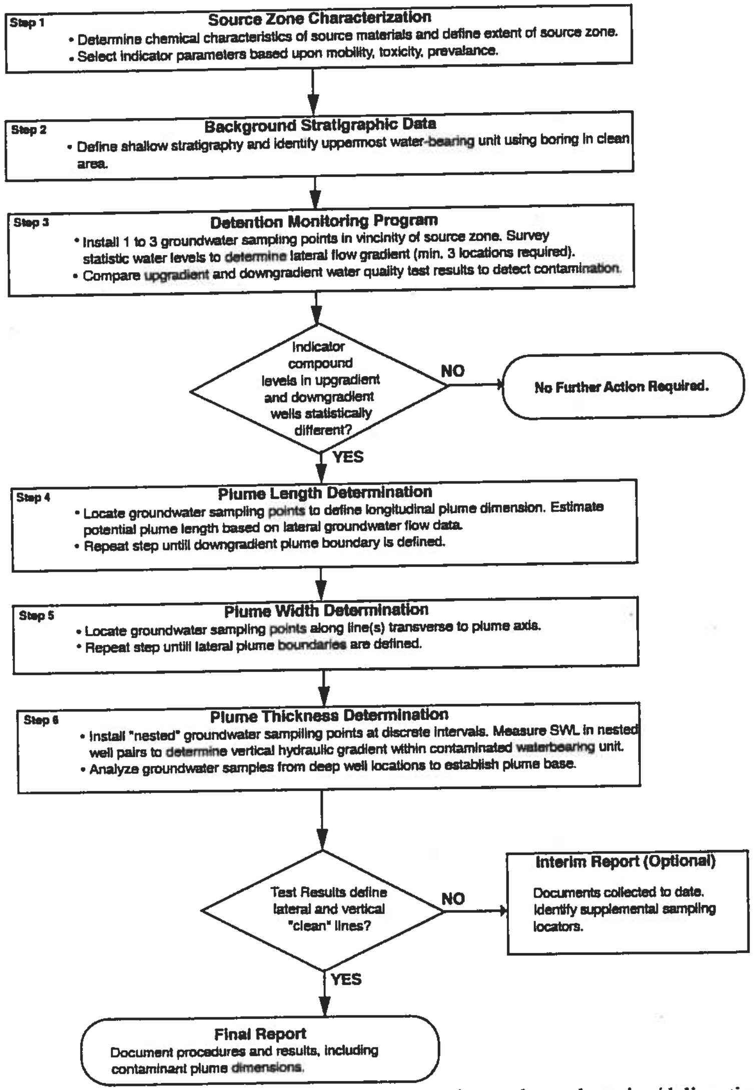


Figure 5.3 Procedures for ground water contaminant plume detection/delineation.

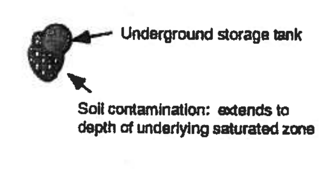
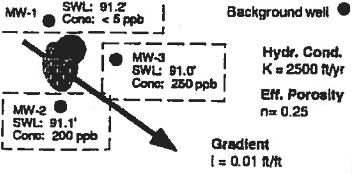
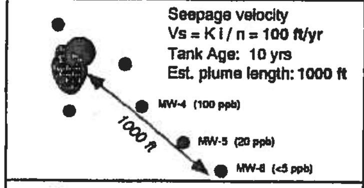
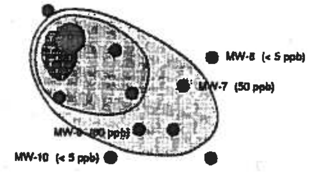
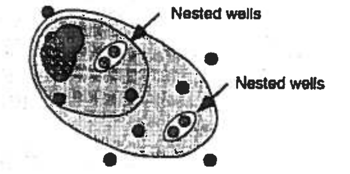
	**Step 1: Source Delineation** • Locate potential sources. • Define lateral and vertical extent of soil contamination. • Characterize contaminant properties: solubility, density, etc. • Select indicator parameters.
	**Step 2: Detection Monitoring** • Drill adjacent to source zone to define stratigraphy and identify uppermost water-bearing unit. • If DNAPLs are indicated, use drilling precautions or outside-in strategy for detection monitoring. • Install at least 3 wells to define ground water flow direction. • Compare indicator compound concentrations in upgradient and downgradient wells. • Run slug tests to define aquifer hydraulic properties
	**Step 3: Plume Length** • Locate wells to define plume length. • Use gradient, porosity, and K to define seepage velocity (v_s). • Use v_s and estimated source age to estimate plume length. • Space downgradient wells accordingly. • Repeat as necessary to determine length.
	**Step 4: Plume Width** • Locate wells on transverse line to determine plume width. • Can estimate width using advection/dispersion equation • Unusual plume shapes indicate possible presence of NAPLs
	**Step 5: Plume Thickness** • Install nested wells to determine depth of contamination. • Estimate vertical gradient by comparing static water levels in deep and shallow nested wells. • Use drilling precautions if presence of DNAPL is indicated.

Figure 5.4 Typical work program for ground water plume delineation.

If the contaminant plume is found to extend through the full thickness of the uppermost water-bearing unit, sampling and analysis of ground water from the next underlying water-bearing stratum may be necessary to establish the vertical limit of contamination. In such case, it is critical that any observation points penetrating the confining layer separating the upper and lower water-bearing strata be completed in a manner not providing an artificial conduit for contaminant migration. Appropriate protective measures are discussed in Section 5.4.

DEVELOPMENT OF A DETAILED SITE INVESTIGATION WORKPLAN

Prior to commencing the hydrogeologic site investigation, the specific field and laboratory tasks required to implement the site investigation strategy described above should be identified and appropriate resources allocated. Preplanning activities should include specification of the number, location, and depth of soil and ground water samples to be collected; sampling procedures and associated equipment requirements; field safety protocol; and field and laboratory test methods. The proposed sampling plan should be reviewed in advance to ensure that the information obtained will be adequate to meet the geologic, hydrologic, and chemical data objectives of the source characterization or ground water plume detection/delineation study.

To provide a technical basis for planning of the site investigation, available site information must be compiled and reviewed to define the general location and duration of the suspected release, the probable contaminants of concern, and general stratigraphic conditions. Typical sources of information include site operating records, regulatory agency records, employee interviews, historical aerial photographs, published geologic references, prior foundation studies or hydrogeologic site investigation reports.

5.4.1 Project Objectives

Both the source zone investigation and the ground water plume investigation should be approached in a step-by-step manner. In addition, the project engineer or scientist must clearly anticipate the end point of the site investigation, as well as actions to be taken in the event that unexpected site conditions are encountered. For example, is the purpose of the sampling merely to confirm the presence or absence of a specific compound or to delineate its full extent? If ground water is encountered during a source characterization study, will a sample be collected for the purpose of contaminant detection?

It is not necessary or even advisable to complete a full hydrogeologic site investigation in one step. Rather, it will generally prove more economical to conduct the project in a phased manner with each work stage having a predefined objective and end point.

Based upon available information, a preliminary plan should be developed regarding the number, location, and depth of samples required to meet the project objectives. All proposed drilling locations should be staked and cleared in advance for the presence of buried utilities. Appropriate sample collection and handling procedures must be specified and relevant equipment provided in working order. Sample kits containing the sample containers and preservatives required for the specified analytical methods should be ordered from the laboratory.

The field supervisor should be provided with a written copy of the sampling plan and project safety plan, specifying project objectives, proposed sampling locations, field test

procedures, and laboratory analyses, as well as the basis for modification of the proposed workplan during implementation. General guidelines for design of the field program are provided below.

5.4.2 Design of Unsaturated Source Zone Characterization Study

General guidelines regarding the number, location, and depth of sampling points required for a source zone characterization study are as follows:

Number and Location of Samples. For initial chemical characterization of the residual waste materials or affected soil zone, analysis of one to four samples collected from known contaminated areas will generally suffice. To define the lateral limits of the source zone, samples can either be located on a rough grid pattern across the suspected contaminant area or completed on a "step-out" pattern, whereby samples are collected at even distances along lines extending radially from the known source area until clean soil conditions are encountered.

To minimize the number of samples required for the source zone delineation, the field program should be focused on establishing the "clean line" (i.e., the perimeter of the contaminant area), rather than defining variations in contaminant concentrations within the source zone. In general, "clean" soil conditions will correspond either to (1) the natural background concentrations of the contaminant compounds occurring in site soils or (2) other cleanup standards established by the state or federal regulatory authority.

Sampling Depth. At each sampling location, soil samples should be collected continuously to the depth of clean soil conditions or to the depth of ground water occurrence, whichever comes first. However, care must be taken not to puncture confining layers (i.e., clay, shale, or other low-permeability strata) which might be serving as a "safety net" against downward migration of contaminants beneath the source zone. For this purpose, at sites where soil contamination may extend beyond the depth of the surface soil stratum, it is advisable to drill at least one "background" soil boring at a known clean location to define site stratigraphy prior to drilling through the contaminant zone.

Sampling and Field Testing Methods. Initial chemical characterization of the source zone materials will typically involve collection of wastes, spilled products, or affected soils for laboratory analyses of a broad range of hazardous chemical constituents potentially associated with the site. Thereafter, sample analyses may be limited to key indicator parameters, including the use of various field tests (such as organic vapor analyses or colorimetric methods). Hand augers may be used to collect soil samples at depths less than 5 ft below grade. For delineation of large contaminant areas or buried waste sites, backhoes are effective to depths of 10 to 15 ft. In general, direct-push soil probing devices or conventional drilling rigs represent the most cost-effective means of soil sample collection at depths greater than 10 ft.

5.4.3 Ground Water Plume Detection/Delineation Studies

General guidelines regarding the number, location, and depth of sampling points required for a plume study are as follows:

Number and Location of Samples. For the purpose of a plume detection study, a minimum of three monitoring wells or piezometers are required to establish the lateral hydraulic flow gradient in the uppermost water-bearing stratum underlying the source area. Water quality measurements from upgradient sampling locations should be compared to data from downgradient locations to confirm the presence or absence of ground water contamination. The strategy for lateral and vertical delineation of the contaminant plume is outlined on Figure 5.4.

Sampling Depth. Wells should be screened within the uppermost water-bearing stratum underlying the suspected source area. Good practice calls for limiting the length of the well screen to no more than 15 ft to minimize potential dilution of dissolved or free-phase contaminants. Consequently, in thick aquifers, installation of "nested" wells (i.e., adjacent wells screened at different depth intervals) may be required at selected locations to define the vertical limit of contaminant migration. To detect free-phase contaminants, well screens should be positioned to intersect either the top (for floating fluids) or the base (for sinking fluids) of the water-bearing stratum. If, upon completion of the plume delineation in the uppermost aquifer unit, sampling of deeper, underlying water-bearing units is required, special care must be taken to avoid inadvertent interconnection of contaminated and uncontaminated layers.

Ground Water Investigation Methods. Drilling and sampling of monitoring wells provides information on site stratigraphy, static water level elevations, and water quality. Consequently, wells are a common component of most ground water detection/delineation studies. However, as discussed in Section 5.4, many other site investigation technologies can be employed to obtain discrete-depth ground water samples or supplementary information regarding site stratigraphy or aquifer hydraulics. The utility of these alternate methods depends on the specific type of information required to complete the "picture" of the ground water contamination problem.

5.4.4 Laboratory Specifications

The appropriate analytical method to be employed for measurement of a specific contaminant or group of contaminants in a soil or ground water sample depends both upon the level of contamination anticipated and the detection limit required. In order to demonstrate "clean" conditions, an analytical method having a detection limit less than the anticipated cleanup standard must be employed. For example, to show that benzene concentrations in a ground water sample are less than the U.S. Primary Drinking Water Standard for this contaminant (i.e., 5 μg/L), a gas-chromatography (GC) or gas-chromatography mass spectroscopy (GCMS) method, providing part-per-billion (ppb) sensitivity, must be employed. However, gross delineation of plumes and characterization of total contaminant mass can be accomplished to a large extent using less sensitive analytical methods (e.g., part-per-million sensitivity level).

Procedures for selection of laboratory samples and the specific analytical methods to be employed must be defined in advance of sample collection. For each test method specified, appropriate sample containers and preservatives must be obtained and arrangements made for completion of the laboratory analysis within the holding time specified under EPA protocol. Detailed information regarding test methods applicable to soil and ground water samples is provided in EPA Publication SW-846 (EPA, 1986).

5.4.5 Data Evaluation and Report Specifications

The project workplan should define what the final product of the study will be, including the specific determinations to be made, the procedures to be employed to make such determinations (e.g., statistical analyses, calculations, etc.), and the manner in which such findings will be presented (e.g., cross-sections, data plots, etc.). The proposed field and laboratory plan should be reviewed to ensure that the data required for completion of the final report will be obtained and properly recorded during the work program.

5.5 DATA COLLECTION METHODS

5.5.1 General Considerations

Traditionally, the methods employed in hydrogeologic site investigations have been those originally developed for the geotechnical, water well, and petroleum industries. Equipment and techniques have been refined to accommodate the special requirements associated with defining the extent of contaminant plumes. New technologies for environmental site investigations are continuously being developed. Many new techniques offer significant cost advantages over more conventional methods, and have gained wide acceptance among regulators. To assist investigators in selection of appropriate field sampling and testing methods, the U.S. EPA maintains a site on its web page (www.epa.gov) in which a wide variety technologies are described and evaluated, with links to other sources of information.

Information concerning the nature of the geologic materials, the occurrence of ground water, and the presence or absence of contaminants in soil and ground water beneath a site can be obtained by both direct observation, that is, collection and analysis of soil and ground water samples, and by indirect means, such as geophysical measurements and in-situ chemical sensing. Use of such indirect methods of assessing site conditions can reduce the cost of the investigation and in some cases can also replace subjective description with more readily comparable numerical data. However, geophysical instrumentation can produce identical responses from a variety of conditions, and a unique and definitive interpretation of the data is often not possible. In-situ chemical data are typically semi- or quasi-quantitative, and may not be considered definitive of site conditions by regulatory agencies. Therefore, such indirect measurements should be, at a minimum, calibrated against, and or confirmed by, "direct" data obtained from soil and ground water samples collected on site.

The following sections describe methods for the acquisition of geologic, hydrologic, and soil and ground water quality (chemical) data. The emphasis is on the more conventional techniques, employing direct observation and measurement of soil and ground water samples. Techniques employing indirect measurement of soil and water properties are treated more briefly, but their value should not be discounted. Use of indirect sampling methods in environmental assessments is an evolving field, and improvements in data quality and cost-effectiveness are likely to continue make such techniques increasingly common in the future.

5.5.2 Project Safety

Safety considerations should figure prominently into all drilling and sampling plans. A project health and safety plan meeting the requirements of 29 CFR §1910.120 is required by federal regulations (OSHA) for all investigations of hazardous waste sites. The plan should be distributed to and reviewed by all project personnel prior to project start-up. Prior to commencement of any drilling operation, the locations must be cleared for underground utilities.

5.5.3 Documentation of Site Conditions

Documentation of field sampling procedures and observations is a critically important aspect of the hydrogeologic site investigation. Without reliable records, the results of field sampling program may be of no value. Therefore, all measurements and relevant observations must be clearly and legibly recorded either in field logbooks or on data collection forms. Subjective observations, a necessary component of the field record should be made in the most precise, unambiguous language possible. In addition to the sample measurements and descriptions, the log should record any site conditions that could affect the observations or measurements, and any deviations from the established scope of work or sampling protocols.

6 GEOLOGIC DATA ACQUISITION

5.6.1 Direct Observation Methods

The essential geologic data required in all hydrogeologic site investigations is a description of the principal stratigraphic units underlying the site, including their thickness, lateral continuity, and water-bearing properties. This is most commonly assessed by direct examination of soil or rock samples collected from core borings. Soil samples collected during this process are also typically submitted for analysis of potential contaminants.

On sites underlain by unconsolidated materials and where drilling depths are shallow (100 ft or less), the collection of core samples from soil borings is a generally cost-effective method of collecting geologic data. In areas underlain by consolidated rock, where site conditions require investigation at greater depths, and where the cost of disposal of investigation-derived wastes (IDWs) is high due to classification of these materials as hazardous wastes, the collection of core samples is more costly and may be augmented or replaced in part by cone penetrometer testing, or surface or borehole geophysical methods, which are described below.

5.6.2 Drilling Methods

A variety of drilling methods are employed during hydrogeologic site investigations. Selection of the drilling method depends on such factors as drilling depth, nature of the geologic formations under investigation, and the specific purpose of the boring, that is, lithologic sampling, soil sampling for chemical analysis, and/or well installation. An additional consideration is the volume of drill cuttings and fluids that are produced, especially at sites where these investigation-derived wastes (IDWs) must be disposed as a hazardous waste.

This summary is intended to be only a brief introduction to the most common drilling methods used in the environmental industry. Driscoll (1986) presents detailed descriptions of drilling techniques used in the water well industry generally. Scalf et al. (1981) includes a description of drilling techniques which focuses on environmental applications.

In conducting environmental site investigations, the introduction of foreign materials into the borehole is generally undesirable due to the possibility of reaction with the geologic media or ground water, which may affect the results of laboratory analysis of soil or ground water samples. Even when a potable water source is used in the preparation of drilling fluids, chlorine may react with naturally occurring organic material in the soil to produce detectable concentrations of trihalomethane compounds (such as chloroform and dichlorobromomethane) in the ground water. Therefore, drilling is frequently performed "dry," that is, without the use of drilling fluids or "mud." Drilling dry also allows identification of the depth of the first occurrence of ground water. When ground water is first encountered, drilling operations should be halted long enough to observe whether or not water rises in the borehole, to determine whether ground water is confined or unconfined. Some drill rigs are equipped for both wet and dry drilling methods and can be switched from auger drilling above the water table to wet-rotary below it. Dry drilling is most commonly performed using either solid-flight or hollow-stem augers as described in the following paragraphs.

Solid Flight Auger Drilling. Solid flight augers consist of sections of solid rod with a continuous ramp of upward spiraling "flights" welded around it (Figure 5.5). The auger sections (each typically 5 ft in length) are pinned together as drilling proceeds. As the drill-stem is rotated, cutting teeth on the lead auger dig into the formation and the loosened soil rides up the flights to the ground surface. The "string" of auger sections is "tripped" out of the hole at each soil sample interval, and samples are collected by hydraulically pushing a thin-walled steel sampling tube ("Shelby tube") or driving "split-spoon" sampler with a percussion hammer, into the underlying undrilled formation. The drill string is then "tripped" back into the hole, and drilling proceeds to the next sample point.

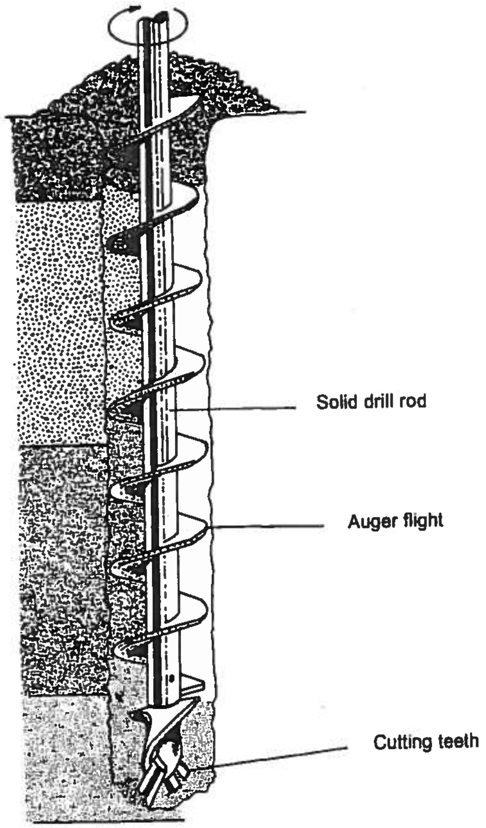


Figure 5.5 Solid-flight auger drilling equipment. Source: Scalf, et al., 1981.

Solid-flight augers are effective in cohesive soils above the saturated zone. Because of the tendency for borehole walls to collapse when the drill string is tripped in and out of the hole, solid flight augers are not useful in loose soils or below the water table and are not generally suitable for monitoring well installation.

Hollow Stem Auger Drilling. Hollow-stem augers are another type of flight auger, but instead of being welded to a solid rod, the flights are welded around a hollow pipe (Figure 5.6), The lead auger is fitted with cutting bits located around the circumference of its

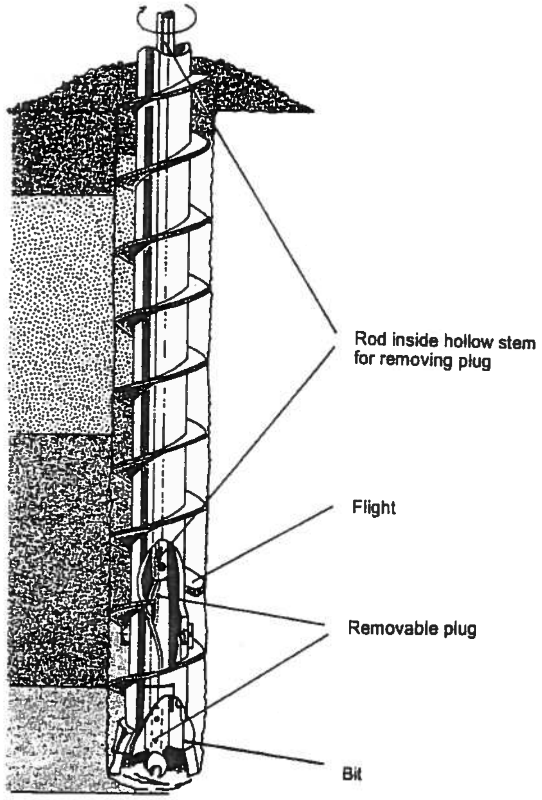


Figure 5.6 Hollow-stem auger drilling and soil sampling equipment. Source: Scalf, et al., 1981.

base. During drilling, a center rod equipped with a pilot bit is lowered inside the auger, and the center rod and hollow-stem are rotated together.

As drilling proceeds, loosened soil rides up the outer ramp of auger flights as with the solid flight auger. A plug, positioned above the bit, prevents soil from traveling up the inside of the hollow-stem. When the sample interval is reached, the center rod, plug, and bit are removed, and the soil sampling tool is lowered inside the hollow-stem, which remains in the borehole to prevent collapse of the walls. The sampling tool, typically a split-spoon or

Shelby tube sampler, is then pushed or driven into the soil ahead of the auger. If a monitoring well is to be installed, the well screen and riser can also be lowered within the hollow stem, which provides a temporary casing, as described later.

Under favorable conditions, hollow-stem auger can be used to depths exceeding 150 feet. However, at depths below about 50 ft, drilling and soil sampling slow down considerably. At greater depths, in harder formations, and in flowing sand conditions, wet rotary is a more effective method.

Wet Rotary Drilling. During wet rotary drilling, a dense drilling fluid or "mud" is pumped down a hollow drill pipe and through holes or "jets" located above the teeth of the drill bit (Figure 5.7). As the fluid is pumped down the hole, drill cuttings are circulated up the borehole to the surface. The drilling mud also cools the drill bit, exerts hydrostatic pressure on the formation, and forms a thin coating or "mudcake" on the borehole wall, which keeps the unconsolidated aquifer material from collapsing and closing the borehole during soil sampling and well installation. In environmental applications, the drilling mud is most commonly prepared from powdered, additive-free bentonite (a mixture of dense clay minerals of volcanic origin) and potable water. During soil sample collection, the drill stem may be removed from the hole and the drill bit replaced with either a split-spoon or Shelby tube sampler.

Wet rotary drilling is effective in environments where auger drilling is not practical, including hard, consolidated formations, such as well cemented sandstones or shales, and very loose, flowing sand formations. In general, drilling and soil sample collection by wet rotary are faster than in hollow-stem operation, particularly as drilling depth increases. Because the borehole does not need to accommodate the auger, a smaller diameter hole may be drilled by wet rotary than with hollow-stem, which can reduce the volume of soil cuttings; however, more fluid wastes are generated due to the use of drilling mud.

Air Rotary Drilling. Formations such as vesicular basalts and highly fissured or cavernous limestones, are frequently drilled by air rotary methods. Air rotary drilling operates on the same principle as wet-rotary. Direct circulation of compressed air down the drill string and through the bit raises cuttings to the surface in small-diameter boreholes without introducing water from the surface. As formation water is blown out of the borehole along with drill cuttings, identification of the upper-most water-bearing zone is possible.

Sonic Drilling. Sonic drilling, also known as vibratory or "rotosonic" drilling, is a relatively new method that has been used in unconsolidated formations and soft of fractured rock to maximum depths of close to 500 ft. The drill bit is advanced into the subsurface by high-frequency vibrations transmitted through a rotating drill pipe. A temporary casing string advanced simultaneously keeps the hole open during drilling. Soil samples are collected from within the casing as the hole is advanced. Upon reaching the required depth, the well is set within the casing, which is subsequently extracted. Sonic drilling is faster than hollow-stem auger and comparable to mud rotary drilling, and it produces less drilling wastes than either auger or wet rotary drilling. To date, the use of sonic drilling has been limited in part by its higher cost relative to more conventional methods.

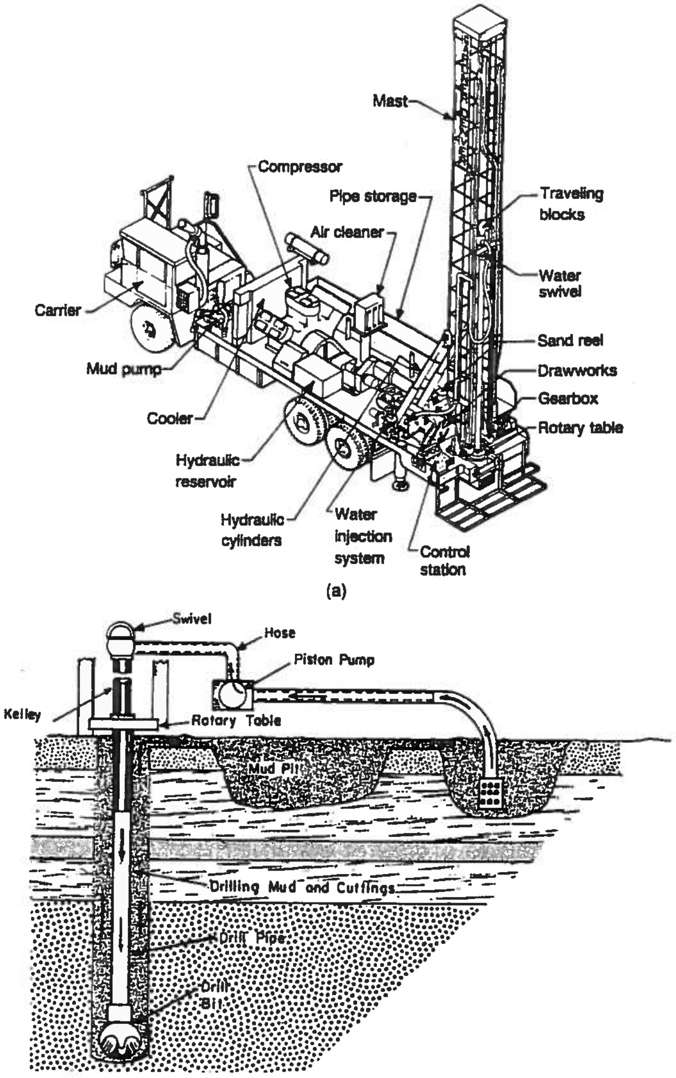


Figure 5.7 Wet rotary drilling equipment. Source: Scalf, et al., 1981.

Direct-Push Soil Probes. Direct-push soil probe systems are another relatively recent technology for collection of soil samples and installation of ground water monitoring points. Direct-push systems are generally smaller than conventional drilling equipment and may be mounted on a pick-up truck or small all-terrain vehicles, and, unlike conventional drill rigs, which have masts extending 30 ft or more vertically, direct push rigs can operate in locations where head space is limited by overhead power lines or piping (Figure 5.8). Direct-push rigs require much less set up time than conventional drill rigs and shallow sample collection is more rapid. On the other hand, because of their size, the practical working depth of direct-push rigs is limited, and a relatively small diameter sample (1–2 in) is obtained. While they have been used to obtain samples from as deep as 100 ft, their relative speed compared with other methods diminishes below 20–30 ft.

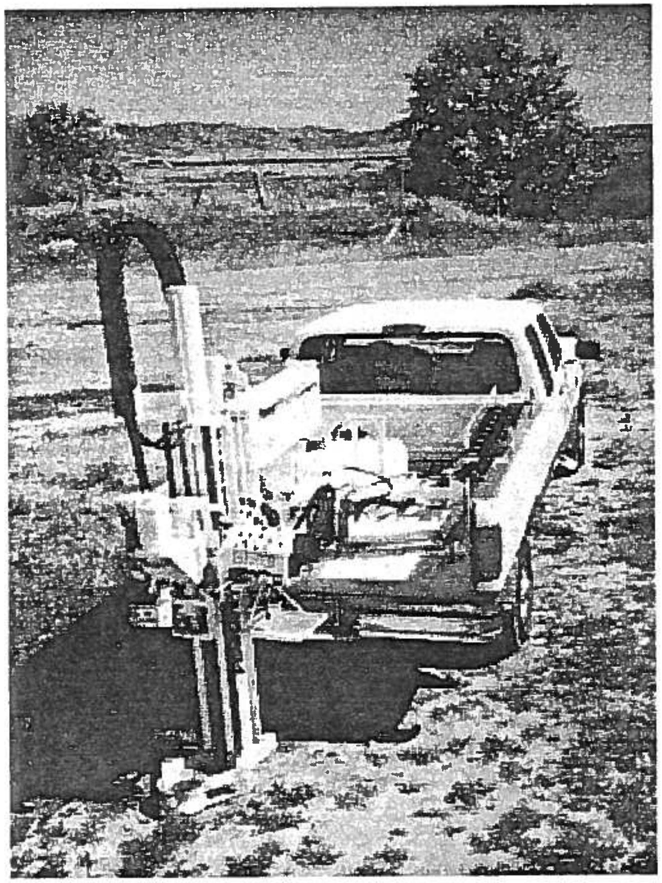


Figure 5.8 Direct-push soil probe.

During direct-push sampling, the sampler is advanced into the subsurface by hydraulic push, augmented by a rapid percussion hammer to penetrate pavements and harder formations. The most common samplers in use are open acrylic-lined sampling tubes and closed piston samplers, described below. The sampler is most commonly lowered within the open borehole, which can result in collection of up-hole materials as the sampler scrapes along the borehole wall. Systems which advance a temporary casing to prevent hole collapse and minimize sample contact with the overlying formation are available, but the effective sampling depth, the sample diameter, and the speed of the operation are all reduced by such enhancements.

Small diameter shallow monitoring wells, constructed as either temporary or permanent installations, can be installed using direct-push rigs. In addition, a wide array of direct-sensing probes for identification of the water table or detection of contaminants have also been developed for use with direct-push rigs.

Unless they are to be converted to monitoring wells, soil core, soil probe, and CPT borings (described below) should be sealed upon completion to prevent migration of fluids from the surface down the borehole. This is especially critical when contamination is present above the water table and the soil boring has been advanced to ground water. The grout seal may consist of neat cement, a cement bentonite mixture, or specially developed sealing materials such as Volclay. Shallow and small diameter boreholes are often sealed with granular or pelletized bentonite. Some state regulatory agencies have specifications for grout composition and density. To ensure distribution of the grout over the full depth of the boring, grout should be placed using the tremie method. A length of pipe is lowered within a few feet of the base of the borehole, and the grout is pumped downhole under pressure.

5.6.3 Soil Sample Collection

A variety of tools and methods are available for soil or rock sampling, depending on subsurface conditions and the drilling equipment used. Some of the more common devices are described below.

Hand Auger. Hand augers are frequently used to collect soil samples from the shallowest portion of the subsurface, for example, depths less than 10 ft. Hand auger borings can be advanced to somewhat deeper depths (approximately 20 ft), but with depth the method becomes increasingly inefficient. Still, it may be the most practical method at locations where the presence of overhead or below-ground structures may prevent access by a truck-mounted drill rig. It can also be an effective means of collecting soil samples from soil trenches, since unshored excavations deeper than 3-4 ft with slopes steeper than one-to-one should not be entered due to the potential for collapse and possible presence of oxygen-deficient conditions.

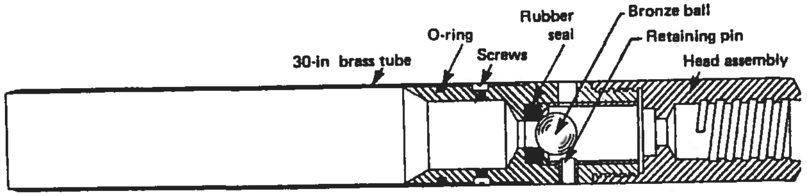


Figure 5.9 Shelby tube soil sampler. Source: Hunt, 1984.

Shelby Tube Sampler. In most conventional environmental drilling applications, subsurface soil samples are collected from cohesive clay soils using a 3-ft long by 3-in. diameter, thin-walled steel tube known as a Shelby tube sampler (Figure 5.9). The sample tube is pushed into and extracted from the soil using the hydraulic system on the drill rig. Once the sample is retrieved to the surface, it is extruded, also using the hydraulic system, and examined. Such soil samples are frequently referred to as "undisturbed" and are suitable for a variety of geotechnical, as well as environmental, analyses.

Following retrieval of the soil sample, the sample interval is drilled out to a diameter slightly larger than the diameter of the sampler prior to collection of the next sample. Drilling out the sample hole prevents the sampler from scraping the borehole en route to successive sample points and collecting soil from intervals already sampled.

Split-Spoon Sampler. In coarser grained, less cohesive soils, such as sands and clay-poor silts, a split-spoon sampler is used. Split-spoon samplers are constructed of two half-cylinders held together by threaded fittings at the top and base to form a 1.5-ft long by 1.5-in. diameter tube (Figure 5.10). The split-spoon sampler is driven into the soil by repeated blows from a rig-mounted hammer, then retrieved to the surface by the rig hydraulic system. The "blow count" or number of hammer blows of a standardized force required to drive the sampler 1 ft into the soil is frequently recorded as a measure of aquifer hardness. A core catcher inserted at the base of the sampler prevents unconsolidated materials from falling out of the sampler as it is removed from the borehole. Upon retrieval, the threaded ends are removed and the two half-cylinders separated to reveal the core for examination.

Due to the repeated impact as the sampler is driven to depth, split spoon samples are referred to as "disturbed" samples. Original sedimentary structures such as cross-bedding are not generally preserved, and any apparent bedding structures are probably artifacts of the sampling process. The upper portion of the sample may contain materials that had accumulated on the borehole floor and should be discarded. As with the Shelby tube sampler, following sample retrieval, the borehole should be drilled out to the next sample interval prior to resuming sample collection.

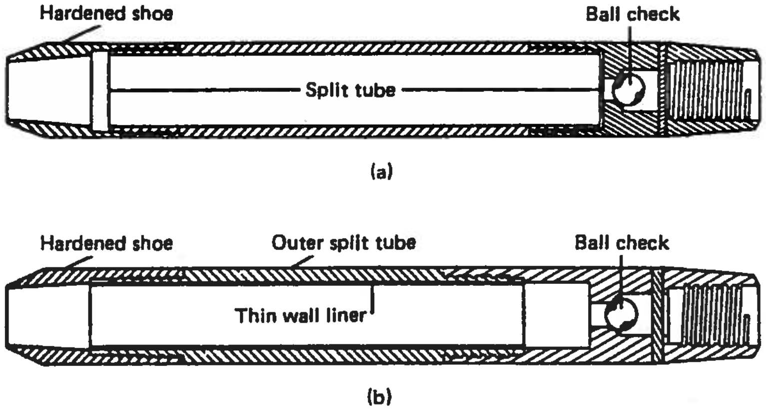
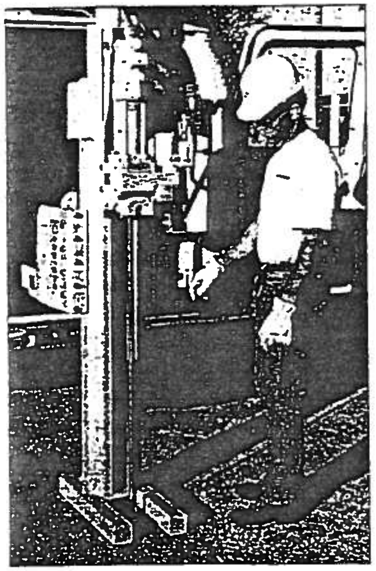


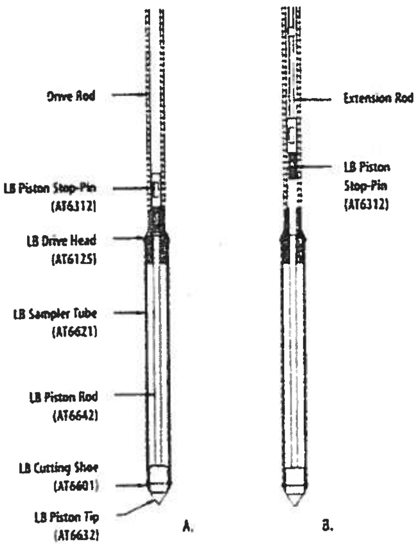
Figure 5.10 (a) Split-spoon soil sampler and (b) Split-spoon soil sampler with liner. Source: Hunt, 1984.

Split-Barrel Sampler. Some hollow-stem augers (see below) are equipped with a core barrel resembling a large split-spoon sampler which is placed inside the hollow-stem and collects a 5-foot continuous core sample during drilling. Under favorable conditions, good quality samples can be collected with a significant time savings over more conventional sampling methods. However, hard clays can pack the front end of the sampler and prevent further movement of soil into the core barrel giving disappointing core recovery. In very loose sand formations, the sample may not be retained. Therefore, these samplers should be used with caution, as significant sample loss may result in the need to re-drill the soil boring.

Direct-Push Samplers. Numerous variations on the basic principal of the pushed or driven sampling tube have been developed for use with direct-push soil probes and cone penetrometer rigs. The most common tools consist of steel tubes or split barrels fitted with acrylic or brass liners, which may be cut open or extruded in the field, or capped and sent directly to a laboratory for analysis. Also in common use are direct-push samplers with a plug at the opening held in place by a piston or other mechanism. These can be driven through an undisturbed soil column to a predetermined depth at which the piston is released and further driving of the sampler results on collection of a sample at the required depth (Figure 5.11).



A discrete soil sample is obtained using the Large Bore Soil Sampler by driving the assembled sampler to depth.



A. Driving the Sealed Sampler.
B. Removing the Piston Stop-Pin in Preparation for Sample Collection.

Figure 5.11 Direct-push sampler.

5.6.4 Rock Core Sample Collection

Samples are collected from formations of consolidated rock using rock coring barrels, which vary in size and design depending on the particular drilling conditions. Hunt (1984) provides a summary of the various designs and their applications.

Generally, the core barrel is fitted at its base with a ring-shaped carbide or diamond-tipped bit, which cuts the core during drilling. The coring device is rotated under pressure while drilling fluid is circulated down the drill string, through the bit, and up the annulus. The bit cuts a circular groove, leaving a column of intact rock standing within the core barrel. When the full length of the core barrel has been drilled, the core is broken from the formation and lodged in the barrel by the core lifter, and the core barrel is retrieved to the surface.

The time required to sample a borehole in a hard rock formation can be reduced by the use of a wire-line core barrel. In this application, a small-diameter core is diverted into a tube, which is brought to the surface by means of a retrieving "spear" lowered on a wire-line within the drill pipe, eliminating the need to trip the drill string out of the hole to retrieve the core barrel. Wire-line coring has also been adapted to rotary drilling in unconsolidated formations.

5.6.5 Core Logging

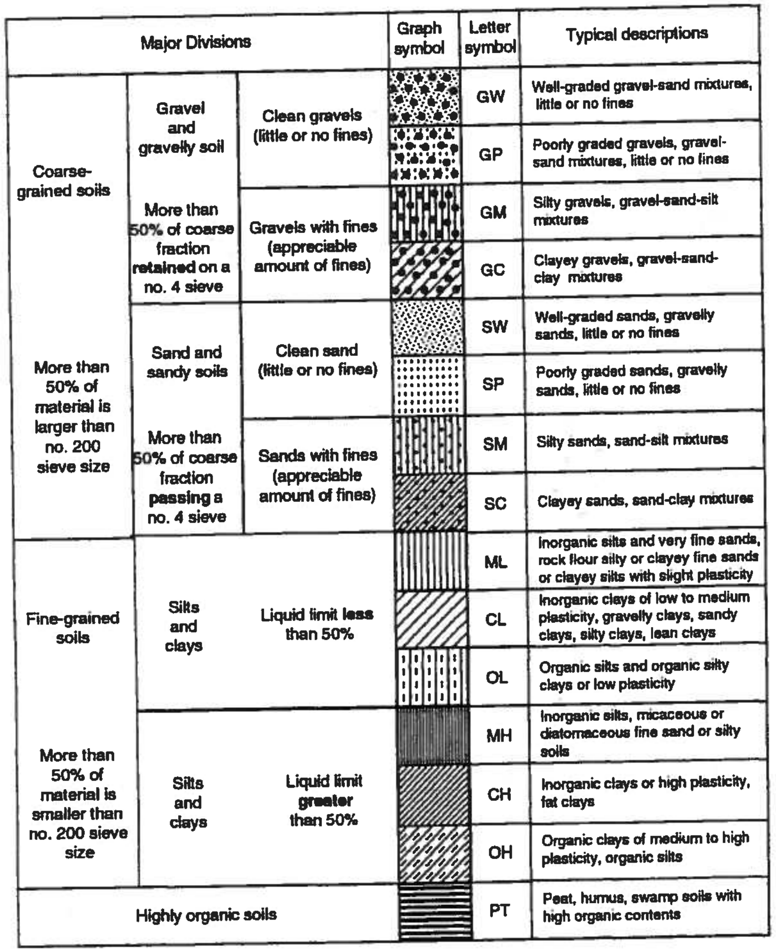
Logging of core samples for the purposes of hydrogeologic site investigations includes a description of both the geologic characteristics and the visual evidence of contamination, if present. Of primary importance from a hydrogeologic standpoint are those characteristics that influence the water-bearing capacity of the soil or rock, including grain size and secondary porosity features. Evidence of contamination may include chemical staining or odor. Core samples collected during drilling may be used for field screening or laboratory analysis. Special handling or preservation of samples is required for many analytical methods.

Soil Core Logging. Numerous soil classification schemes have been developed for various purposes. The system most commonly used in the environmental industry is the Unified Soil Classification System (USCS, Figure 5.12) and Hunt (1984). The USCS places most soils into one of two major divisions: coarse-grained soils including gravelly and sandy soils, and fine-grained soils including silts and clays. This binary scheme is appropriate to hydrogeologic site investigations where a primary objective is the differentiation of permeable water-bearing and low-permeability confining strata. In general, unconsolidated aquifers are composed of gravels, sands, and low plasticity silts, while clays and clay-rich or highly compacted silts form aquitards or aquicludes. Highly organic soils, such as peat and humus, form a third, smaller division.

In logging cores using the USCS, soils are classified on the basis of the major constituent: gravel, sand, silt, or clay. Modifiers referring to secondary constituents are used when that constituent accounts for 10% or more of the sample. Thus, a silty sand or clayey sand (SM or SC in USCS shorthand) contains greater than 50% sand and 10% or more silt or clay, respectively. If the silt or clay content is less than 10 per cent, the sand is either a well-graded or poorly-graded sand (SW or SP), with minor or trace silt or clay. Under the USCS, clay soils are divided into high and low-plasticity varieties based on the liquid and plastic limit values which are determined by laboratory testing (Hunt, 1984).

Although precise quantification of grain size distribution and liquid and plastic limits are determined by laboratory testing, field classification of soils with borderline compositions must be based on judgment. As a rule of thumb, high-plasticity clays can be rolled between the hands to form elongate strings, while low-plasticity clays will crumble when rolled. If a soil sample which appears to be either a silty clay or a clayey silt yields free ground water, it is more likely a clayey silt.

Secondary porosity features in fine-grained soils can transmit fluids at much higher rates than through the soil formation as a whole. Slickenside fractures, horizons of woody or



Major Divisions			Graph symbol	Letter symbol	Typical descriptions
Coarse-grained soils More than 50% of material is larger than no. 200 sieve size	Gravel and gravelly soil	Clean gravels (little or no fines)		GW	Well-graded gravel-sand mixtures, little or no fines
				GP	Poorly graded gravels, gravel-sand mixtures, little or no fines
	More than 50% of coarse fraction retained on a no. 4 sieve	Gravels with fines (appreciable amount of fines)		GM	Silty gravels, gravel-sand-silt mixtures
				GC	Clayey gravels, gravel-sand-clay mixtures
	Sand and sandy soils	Clean sand (little or no fines)		SW	Well-graded sands, gravelly sands, little or no fines
				SP	Poorly graded sands, gravelly sands, little or no fines
	More than 50% of coarse fraction passing a no. 4 sieve	Sands with fines (appreciable amount of fines)		SM	Silty sands, sand-silt mixtures
				SC	Clayey sands, sand-clay mixtures
Fine-grained soils More than 50% of material is smaller than no. 200 sieve size	Silts and clays	Liquid limit less than 50%		ML	Inorganic silts and very fine sands, rock flour silty or clayey fine sands or clayey silts with slight plasticity
				CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
				OL	Organic silts and organic silty clays or low plasticity
	Silts and clays	Liquid limit greater than 50%		MH	Inorganic silts, micaceous or diatomaceous fine sand or silty soils
				CH	Inorganic clays or high plasticity, fat clays
				OH	Organic clays of medium to high plasticity, organic silts
Highly organic soils				PT	Peat, humus, swamp soils with high organic contents

Figure 5.12 Unified soil classification system.

organic material, root zones, burrows, calcareous or other mineralized zones, and desiccation features frequently provide avenues of contaminant migration through low-permeability soils into underlying aquifers.

Other descriptive features such as color should be noted to the extent that they can be used to distinguish strata of similar composition from one another and may sometimes provide consistent stratigraphic markers, such as a gray clay overlying a red clay.

Rock Classification and Description. Rocks are broadly classified in terms of their origin as igneous (those having formed from a molten fluid, or magma), metamorphic (those having formed by recrystallization of a pre-existing rock subjected to heat and/or pressure), and sedimentary (those having formed from deposition and consolidation of soil or rock particles or as chemical precipitates from mineral saturated water. Core samples should be logged in terms of their mineralogic composition, as well as their water-bearing (Hunt, 1984).

Sedimentary rocks that have formed by accumulation and consolidation of soil or rock fragments, ranging in size from fine powders to house-sized boulders, are referred to as clastic or detrital rocks. The most commonly encountered water-bearing varieties include sandstones and conglomerates (rocks composed of grains of variable sizes, e.g., gravel and sand). The porosity in these rocks may be primary (intergranular porosity, as encountered in well sorted, poorly cemented sandstones) or secondary (fracture porosity, as may be encountered in well-cemented, jointed rocks), or both. Rocks which formed by chemical precipitation from a mineral-saturated water body include carbonate rocks (limestones and dolomites) and the less common evaporites (halites, gypsum, and anhydrites). Porosity in these rocks is usually secondary, occurring as fractures or solution cavities. The water-bearing capacity of sedimentary rocks can also be influenced by the degree of weathering.

In igneous and metamorphic rocks, significant water flow is generally limited to within fractures. A notable exception to this rule is vesicular basalt, which may have significant primary porosity due to entrapment of gas bubbles in the molten lava as it cooled and hardened.

5.6.6 Cone Penetrometer Testing

Subsurface formations can also be logged or inferred from a variety of what may be referred to as indirect methods; methods in which soil or rock is characterized by instrumental measurement of geophysical properties, rather than direct examination of pieces of the formation. Such methods can dramatically speed up the investigation, limit the potential for exposure to hazardous constituents, and minimize the need to manage investigation-derived wastes, all of which help control investigation costs. However, by their nature, such data must be interpreted, and interpretations are not necessarily unique, since more than one subsurface condition may produce an identical instrument response. Therefore, indirect methods should be used in conjunction with direct observation methods and instrument response calibrated to subsurface conditions whenever possible.

Originally developed for geotechnical investigation, the cone penetrometer test (or CPT) can be useful for defining stratigraphy to depths of up to 100 ft (rarely more) in fine-grained soils and unconsolidated sands. In cone penetrometer testing, electronic strain gauges mounted in a steel cone-shaped probe are pushed at a constant rate into the subsurface by a

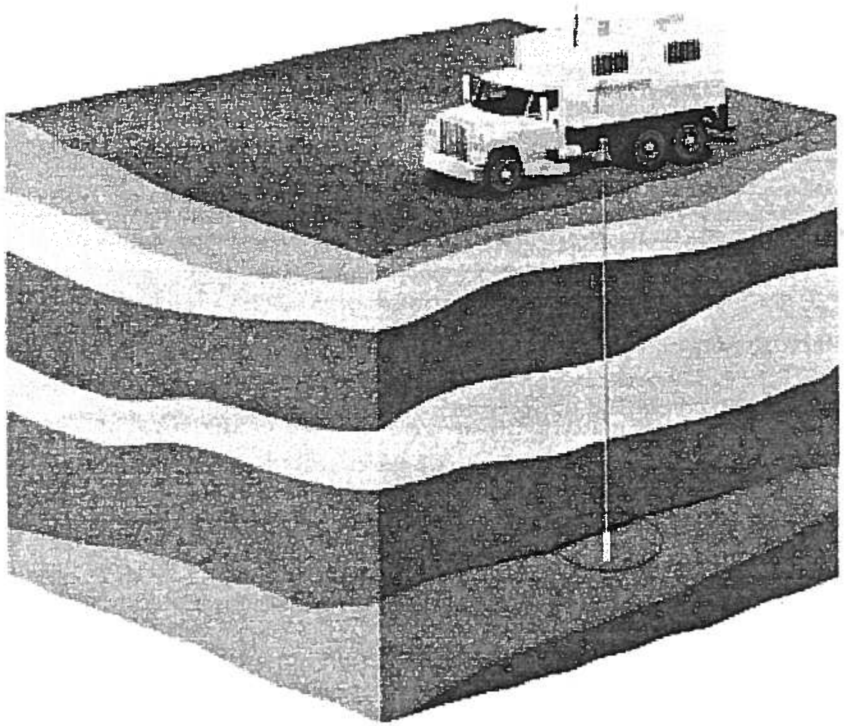


Figure 5.13 Schematic of cone penetrometer testing.

truck-mounted hydraulic system (Figure 5.13). The gauges measure the resistance encountered at the tip of the cone tool, and the friction encountered along its side as the tool is advanced, producing a continuous, real-time log of these soil properties with depth (Figure 5.14). Empirical relationships for soils in various regions of the country have been developed to allow interpretation of soil type based on the resulting set of curves. High tip resistance and low friction indicate coarser grained soils; lower tip resistance and higher friction indicate finer grained soils. It is advisable to locate at least one CPT immediately adjacent to a continuously sampled soil boring, preferably one encountering a variety of soil types to allow correlation of the CPT response to local soil conditions.

In addition to the standard lithologic data, instrumentation has been developed to measure other physical properties for expanded interpretation of subsurface conditions. Electrical conductivity measurements can be used to identify the presence of ground water and hydrocarbon fluids; pore pressure measurements can be used to assess formation permeability; and laser-induced fluorescence can be used to identify the presence of specific free-phase hydrocarbon fluids in the subsurface.

Upon completion of cone testing, a small diameter monitoring well can be installed within the CPT hole. Limited soil sampling can also be performed with the cone penetrometer rig, though sample quality can be poor, and continuous sampling is not practical or cost-effective. Technologies under current development include high-resolution video cameras which can provide a "worm's eye view" of the subsurface geologic materials and free-phase contaminants.

A major advantage of the cone penetrometer is the speed and cost of data collection. At a rate of 2 cm/sec, a continuous log to a depth of 50 ft can be obtained in less than 15 min., while a continuously sampled soil boring to the same depth can take several hours. Footage rates for cone testing can be as little as half those of auger drilling. Investigation costs are further reduced by the absence of IDWs produced by this method. As an added benefit, delineation of nonaqueous phase liquids can in some instances be achieved by examining the grout returns during sealing of the CPT hole.

A second major advantage is that the lithologic data obtained, though subject to interpretation, are numerical measurements of soil properties, which can lend a degree of objectivity and consistency frequently missing on sites where soil cores have been described by numerous individual investigators. In addition, the data are continuous and can reveal subtle changes in soil properties on a much finer scale than can data changes in practice be recorded based on soil core description.

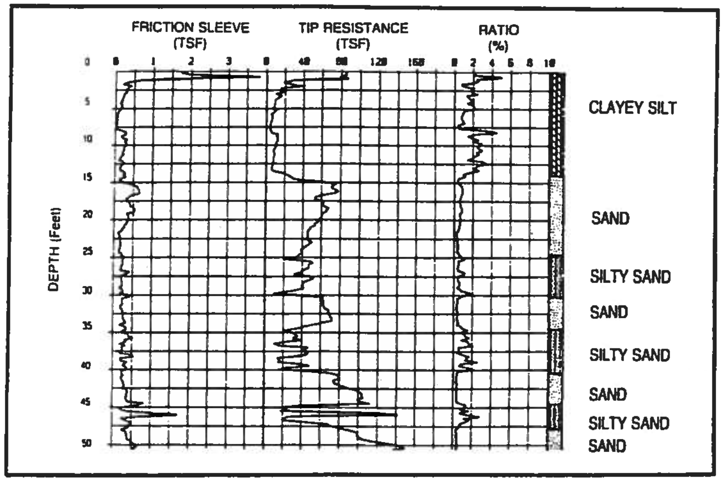


Figure 5.14 Log of cone penetrometer test. Source: Fugro Geosciences, Inc.

Apart from the inherent disadvantage of any indirect measurement (i.e., that the data are subject to interpretation), the major disadvantage of the cone rig is its size and weight, which can limit its mobility, particularly on unpaved sites.

5.6.7 Borehole and Surface Geophysical Methods

Subsurface geological conditions can also be evaluated indirectly using a variety of geophysical methods. Geologic strata or other buried features are differentiated by measuring the contrasting responses of differing geologic materials to physical forces such as electricity, magnetism, or seismic energy, or by measuring physical properties inherent in earth materials such as naturally occurring radioactivity. Geophysical methods are broadly divided into surface methods and borehole methods. Zohody et al. (1984) and Keys and MacCary (1971) provide guidelines for the applicability, acquisition, and interpretation of surface and borehole geophysical data, respectively.

In surface geophysical surveys, measurements are collected at regularly spaced intervals along a traverse or on a grid to produce a subsurface profile. Examples include conductivity surveys, most commonly used to identify salinity contrasts within an aquifer; magnetometer surveys, frequently used to identify buried drums, tanks, or ordnance, and ground penetrating radar (GPR), useful for identifying large scale buried geological or man-made features. The chief advantage of such methods is that broad regions of the subsurface can be surveyed rapidly in a noninvasive manner.

Borehole techniques utilize a variety of probes or sondes that measure physical properties of the soil or rock or contrasts between the drilling fluid and the fluids in the formation. Methods such as spontaneous potential and natural gamma ray logging are often used in lieu of core sampling to reduce costs, particularly when drilling conditions are difficult and required drilling depths are deep.

Application of surface and borehole geophysical methods to the environmental industry has been limited by the fact that a unique and definitive interpretation of the data is not generally possible. Because identical responses can be caused by a variety of conditions, the use of two or more types of measurements with interpretation by a highly knowledgeable specialist is frequently required to eliminate ambiguity. The need to run numerous tests, especially those employing the more sophisticated techniques, limits the ability of geophysical methods to compete cost-wise with drilling and sampling at shallow depths.

.7 HYDROLOGIC DATA ACQUISITION

Assessment of the direction and rate of ground water flow beneath a site requires the following hydrologic data: lateral hydraulic gradient, hydraulic conductivity, and effective porosity. Of these, hydraulic gradient and conductivity are obtained by field measurements made in monitoring wells. Effective porosity (i.e., connected pore spaces through which ground water flows) is generally an estimated value (see Chapter 2). Because such determinations are most commonly made from measurements in piezometers and monitoring wells, we begin with a description of monitoring well construction.

5.7.1 Monitoring Well Construction

The monitoring well is the primary source of hydrologic and ground water quality data used in hydrogeologic site assessments. Most of the special requirements for monitoring well construction are due to their use in the collection of ground water quality data. For collection of hydrologic data, a piece of slotted pipe inserted into a borehole would be sufficient in most instances, but because of the dual purpose monitoring wells serve, careful attention must be paid to the materials used and the methods of construction. Many state environmental regulatory agencies have very particular construction specifications and require that well installation be performed by licensed drillers.

Hydrogeologic site investigations frequently require installation of a permanent monitoring well network to permit resampling and evaluation of changing site conditions. However, monitoring well installation is fairly expensive. To reduce the cost of a ground water plume delineation program, the use of temporary ground water sampling points is becoming increasingly common. A variety of configurations may be installed using a drill rig, direct-push soil probe rig, or cone penetrometer rig to provide samples for lateral and vertical plume delineation in a fraction of the time required to install a well. Following delineation, a relatively small number of permanent wells can be installed at strategic locations and depths to confirm plume boundaries and facilitate future monitoring.

The essential elements of a monitoring well are the well screen and riser, the filter pack, and the annular seal (Figure 5.15). The well screen, typically a section of slotted pipe, allows water to flow from the formation into the well while screening out coarse soil particles. The riser is a solid-walled or "blank" pipe that connects the well screen with the surface. The filter pack, also referred to as the sand or gravel pack, limits the influx of fine surface. The filter pack, also referred to as the sand or gravel pack, limits the influx of fine sediment from the formation. Above the gravel pack, a seal composed of low permeability material prevents fluids from above the screened interval (including percolating rainwater) from entering the well.

Well Design. Monitoring wells should be designed on the basis of the purpose of the well, the hydrogeologic setting, and the expected contaminants in the ground water, as well as cost. Monitoring objectives will determine such factors as the length and placement of the screen interval. Construction materials that are selected should minimize the potential for reaction with the formation fluids and the expected contaminants while providing adequate strength to withstand the pressures exerted by the formation.

For measuring the potentiometric surface, wells screens are positioned to intersect the top of the aquifer in confined flow systems, or to straddle the expected zone of water table fluctuation in unconfined aquifers. Placement of the screen across the top of the water-bearing zone permits detection of floating accumulations of light nonaqueous phase liquids (LNAPLs), while for investigation of dense nonaqueous phase liquids (DNAPLs), intersec-

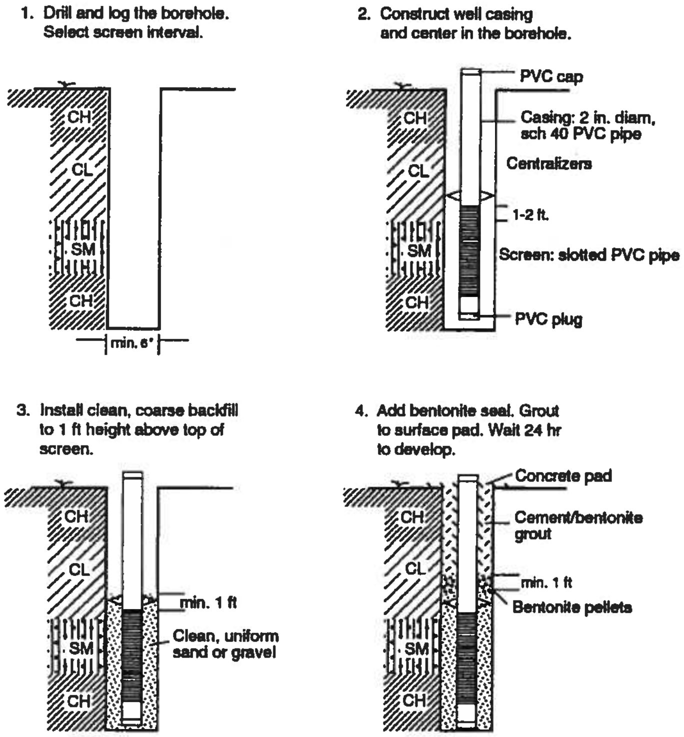


Figure 5.15 Typical monitoring well installation.

tion of the screen with the base of the aquifer is more appropriate. Long screen sections yield water samples representing an average of conditions across their length; shorter screens (10 ft or less) yield more depth-specific data and are generally preferred, since low levels of contamination present over a limited depth interval may be overlooked due to dilution of the sample by uncontaminated water from elsewhere in the screen interval. In general screens in excess of 15 ft are avoided. Well diameters of 2 in. and 4 in., installed in 6 in. and 10 in. diameter boreholes, are most common.

To establish the vertical extent of ground water contamination, it may be necessary to drill monitoring wells through a contaminated upper zone into an uncontaminated lower zone. In such cases, it is necessary to first install isolation casing, consisting of a length of blank pipe sealed in place with cement or grout to prevent entrainment of contaminants from the upper zone to the lower zone during drilling. Once the casing is installed, drilling and well installation are resumed within the casing.

Materials of Construction. Well screens and risers are most commonly constructed of PVC. Threaded joints are generally specified, since the use of glues that contain organic solvents is discouraged. However, PVC reacts with some contaminants and is not always suitable. For example, high concentrations of chlorinated solvents can attack PVC, compromising ground water samples or damaging the well. In addition, the strength of PVC may not be adequate for very deep installations. Stainless steel is frequently used under such conditions, at significantly greater expense. Materials such as Teflon minimize reaction with contaminants, but their use is usually cost-prohibitive. Information on compatibility of various well materials with common contaminants can be found in Driscoll (1986).

Filter packs should be composed of graded silica sand. Blasting sand and other general-use sands may contain minerals that adsorb dissolved metals, potentially compromising the integrity of the ground water sample. The grain size interval of the filter pack material should be selected based on analysis of aquifer grain size distribution as described by Driscoll (1986).

Annular seals are most often composed of bentonite, frequently in combination with other materials. A 1 ft. to 2 ft. thick layer of bentonite pellets is usually placed atop the filter pack to protect the filter pack from invasion by the grout, which completes the seal to the ground surface. Grout may be composed of neat Portland cement, a mixture of cement and powdered bentonite, or other specialty materials such as Volclay.

Installation Procedures. In monitoring well installation, both the drilling and sampling equipment and the well construction materials must be free of contamination to prevent contamination of collection of ground water samples. Drilling equipment should be cleaned with pressurized hot water or steam and detergent, as needed, prior to drilling at each location. Well screen and riser should be packaged and handled to prevent fouling prior to well installation. Drilling and sampling personnel should handle the well pipe with clean gloves.

When wells are drilled using hollow-stem augers, the well screen and riser are lowered within the augers. For rotary drilled wells, the well is lowered within the open borehole. Drilling mud should be thinned by dilution with potable water to the extent practical prior to well installation to facilitate well development. A bottom cap or plug at the base of the well pipe prevents the flow of sediment into the bottom of the well. Silt traps or sumps, consisting of a short section of riser are frequently installed beneath the well screen to prevent fine sediment entering the well from accumulating in and clogging the screened interval. In deeper wells, "centralizers" may be placed above the screen section to maintain distance from borehole wall and ensure proper filter pack placement. Proper placement of the screen should be verified by careful measurement.

Once the screen and riser are in position, the filter pack is installed within the annulus around the well screen (Figure 5.15). The filter pack is generally placed from the base of the well to 1 ft to 2 ft above the top of the screen. In wells drilled by hollow-stem, the filter pack material is usually poured down the inside of the augers. The auger sections are pulled from the hole one at a time as the annulus is filled with sand. In deeper wells and wells drilled by wet rotary methods, it is frequently placed using the tremie method. Potable water is used to wash the filter material down a pipe lowered to the base of the well.

Following placement of the filter pack, the well is sealed to the ground surface to prevent migration of fluids from the surface or water-bearing zones above the screened interval down the borehole. Grout is frequently placed using the tremie method to ensure even placement up the borehole.

Monitoring wells are completed at the surface with a locking caps and/or casing to prevent tampering and a concrete surface pad to protect the annular seal. The elevations of the ground surface and top of well casings should be surveyed relative to a common datum such as mean sea level or an arbitrary datum established by a site benchmark. Top of casing elevations are required to convert depth to water measurements to static water level elevations and should be surveyed to the nearest 0.01 ft, and the point of measurement marked on the top of the well casing.

Well Development Procedures. Following installation, wells are developed to remove fine sediment and drilling mud from the filter pack and ensure collection of ground water samples that are representative of formation conditions, and prevent clogging of the well screen and pump damage. If the well has been installed in a low permeability aquifer using a dry drilling method, bailing out three to ten casing volumes may be sufficient to permit collection of representative ground water samples. If fluids have been introduced during drilling, larger volumes of water must be removed.

Development usually consists of a combination of pumping and surging. Surging the well, by running a close fitting cylinder up and down the inside of the well over the screened interval, causes a back-flushing action in the gravel pack, loosening fine sediment. Pumping from the well (preferably at a rate higher than the expected normal pumping rate) pulls fine sediment through the well screen into the well where it can be pumped to the surface.

5.7.2 Determination of Ground Water Flow Gradients

Ground water flow gradients are determined by measurement of water level elevations in site wells. In addition to the lateral gradient, determined by measurement of wells within the same water-bearing zone, the vertical gradient may be determined by measurement of closely spaced "nested pairs" of wells screened in different aquifers or within the upper and lower portions of the same aquifer. The presence of surface water features should be noted and surface water elevations determined to evaluate possible recharge/discharge relationships. The presence and discharge rate of any pumping wells on site should also be noted.

The water level in each well is measured to the nearest 0.01 ft using an appropriate instrument such as a water-sensitive probe on a graduated tape. The elevation of the potentiometric surface is obtained by subtracting the depth to water from the top of casing elevation. Ideally, water level surveys represent the potentiometric surface at one instant in time. Therefore, measurements should be made in as short a time frame as possible, since water levels within wells respond to such factors as barometric pressure or tidal influence. On sites with large numbers of wells, requiring several hours to survey, the first well measured should be remeasured at the end of the survey to detect possible changes in the potentiometric surface during the period of the survey. If more than one instrument is to be used in the survey, a common well should be measured simultaneously using each instrument to confirm that all instruments give the same reading.

On sites with LNAPLs, the water level survey should also include inspection of wells for the presence floating free-phase layers. If an LNAPL accumulation atop the water column is found, the water level must be corrected for its presence. The thickness of the LNAPL layer, measured with minimal disturbance using an electric interface probe, is multiplied by the specific gravity of the LNAPL (e.g., 0.75 for a typical gasoline). This value is added to the *measured* water level elevation to obtain the *corrected* water level elevation. (Note that the thickness of an LNAPL layer in a well is influenced by a number of factors and typically does not reflect an equivalent accumulation in the adjacent formation).

Upon completion of the survey, water level elevations are plotted on a scaled site map and potentiometric surface contours are drawn, and lateral and vertical flow gradients are determined as described in Section 5.8.

5.7.3 Determination of Hydraulic Conductivity

Slug Tests. Single-well slug tests are a common, cost-effective method for the estimation of hydraulic conductivity in hydrogeologic site assessments. Two major varieties, rising-head tests and falling-head tests can be used. Falling-head tests are more difficult to perform and analyze, and require addition of water to the well. Therefore, rising-head slug tests are more commonly performed.

During a rising-head test, the static water level in the well is first measured and then a "slug," typically a solid cylinder, of known volume is lowered within the well to just below the static level. Following re-equilibration of the water level in the well with that in the aquifer, the slug is removed from the well instantaneously, causing a sudden drop in the water level or head. The return of the water level to static conditions is then monitored. The rising head can be measured by hand in low permeability systems. Higher yield systems may recover too quickly to permit manual collection of the most critical early data, and require the use of pressure transducers placed in the well and monitored with an electronic data logger.

The resultant change in head over time is plotted on semi-log paper, and the curve analyzed according to one of several methods, depending on aquifer and well conditions. The method of analysis will depend on such factors as whether the aquifer is confined or unconfined, and what percentage of the saturated interval is screened in the well. Analytical methods for slug tests are described in Chapter 3.

Slug tests evaluate only the portion of the aquifer immediately surrounding the tested well. Therefore, tests should be performed at a selection of site wells, to best represent the variability in hydraulic conductivity for the aquifer.

Constant-Rate Pump Tests and Well Performance Tests. While slug tests provide reasonable estimates of hydraulic conductivity, they evaluate only the portion of the aquifer immediately adjacent to the well and are generally not adequate for the detailed design of a ground water pumping system. Constant-rate aquifer pumping tests are used to characterize conditions over a larger portion of the aquifer by measuring the response of the aquifer to pumping at observation wells located some distance from the pumping well, typically over a period of 24 hrs. or more. Analysis of constant rate tests is performed by plotting water level drawdown in individual observation wells versus elapsed pumping time, or drawdown in two or more observation wells versus distance from the pumping well at a specific time. The resulting curves are used to calculate aquifer transmissivity and storativity, well efficiency, and radius of influence, all of which are necessary for design of an efficient ground water pumping system. The more common methods of analysis are summarized in Chapter 3. Because constant rate tests are expensive to conduct, they are usually deferred until the detailed design phase of a ground water remediation program.

Stepped-rate well performance tests provide a measure of the specific capacity (discharge rate, Q, divided by drawdown, s) of a pumping well, from which transmissivity, T, [gpd/ft] can be estimated from the empirical relationship $Q/s = T/2000$ for a confined aquifer, or $Q/s = T/1500$ for unconfined units. Small scale well performance tests can be conducted during well development at relatively little extra cost. A stepped-rate pumping test, also referred to as a step-drawdown test, is generally conducted before a constant-rate aquifer pump test to determine the optimal pumping rate for the latter test. During a stepped rate test, the well is pumped at a constant rate until the water level in the well stabilizes. The specific capacity of the well is calculated, and the pumping rate can then be increased (stepped up) and the water level observed until it stabilizes again.

.8 ACQUISITION OF SOIL AND GROUND WATER QUALITY DATA

Chemical analysis of soil and ground water samples is required to identify the contaminants, quantify their respective concentrations, and delineate their lateral and vertical extent. This section describes procedures for collection and handling of soil and ground water samples. The following discussion is intended only as a general guide. The project workplan should specify sampling and analysis protocol based on project goals and applicable regulations or guidelines.

5.8.1 General Sampling Procedures

To assure collection of data that accurately represent site conditions, proper protocol must be followed during sample collection and handling. In addition to providing design basis information for site clean-up, the data must also be of a quality acceptable to regulatory agencies. Data may also be admitted as evidence in legal proceedings and must withstand the scrutiny of opposing legal counsel.

Measures must be taken to ensure sample integrity, for example, to prevent the loss of contaminant mass from the sample as by volatilization or biodegradation. Equipment and tools that contact the samples should be composed of stainless steel, Teflon, or other materials, which will not react with the contaminants in the sample. Samples should be sealed in appropriate sample containers with preservatives specified by the analytical method (often an acid to inhibit microbial activity). Samples are retained on ice pending delivery to the laboratory and there refrigerated until tested to prevent loss of volatile constituents.

Equally important is preventing the introduction of contaminants into the sample from some other source (cross-contamination). The use of disposable or "dedicated" equipment minimizes the potential for cross-contamination. Alternatively, sampling equipment should be thoroughly cleansed between sample locations. Where possible, locations should be sampled in order of increasing contamination to minimize the possibility of cross-contamination between locations.

Most analyses have a specified maximum holding time between sample collection and analysis. Samples should be transported to the laboratory as expeditiously as possible, generally within 24 hrs. of collection. The shipment of samples must be accompanied by a chain-of-custody form, which includes the signatures and affiliations of the personnel collecting, relinquishing and receiving the samples, as well as the date and time of the transfer. Essential sample collection data (sample identification number, date, and time of collection) and the specifications of the laboratory program must also be included.

Soil Sample Collection and Handling Procedures. Soil samples should always be collected using clean sample tools composed of inert materials, such as stainless steel, Teflon, or nonreactive plastics. Tools should be thoroughly cleansed using hot water, steam, and/or detergents and rinsed, preferably with deionized water prior to use and between sampling locations.

Soil samples should be collected in clean glass jars (unless otherwise specified by laboratory procedure) with tight-fitting lids, and identified with an appropriate label bearing the unique identification number of the sample. The outer surface of soil cores should be trimmed using a clean knife prior to shipment to the laboratory to ensure that soils that have been in contact with formation fluids above the sample point or with the inside wall of the sampler are not tested.

Ground Water Sample Collection and Handling. Ground water sampling is usually preceded by measurement of water level in the well. The well should also be inspected for the presence of NAPLs using a hydrocarbon interface probe or transparent bailer, if there is reasonable potential for them to be present, and any accumulation or sheen is noted. Because ground water samples containing "free product" may not accurately represent dissolved phase concentrations, samples from wells containing NAPLs are frequently not analyzed.

To ensure collection of ground water samples that are representative of formation conditions to the maximum extent practical, monitoring wells are usually "purged" of water that has been standing in the well by pumping or bailing. Removal of three to five saturated casing volumes is a generally accepted minimum purge. Alternatively, wells are purged until measurements of water quality parameters such as temperature, specific conductance, and pH have stabilized. Samples are then collected in appropriate containers and preserved as specified by the analytical method.

As an alternative method, so-called low-flow purging and sampling has been gaining wider acceptance in recent years. The pump intake is set within the screen interval and water is pumped at a rate as low as 0.1 L/min. so that minimal drawdown occurs. Water quality parameters are measured continuously, and upon stabilization, the samples are collected. In addition to those mentioned above, dissolved oxygen and redox potential are frequently measured. No drawdown in the well indicates that the pump discharge is due primarily to flow into the well rather than exchange of water in casing storage.

Proponents of low-flow sampling claim less agitation and mixing of the water column results in collection of samples that are more representative of formation conditions. In addition, the volume of purge water requiring management as a waste is minimized. On the other hand, low-flow sampling can be more time consuming and require more highly trained sampling personnel than are required for conventional methods. In addition, dedicated low-flow pumps permanently installed in the wells are generally preferred, resulting in potentially significant capital costs. Use of peristaltic pumps can minimize the expense by requiring only dedicated tubing. However, use of peristaltic pumps is not universally accepted for collection of samples to be tested for volatile organic compounds and is limited to aquifers with water levels within the reach of suction lift.

Ground Water Field Measurements. Ground water sampling programs usually include field measurements of such general water quality parameters as temperature, specific conductivity, and pH, often to confirm adequate well purging. Redox potential (E_H) and dissolved oxygen content are also frequently measured at the time of sample collection to assess the potential for biodegradation and for design of treatment systems. Sample turbidity is frequently measured to assess the presence of suspended sediments on the results of metals analyses.

Sampling Quality Control Measures. Blank samples prepared from deionized water are frequently submitted for analysis as a quality control check on field and laboratory procedures. "Field blank" or "equipment blank" samples prepared in the field provide a quality control check on field sampling and equipment decontamination procedures. A sample of deionized water is decanted from the bailer or run through the sampling pump following the normal decontamination procedure, and submitted for laboratory analysis.

Workplans also often specify analysis of "trip blank" samples, usually for volatile organic compounds. This is a blank sample prepared in the laboratory and packed in the sample coolers, and which accompanies the other samples through the collection, transport, and analytical process.

Ground water samples collected for analysis of volatile organic constituents must be collected free of head space (air bubbles) to prevent volatile constituents from coming out of solution. Note, too, that excessive fine sediment content can interfere with some analyses, resulting in unacceptably high detection limits. Acids used in the preservation of samples collected for heavy metals analyses can leach naturally occurring metals from sediments in the sample, yielding false ground water sample results. Sample turbidity is frequently measured and filtered samples are sometimes collected to assess potential effects from suspended sediment.

5.8.2 Field Testing Methods

To aid in the preliminary assessment of the limits of the contaminated zone and to facilitate selection of samples for laboratory analysis, a variety of field testing methods are available for soil and ground water. Some service companies provide mobile laboratories that follow EPA-approved laboratory QA/QC procedures, and can provide results on-site within a few hours of collection. Also available are less expensive alternative methods, typically with relatively high detection limits (i.e., ppm vs. ppb) or merely semi-quantitative results, indicating the presence of the constituent. These can be used to establish the general limits of the contaminated zone, though confirmation of contaminant concentrations by an approved laboratory method is generally required.

Soil Gas Surveys. Soil gas surveys are a means of evaluating the presence of volatile organic constituents present in near-surface soils and ground water without actually collecting soil or ground water samples. A probe mounted on hollow pipe is pushed into the soil to the desired depth. Vapors are extracted from the probe by means of a vacuum pump and analyzed by a detection instrument, such as an organic vapor analyzer or portable gas chromatograph (GC) at the surface.

Because the results of vapor analyses are affected by a wide range of variables, and are frequently not acceptable to regulatory agencies as definitive of site conditions, soil gas surveys are most commonly used as a quantitative tool for assessing site conditions prior to a drilling and sampling program.

Soil Sample Headspace Vapor Analyses. An organic vapor analyzer or portable GC can also be used to measure the organic vapors in soil sample jar head space. Samples collected for this purpose must be sealed tightly in a partially filled jar and either agitated or allowed to sit for a period to permit constituents to volatilize. If laboratory analysis of volatile organics is also to be performed, the sample should be split and a portion properly stored for shipment to the laboratory.

The results of such head space analyses depend on variables such as soil type, the volatility of the constituents present, the temperature of the sample, residence time in the sample container, and the volume of soil versus head space in the container. Accordingly, they should be viewed as qualitative, providing a relative measure of the constituents present in the samples.

Colorimetric and Immunoassay Tests. Contaminant-specific test methods are also available for metals and organic compounds in soil and ground water. For soil samples, these methods typically require an extraction procedure followed by analysis of a liquid extract sample; ground water samples usually are tested directly. Most available field tests rely on either a chemical reaction or an immunoassay test to produce a coloration of the sample to detect the presence of particular contaminant or contaminant group. Immunoassay methods employ antibodies developed to exhibit a high sensitivity to a specific contaminant. The hue and intensity of the color developed in the sample is then usually compared to a chart that has been prepared using samples of known concentration to provide a semi-quantitative result.

Used in conjunction with a temporary ground water sampling installation, these methods can result in significant savings to the project budget by rapidly providing screening level data preventing the installation of an unnecessary number of monitoring wells. However, the cost of the test kit and time required to perform the extraction and analytical procedures, and the limited quality of the data must be weighed against the cost of a more definitive laboratory analysis to ascertain whether such tests are worth conducting. Field screening tests generally do not have detection limits sufficiently low to provide definitive ground water plume delineation. The quality control and repeatability of the data are also inadequate for regulatory purposes in most instances. Therefore, results are generally confirmed by laboratory analysis of duplicate samples.

5.9 DATA EVALUATION PROCEDURES

Upon completion of the field and laboratory programs, site data must be integrated to construct a working model of contaminant plume migration within the ground water flow regime. As discussed earlier in this chapter, the key components of this hydrogeologic site characterization are the geologic, hydrologic, and chemical data defining the occurrence and movement of fluids in the subsurface and the entrainment of contaminants in this natural flow system. Procedures for data organization and presentation are outlined below.

5.9.1 Geologic Data Evaluation

Available geologic data must be compiled to define the lateral and vertical configuration of permeable and impermeable strata comprising the framework within which subsurface fluids collect and flow. Conventional data presentation techniques include the following.

Scaled geologic logs should be prepared for each soil boring, monitoring well, or geophysical profile completed on the site. As shown in Figure 5.16, in addition to a description of the type and thickness of each stratum encountered, the log should indicate the drilling location, ground surface elevation, drilling method, depth of ground water occurrence, driller identification and date of completion (Hunt, 1984). For monitoring wells, as-built diagrams should be prepared showing well construction and static water elevation with respect to stratigraphy.

Cross-section diagrams should illustrate the bedding and lateral continuity of the principal stratigraphic units underlying the site. General guidelines for cross-section preparation are provided in Hunt, 1984 and Tearpock and Bischke, 1991. Given the extreme variability of shallow strata, care should be taken to avoid extrapolation of stratigraphic interpretations beyond the area of available geologic logs. An example is provided on Figure 5.17.

Structure maps and isopach drawings can be employed to characterize the physical constraints on ground water or contaminant flow through a water-bearing unit. Within a confined aquifer unit, a structure map (i.e., a topographic map of the upper surface of the water-bearing unit) can be used to identify topographic highs or "traps" wherein floating

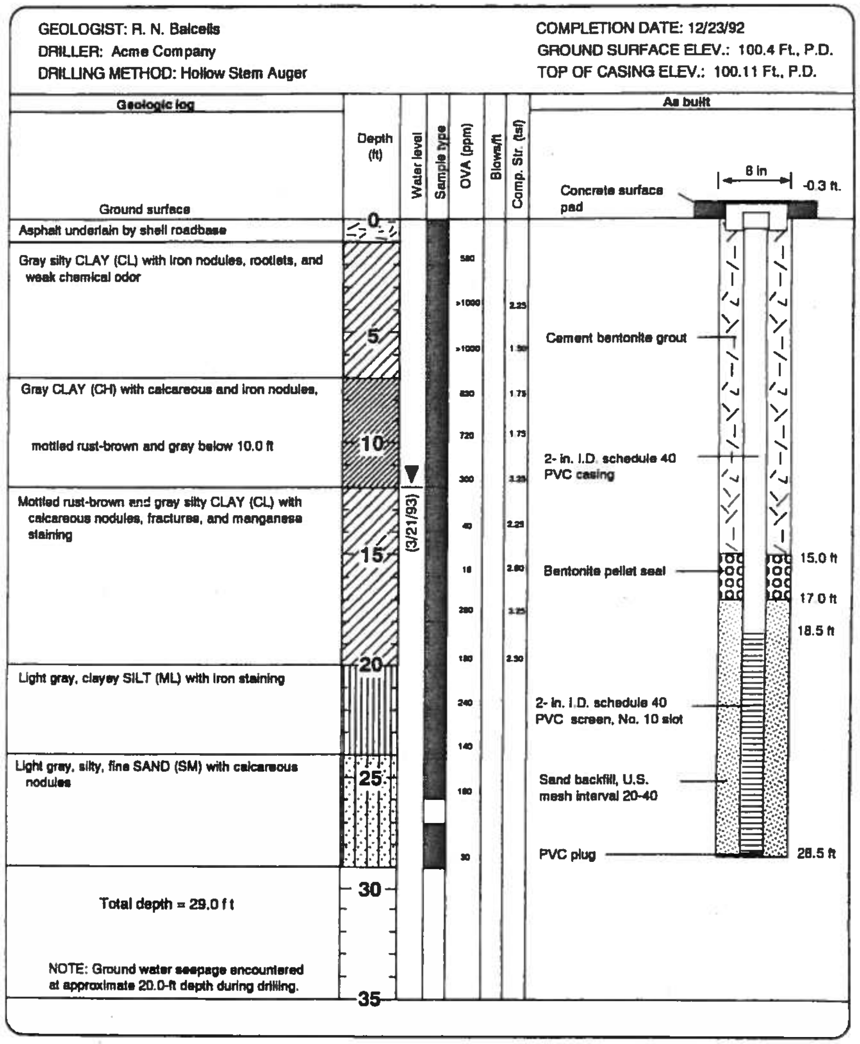


Figure 5.16 Typical drilling log and as-built diagram for monitoring well.

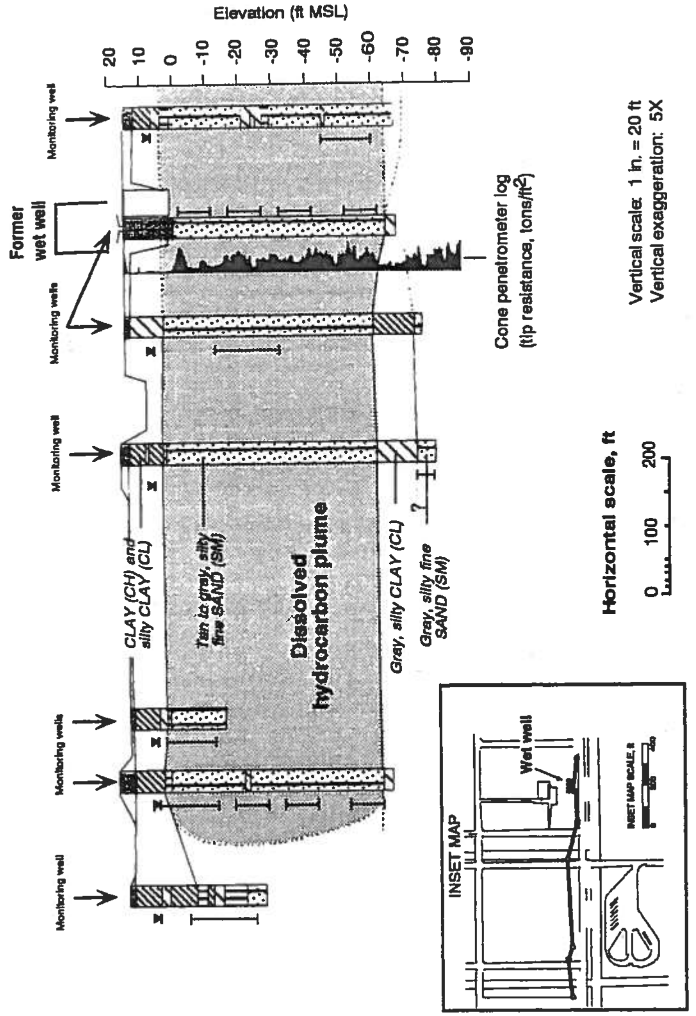


Figure 5.17 Geologic cross-section, west-east orientation, Case Study 1.

hydrocarbons might collect. Isopach drawings (i.e., contour maps of the thickness of the water-bearing stratum encountered at each drilling location) clearly illustrate lateral discontinuities or "pinch-outs" of the aquifer unit, as well as preferential flow paths.

5.9.2 Hydrologic Data Evaluation

Hydrologic data collected during the site investigation should be evaluated to define the direction and rate of natural ground water flow through the principal water-bearing strata underlying the study area. Data evaluation requirements include the following analyses.

Geologic logs and cross-sections should be reviewed to identify the uppermost water-bearing stratum underlying the site. Typically, this will be the first water-saturated stratum encountered beneath the site with sufficient hydraulic conductivity to yield water to wells (e.g., $K > 10^{-4}$ cm/sec). Static water levels should be superimposed on geologic log and cross-section diagrams to classify the aquifer unit as either confined (static water level above top of water-bearing unit), unconfined (static water level below top of water-bearing unit), or partially confined (confined at some locations and unconfined at other locations).

Within permeable strata, ground water movement is primarily horizontal, with a slight dip in the direction of flow. To define lateral ground water flow patterns, static water level elevations measured within monitoring wells or piezometers screened within the same water-bearing stratum should be plotted on a scaled site plan, and the values contoured to develop a potentiometric surface map of the water-bearing unit (Figure 5.18). Ground water flow is perpendicular to such equipotential lines, in the direction of lower hydraulic head. A potentiometric map calculates the lateral hydraulic flow gradient ($\Delta h/L$) is calculated as the change in head (Δh) divided by the lateral distance (L) between equipotential lines, and is commonly expressed as a dimensionless value (i.e., ft/ft). Alternatively, hydraulic gradient can be determined by means of triangulation between any three well locations as described in Heath, 1983.

The vertical hydraulic flow gradient within a single water-bearing stratum can be determined by comparison of static water level elevations from "nested" well pairs screened at different depths within the same unit. In such case, the vertical gradient is estimated as the difference in static water level elevations (Δh) divided by the vertical distance between the midpoints of the well screens. Vertical gradients between separate water-bearing strata can be determined either from nested well measurements or comparison of potentiometric surface maps at any one point.

The hydraulic conductivity of a water-bearing stratum can be measured by means of single-well slug tests or constant-rate aquifer pumping tests conducted on wells screened within that unit. Test procedures and calculation methods are discussed in Chapter 3. In the absence of direct field measurements, rough approximations of hydraulic conductivity can be made on the basis of aquifer soil or rock characteristics (see Chapters 2 and 3).

Finally, the lateral ground water seepage velocity within a water-bearing stratum, representing the actual rate of ground water movement, can be estimated using Darcy's Law. Note that hydraulic conductivity measurements are usually determined from field tests, while porosity is typically estimated on the basis of soil or rock type.

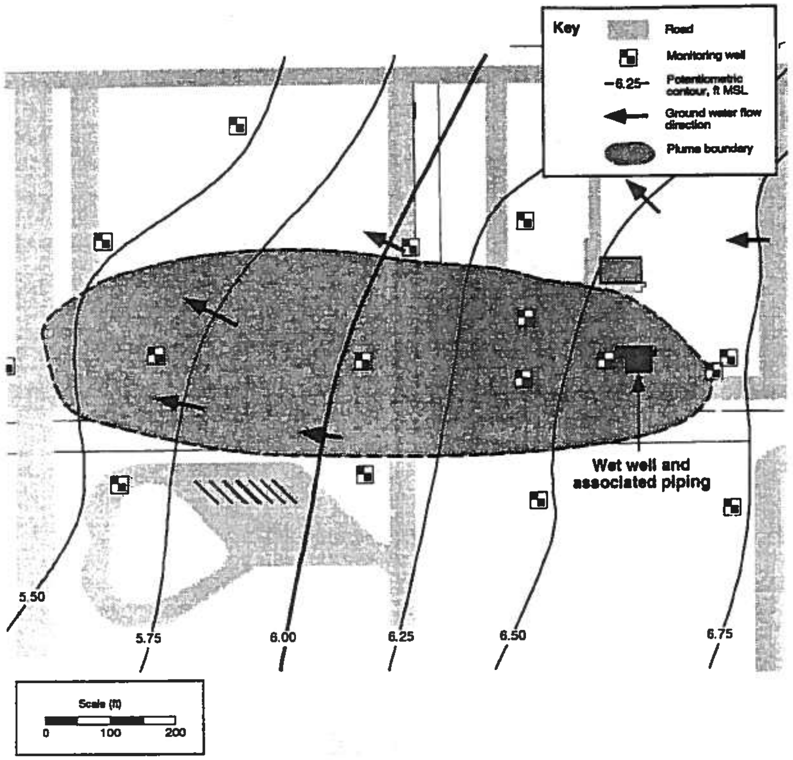


Figure 5.18 Potentiometric surface and plume location, Case Study 1.

5.9.3 Chemical Data Evaluation

Results of chemical analyses or indicator tests conducted on soil and ground water samples in either the field or laboratory must be plotted on scaled site plans and correlated with available geologic logs and cross-sections to define the lateral and vertical limits of contaminant migration. General procedures for laboratory data review and interpretation are as follows:

Data Validation Procedures. Upon receipt from the laboratory, all test results should be carefully reviewed to confirm laboratory accuracy and precision and compliance with relevant quality control standards. Formal data validation procedures are outlined in EPA, 1986, 1988, 1989a. Following confirmation of data validity, contaminant concentrations reported for soil and ground water samples should be corrected for those compounds detected in field, trip, or laboratory blank samples. Special attention should be paid to low concentrations of laboratory solvents (e.g., acetone, methylene chloride) or plasticizers (e.g., phthalate esters), which may represent inadvertent laboratory contamination of the soil or ground water samples.

Data Interpretation. Soil and ground water test results should be used to establish vertical and lateral "clean lines," the boundary beyond which contaminant concentrators are either less than natural background levels or less than the applicable cleanup standards specified by the regulatory authority. Various statistical methods can be employed to characterize background conditions and make comparisons to concentrations detected at individual sampling points (EPA, 1989b). Due to the variability of individual compound concentrations, it is usually instructive to define source zone or plume dimensions on the basis of the total organic or total inorganic contaminant levels detected at each sampling location. Data should be plotted on scaled site plans and cross-sections, and "clean lines" defined on the basis of clean sampling points. The delineation study is complete when a clean line can be drawn around all sides of the source zone or ground plume area, and the depth to clean soil or ground water has been established. These data should be sufficient to define the full volume of contaminated soil and ground water at the site.

Following completion of the delineation study, contaminant concentrations within the source zone or ground water plume should be inspected (and, if feasible, contoured according to lines of equal concentration) to confirm the location of the suspected contaminant source. In general, total contaminant concentrations should decrease with increasing distance from the point of release. Irregular concentration patterns may suggest (1) variable rates of contaminant release over time, or (2) the presence of multiple sources, or (3) complex hydrogeology. In such case, available site data should be carefully reviewed to confirm that all potential source areas have been identified and adequately outlined.

SUMMARY

This chapter summarizes field methods for collection of geologic, hydrologic, and water quality data. The geologic, hydrologic, and chemical data collected during the site investigation should fit together as an overall conceptual picture of a site. Geologic cross-sections and isopach maps should define stratigraphic conditions that are consistent with general depositional patterns observed in the site region. The apparent variability of ground water flow patterns indicated on potentiometric surface maps should correlate with actual stratigraphic variations or the locations of actual ground water recharge or discharge features (e.g., ponds, streams). Hydraulic conductivity measurements should be generally consistent with the soil or rock types observed during the drilling program. Dissolved contaminants should move in the direction of ground water flow, diminishing in concentration with distance from the source area. Geologic, hydrologic, and chemical data should be correlated in this manner, and inconsistencies resolved as needed to provide an accurate technical basis for corrective action design.

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CHAPTER 6

CONTAMINANT TRANSPORT MECHANISMS

6.1 INTRODUCTION

This chapter explores transport concepts relating to the migration and fate of contaminants from hazardous waste sites dissolved in ground water. The discussion will include case studies with applications for environmental engineers, hydrologists, hydrogeologists, and others in the ground water area. The approach considers the advective and dispersive transport of solutes dissolved in ground water, which may undergo simple first order decay or linear adsorption. Much effort has been devoted to solving the governing partial differential equations over the past two decades. Both one-dimensional (soil column) and two-dimensional (landfill plume) problems have generally been addressed. Mathematical derivations of the governing mass transport equations are reviewed in Section 6.4, and have been presented earlier by Ogata (1970), Bear (1972, 1979), and Freeze and Cherry (1979). This chapter deals primarily