PDHonline Course C178 (3 PDH)

Guidelines for Contaminated Ground Water Plume Management

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Solidified masses of toxic chemical precipitates can also be removed by mechanical scouring. Mechanical scouring techniques include the use of power rodding machines (“snakes”), which pull or push scrapers, augers, or brushes through the sewer line. “Pigs” are bullet-shaped plastic balls lined with scouring strips that are hydraulically propelled at high velocity through water mains to scrape the interior pipe surface.

b. Hydraulic Scouring. Contaminated sewer lines can be cleaned by running high-pressure fire hoses through manholes into the sewer and flushing out sections. Hydraulic scouring is often used after mechanical scouring devices have cleared the line of solid debris or loosened contaminated sediments and sludges coating the interior surface of the pipe. When using hydraulic scouring techniques large volumes of contaminated water may be produced.

c. Bucket Dredging and Suction Cleaning. A bucket machine can be used to remove grit or contaminated soil from a sewer line. Power winches are set up over adjacent manholes with cable connections to both ends of the collection bucket. The bucket is then pulled through the sewer line until loaded with debris. The same technique can also be used to pull “sewer balls” or “porcupine scrapers” through obstructed sewer lines. Suction devices such as pumps or vacuum trucks may be used to clean sewer lines of toxic liquids and debris.

Section II. Contaminated Ground-Water Plume Management

3-12. Ground-Water Pumping Systems. Two common ground-water pumping systems use either wellpoints or extraction/injection wells.

3-13. Wellpoint Systems. Wellpoint systems are generally used to control ground-water levels or flow patterns at construction sites. They are inexpensive to install and use techniques and equipment that are readily available. Major disadvantages are the requirement for maintenance and the energy used for pumping.

a. Applications.

(1) Wellpoint systems may be used to lower the water table or to dewater a selected area. They consist of a series of wellpoints with one or more pumping systems and can serve a variety of purposes. The withdrawn water can be discharged with or without further treatment.

(2) These systems are generally used at sites with relatively shallow water tables and fairly permeable soils. In general, if the water table is near the surface and is to be lowered to a depth of 6.1 m (20 feet) or less, wellpoints and suction pumps can be employed. If deeper drawdown is needed, a well system using jet or submersible pumps or eductor wellpoints must be employed.

b. Design and Construction Considerations. The lowering of the water table by using a wellpoint dewatering system is presented in Figure 3-15. The system consists of a group of closely spaced wells, usually connected by a header pipe and pumped by suction centrifugal pumps, submersible pumps, or jet ejector pumps, depending on the depth of pumping and the volume to be dewatered.

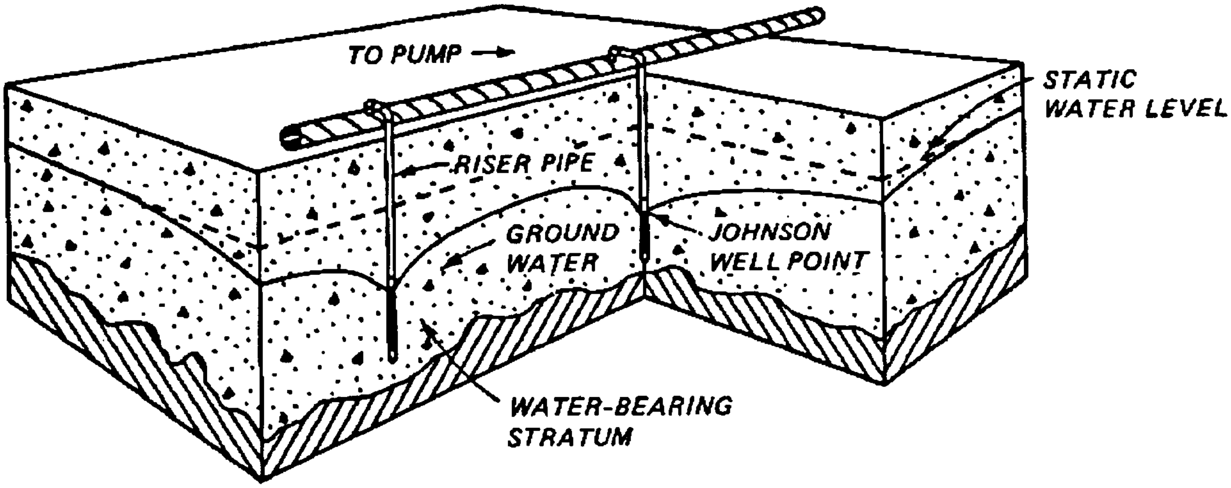


Figure 3-15. Schematic of a Wellpoint Dewatering System

(1) Hydraulic gradient. The hydraulic gradient increases as the flow converges toward a well. As a result, the lowered water surface develops a continually steeper slope toward the well. The form of this surface resembles a cone-shaped depression. The distance from the center of the well to the limit of this cone of depression is called the radius of influence. The hydraulic conductivity (K) is measured using the Darcy, defined as the permeability that will lead to a specific discharge of 1 cm/s for a fluid with a viscosity of 1 cp. It is approximately equal to 10^{-8} cm/s. The value of K depends upon the size and arrangement of the particles in an unconsolidated formation and the size and characteristics of the surfaces of crevices fractures, or solution openings in a consolidated formation. Figure 3-16 shows typical hydraulic conductivity for various soil and rock types. Darcy*s law remains valid only under conditions of laminar flow, involving fluids with a density not significantly higher than pure water.

(2) Transmissivity and storage coefficients. Two other factors, the transmissivity (T) and storage (S) coefficients, also affect the rate of flow. The coefficient of transmissivity indicates how much water will move through a formation and is equivalent to the permeability times the saturation thickness of the aquifer. The coefficient of storage indicates how much water can be removed by pumping and draining and is defined as the volume of water released from or taken into storage per unit area of aquifer per unit change in hydraulic head normal to the surface.

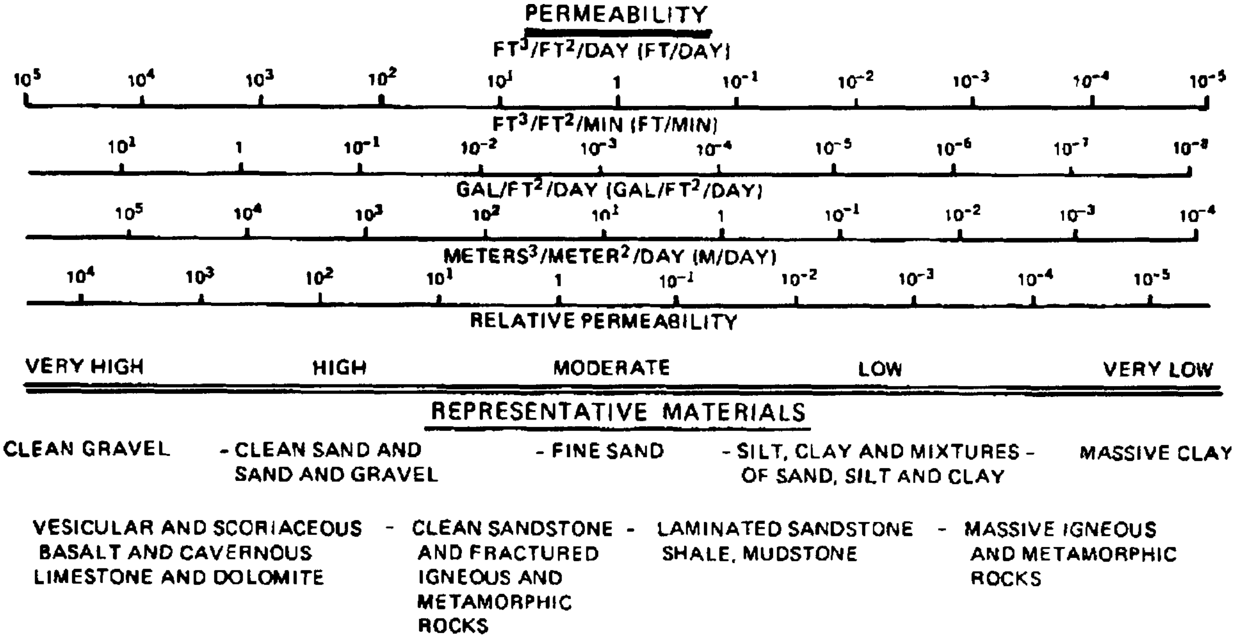


Figure 3-16. Hydraulic Conductivities of Soil and Rock

(3) Cone of depression. Lowering the ground-water level over the complete site involves creating a composite cone of depression by pumping from the wellpoint system. The individual cones of depression must be close together so that they overlap and thus pull the water table down several feet at intermediate points between pairs of wells.

(4) Stagnation points. Stagnation points occur when areas in the wellpoint field lie outside the area of influence of any of the wells. Design of the well-array should strive to reduce or eliminate stagnation points. Their presence leaves zones of high contaminant concentration and greatly lengthens the time necessary to clean the aquifer. The inclusion of injection wells can aid in the elimination of stagnation points.

(5) Drawdown. Once the aquifer properties of transmissivity and storativity have been determined, it is possible to predict the drawdown in hydraulic head in a confined aquifer at a distance (r) from the well and at a time (t) for a given pumping rate (Q). Thus, by determining the drawdown at various radii from the well, one can determine the radius of influence for a given pumping rate. For a given aquifer, the cone of depression initially increases in depth and extent with increasing pumping time until eventually it levels off. Drawdown at any point at a given time is directly proportional to the pumping rate and inversely proportional to aquifer transmissivity and storativity.

(6) Design considerations. Designs of wellpoint dewatering systems can vary considerably, depending on the depth to which dewatering is required, the transmissivity and storativity of the aquifer, the size of the site, and the depth of the waterbearing formation.

(7) Spacing. Wellpoint spacing is based on the radius of influence of each well and the composite radii of influence needed to lower the water table. Once storage and transmissivity coefficients have been determined, the drawdown and area of influence may be calculated. In practice, spacing for a few wellpoints would be determined and then field tested; any necessary adjustments would then be made to account for the fact that wells do not always meet the idealized conditions assumed in equations to estimate drawdown.

(8) Time to clean up. The time to clean up an aquifer is difficult to predict as it depends upon a wide variety of factors:

Contaminant type	Water solubility, volatility, mobility, polarity, absorption characteristics
Site soil type	Permeability, storage capacity, clay type and content, grain size, presence of clay lenses and impermeable barriers
Aquifer characteristics	Rate of flow, depth and thickness, recharge rate, perched water tables, contaminate concentrations

Pumping may be necessary for extended periods of time. Typically the concentration of contaminants in the extracted ground water falls asymptotically toward zero so that the demand on treatment equipment lessens over time. A good design will take into account this effect by incorporating unit operations that can be removed or reworked to be effective on the lower and lower contaminant concentrations. This is especially important to bioremediation systems where contaminant concentrations may soon fall to levels which will not sustain microbe populations. Further, “When is an aquifer clean?” is a difficult question.

(9) Ground-water treatment and disposal. The treatment of the contaminated ground water is a major consideration. Extracted ground water must be treated before discharge or reinjection. Treatment systems have been designed with stripping (air or steam) units for volatiles (perhaps with carbon absorption or incineration units for the stripped air stream), carbon absorption units, ion-exchange units, and/or bioreactors. These can be arranged singly or in series. Treated effluent may be discharged to the local publicly owned treatment works (POTW)(which may remove the need for pretreatment), injection wells incorporated into ground-water cleanup design, and seepage basins or trenches. Disposal of large volumes of extracted ground water over long time periods can be a major consideration and expense.

c. Installation.

(1) Wellpoints are made to be driven in place, to be jetted down, or to be installed in open holes. The most common practice is to jet the wellpoints down to the desired depth, to flush out the fines, leaving the coarser fraction of material to collect in the bottom of the hole, and then to drive the point into the coarser materials.

(2) A method used in some unstable material consists of jetting down or otherwise sinking temporary casing into which the wellpoint and riser pipe are installed. As the casing is pulled, gravel may be placed around the wellpoint.

d. Special Cases.

(1) In special cases, design modifications will be required or at least various methods should be compared for cost-effectiveness. Fine silts and other slowly permeable materials cannot be readily drained by wellpoint systems alone. However, soils can be partially drained and stabilized by vacuum wells or wellpoint systems that create negative pore pressure or tension in the soil. The wellpoints should be gravel packed from the bottom of the hole to within a few feet from the surface of the poorly permeable material. The remainder of the hole should be sealed with bentonite or other impermeable materials. If a vacuum is maintained in the well screen or pack, flow toward the wellpoints is increased. Such a system usually requires closely spaced wellpoints, and pumping capacity is reduced. Vacuum booster pumps may be required on the headers or individual wells for effective operation.

(2) Vertical sand drains may be used in conjunction with wellpoints to facilitate drainage in stratified soils. The drains, usually 406 to 508 mm (16 to 20 inches) in diameter, are installed on 1.8 to 3 m (6- to 10-foot) centers through the impermeable layers that need to be dewatered and are extended to underlying permeable layers where wellpoints are placed.

(3) Two or more wellpoint systems may be required when two or more strata of water-bearing sand are separated by impermeable barriers. The depth for dewatering will be different for each system, and consequently pipe lengths and diameters and pumping requirements will be determined independently.

(4) Potential enhancements of ground-water cleanup may involve the use of in-situ bioremediation. Introduction of nutrients and/or oxygen (or hydrogen peroxide) into the injection wells may greatly increase the rate of in-situ contaminant breakdown and thus enhance cleanup. Steam or hot water injection may help to dissolve or mobilize slightly soluble or adsorbed contaminants and increase their rate of removal.

e. Advantages and Disadvantages. Advantages and disadvantages of wellpoint pumping to adjust the water table are as follows:

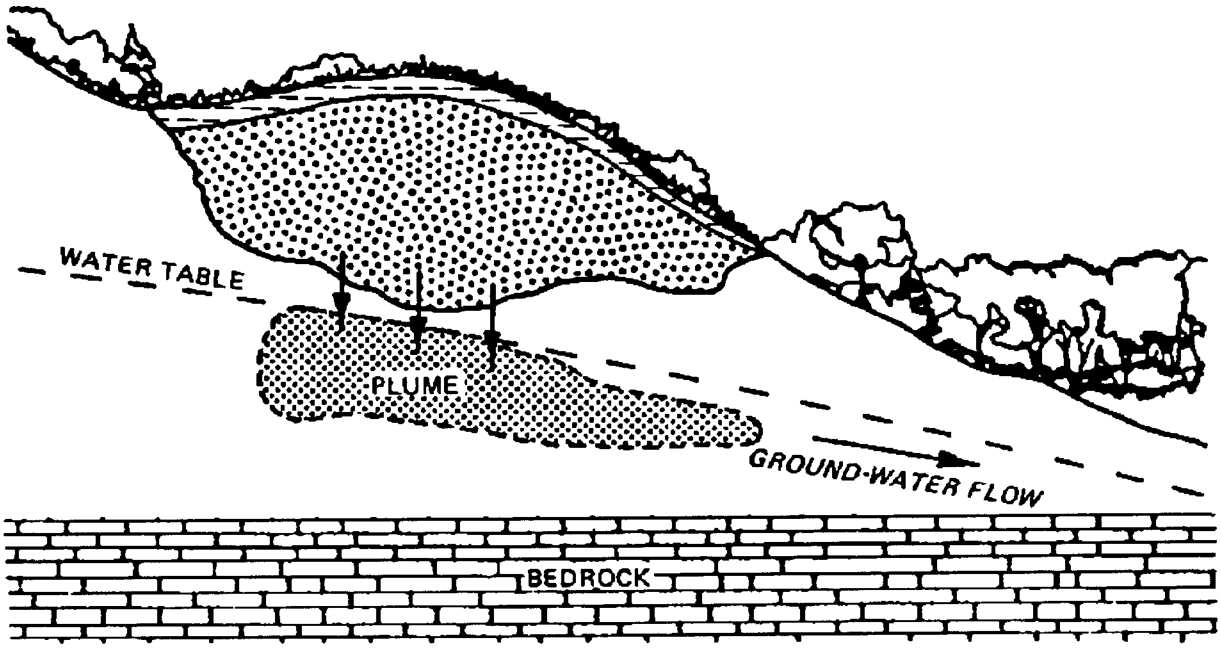
Advantages	Disadvantages
High design flexibility	May not adequately drain fine silty soils, and flexibility is reduced in this medium
Good onsite flexibility since the system can be easily dismantled	Higher operation and maintenance costs than for artificial ground-water barriers
Construction costs may be lower than for construction of artificial ground-water barriers	System failures could result in contaminated drinking water
Good reliability when properly monitored	

3-14. Extraction/Injection Well Systems. Extraction/injection control systems have been used at waste sites to alter natural ground-water gradients to prevent pollutants from leaving a site or to divert ground water that might enter a site. Where hazardous wastes are involved, pumped systems may be used in conjunction with ground-water barriers. Pumped systems that result in mixing contaminated and uncontaminated ground waters can create large volumes of contaminated ground water to be treated. In most cases contaminated ground water at waste sites is contained by installing extraction wells to extract ground water from under the site, collecting contaminants leaking from the waste and creating a local gradient toward the site. Water withdrawn from under the site may have to be treated before discharge or reinjection. Two applications of extraction/injection systems to contain a plume are the use of a series of extraction and injection wells that will allow water within the plume to be pumped, treated, and pumped back into the aquifer and pumping and treatment of the plume followed by recharge using seepage basins.

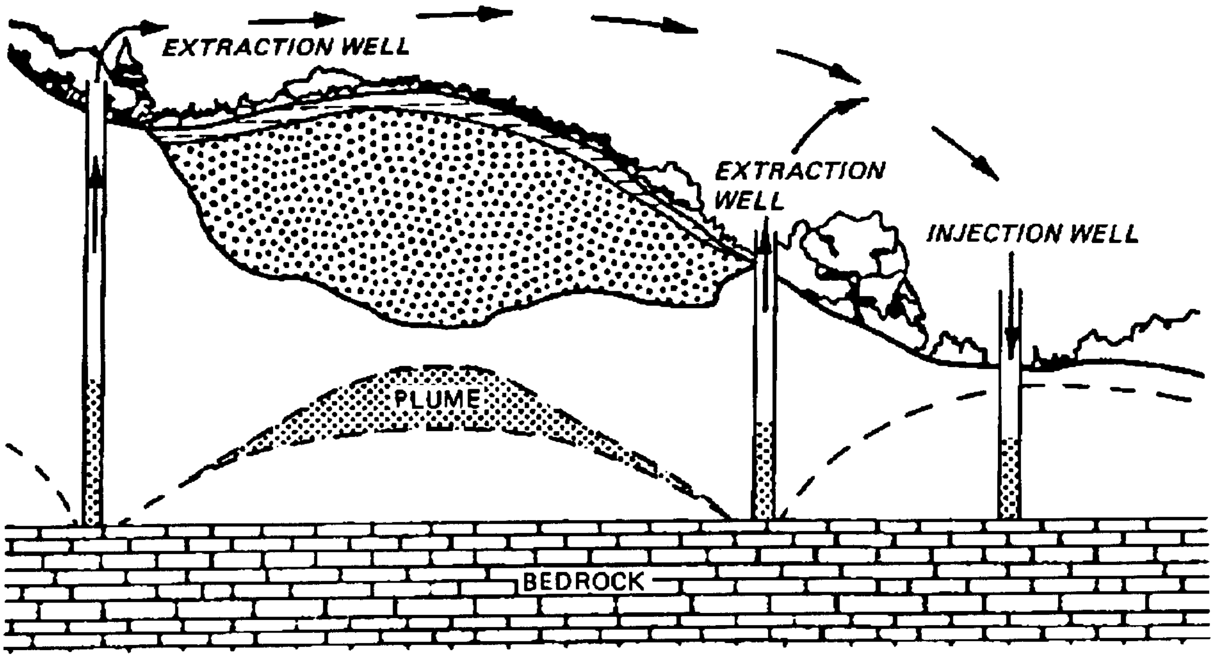
a. Applications.

(1) Hydraulic barriers. Plume containment with the use of extraction/injection wells is an effective means of preventing the eventual contamination of drinking water wells or the pollution of streams or confined aquifers that are hydraulically connected to the contaminated ground water (Figure 3-17). The technique may be particularly useful for surface impoundments. One design would use extraction/injection wells separated by physical barriers (slurry wall or sheet pilings). The extraction wells are placed upgradient from the barrier; the extracted ground water is treated and reinjected on the downgradient side of the barrier. This design can keep contaminated ground water from leaving the site.

(2) Plume and floating product recovery. Extraction wells are used to directly recover separate liquid phases such as petroleum products which are floating at the water table. Well screens are placed such that the product can be collected and separated from any contamination ground water at the land surface in standard oil-separation units. Separated ground water usually must be treated to remove any soluble organics, carbon absorption, or biotreatment being used. Soluble materials dissolved in the ground water can also be



BEFORE PUMPING



AFTER PUMPING

Figure 3-17. Use of Extraction/Injection Wells for Plume Containment (Source: EPA 1982) separated and recovered using extraction wells followed by carbon absorption or reverse osmosis, or they can be destroyed using biotreatment. Judicious placement of injection wells can increase the rate of cleansing of the aquifer.

b. Design and Construction Considerations.

(1) Definition of the plume area, depth, and flow rate and direction must be determined before any further design considerations can be addressed. Pump tests should include determination of transmissivity and storage coefficients, and radii of influence of test wells. The presence of perched water tables or other anomalies must also be assessed.

(2) The basis of plume management by pumping depends upon incorporating the plume within the radius of influence of an extraction well. Such a system requires careful monitoring to determine the extent of the plume and any changes that may occur in the plume as pumping continues.

(3) The effect of the injection wells on the drawdown and radius of influence of the extraction wells is illustrated Figure 3-18. As the cone of depression expands and eventually encounters the cone of impression from the recharge well, both the rate of expansion of the cone and the rate of drawdown are slowed. With continued pumping, the cone of depression expands more slowly until the rate of recharge equals the rate of extraction and the drawdown stabilizes. Thus, the effect of the injection well is to narrow the radius of influence and to decrease the drawdown with increasing distance from the well.

(4) By combining extraction and injection wells in the design, the rate of cleanup of the aquifer and the amount of groundwater contaminated may be decreased. The cone of impression (Figure 3-18) of the injection well will serve to isolate the extraction wells from the surrounding ground water and increase the rate of flow (head gradient) toward the extraction well.

(5) The simplest extraction/injection well systems are designed so that the radii of influence do not overlap. Another important reason for placing the wells distant enough so that their radii of influence do not overlap is that any changes that must be made in pumping as a result of changes in the plume due to age of the landfill, quantity of precipitation, and physical changes in the size of the landfill, due to compaction or excavation, would be complicated by the effect of the overlap of the areas of influence.

(6) In some instances site limitations may require that the extraction and injection wells be placed so close together that the radii of influence overlap. Overlapping injection/extraction well zones of influence may be used to increase the rate of flow of ground water through the contaminated site in order to increase the rate of flushing of the contaminants.

(7) An example of an effective system for plume containment is currently operating at the Rocky Mountain Arsenal. Ground water is extracted, treated, and recharged through injection wells to the downgradient side of an impermeable barrier (slurry wall). The completed system will handle a flow of

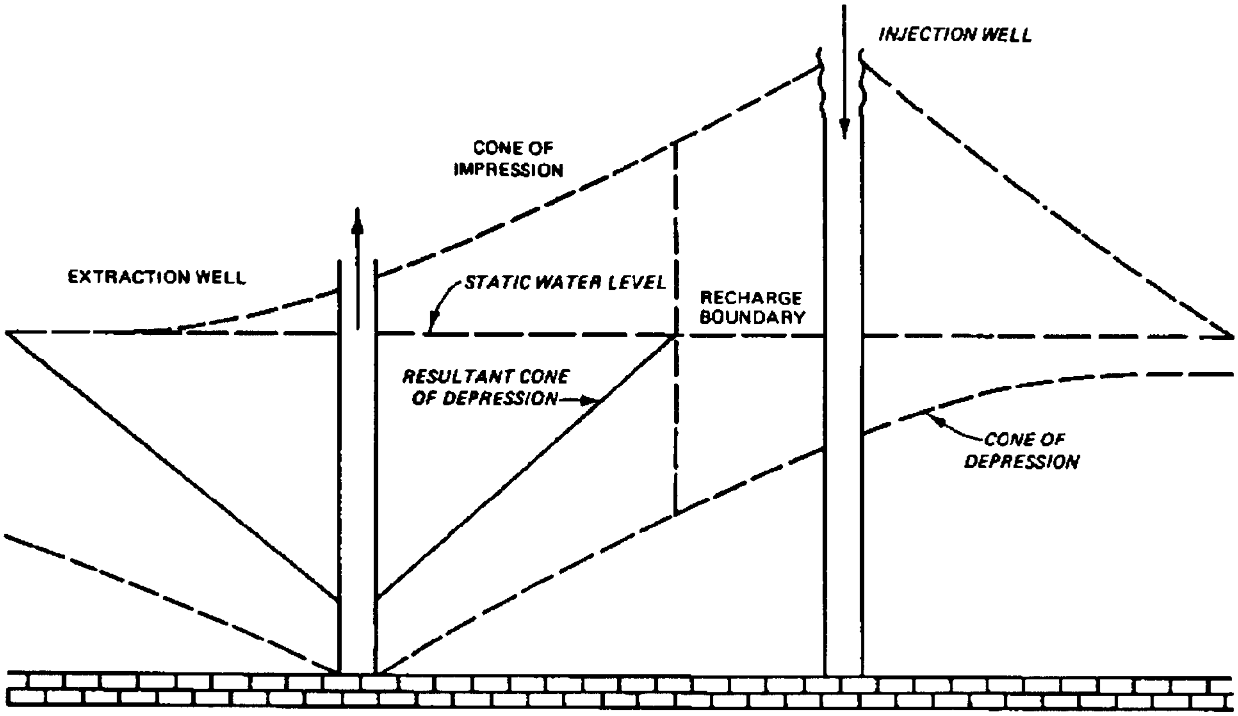


Figure 3-18. Effect of an Injection Well on the Cone of Depression

28 ℓ/s (443 gpm) and extend for 1585 m (5,200 feet). The system will consist of about 33 extraction wells, most of which are 203 mm (8 inches) in diameter, and approximately 40 injection wells with a diameter of 406 to 508 mm (16 to 18 inches). The extraction and injection systems are separated by an impermeable barrier to prevent mixing of contaminated and uncontaminated water.

c. Ground-water Pumping with Recharge through Seepage Basins.

(1) As a less costly alternative to recharging water through injection wells, seepage basins or recharge basins can be used. Since seepage basins require a high degree of maintenance to ensure that porosity is not reduced, they would not be practical where several basins are required for recharge of large volumes of water or where adequate maintenance staff is not available.

(2) As is the case for extraction/injection well systems, the effects of recharge on the cone of depression must be accounted for in designing a system that will contain the plume. Ideally, the recharge basins should be located outside the area of influence of the extraction wells.

(3) The dimensions of a recharge basin vary considerably. The basin should be designed to include an emergency overflow and a sediment trap for run-off from rainwater. The side walls of the basin should be pervious since considerable recharge can occur through the walls.

d. Advantages and Disadvantages. The advantages and disadvantages of the extraction/injection systems used for plume containment are as follows:

Advantages	Disadvantages
System may be less costly than construction of an impermeable barrier	Plume volume and characteristics will vary with time, climatic conditions, and changes in the site resulting in costly and frequent monitoring
High degree of design flexibility	
Moderate to high operational flexibility, which will allow the system to meet increased or decreased pumping demands as site conditions change	System failures could lead to contamination of drinking water
	O&M costs are higher than for artificial barrier

3-15. Subsurface Barriers. The most common subsurface barriers are slurry-trench cutoff walls, grout curtains, sheet pile cutoff walls, membranes and synthetic sheet curtains, and combination barrier pumping systems.

3-16. Slurry-trench Cutoff Walls. Slurry trenching is a method of constructing a passive subsurface barrier or slurry wall to impede or redirect the flow of ground water. This practice covers a range of construction techniques from the simple to the quite complex, and though it is becoming more common, is still performed by only a few specialty contractors. In recent years the success and economy of slurry trench cutoffs has largely brought about the replacement of other methods such as grout curtain and sheet piling cutoffs.

a. Description.

(1) Slurry walls are fixed underground barriers formed by pumping slurry into a trench as excavation proceeds. The slurry is usually a soil or cement, bentonite, and water mixture pumped into the trench to maintain a slurry-full trench condition. The cement-bentonite slurry is allowed to set. The soil-bentonite trench filling is produced by backfilling the trench with a suitably engineered backfill which often includes local or excavated site soil.

(2) The slurry used in the soil-bentonite is essentially a 4 to 7 percent by weight suspension of bentonite in water. Bentonite is a clay of the montmorillonite group of 2:1 expanding lattice clays. Excavated materials that are removed from the slurry-filled trench are placed at the trench sides and excess slurry drains back into the trench. Selected backfill material is dumped into the trench and sinks through the bentonite forcing some slurry out of the trench. Excess slurry is pumped to a holding area where the slurry can be “desanded” if necessary and adjusted to the specified density for reintroduction into the trench. No compaction of a finished slurry trench is required.

3) For proper displacement of slurry by the backfill material, the unit weight of backfill material should be 240.3 kg/m^3 (15 lb/ft^3) greater than that of the slurry (soil-bentonite). Typical soil-bentonite unit weights are 1442 kg/m^3 to 1682 kg/m^3 (90 to 105 lb/ft^3) and for cement-bentonite slurry 1922 kg/m^3 (120 lb/ft^3). Density requirements for a cement-bentonite slurry are less important because it is not backfill displaced; however, a 90-day minimum set time is important.

b. Applications.

(1) Slurry walls were first used to effect ground-water cutoff in conjunction with large dam projects. In recent years, they have found use as both ground-water and leachate barriers around hazardous waste disposal sites. Placement of the wall depends on the direction and gradient of ground-water flow as well as location of the wastes. When placed on the upgradient side of the waste site, a slurry wall will force the ground water to flow around the wastes. In some instances, it may be unnecessary to sink the wall down to an impervious stratum. A wall sunk far enough into the water table upgradient from the wastes can reduce the head of the ground-water flow, causing it to flow at greater depth beneath the wastes.

(2) Most commonly, the trench is excavated down to, and often into, an impervious layer in order to retard and minimize a ground-water flow. This may not be the case when only a lowering of the water table is required. The width of the trench is typically from 0.61 to 1.5 m (2 to 5 feet) and can be up to 24.4 m or 30.5 m (80 or 100 feet) deep. Typically, a backhoe, clamshell, or dragline is used for excavation.

(3) Grades of 10 percent and higher provide problems for slurry-trench construction.

(4) Ground-water chemistry can severely affect the behavior at the bentonite slurry. Adverse reactions such as thickening or flocculation may result if grout and ground water are not compatible. Compatibility tests have been conducted to determine the ability of bentonite slurry walls to withstand the effects of certain pollutants, and the results are encouraging. Of the chemicals tested, only alcohols were found to completely destroy the slurry wall. To determine the probable effectiveness of a slurry wall for a particular site, however, compatibility tests should be conducted using the actual leachate from the site.

(5) In certain settings, a slurry wall can be installed to completely surround the site. In some cases, the ground water inside the slurry wall is extracted and treated, and in some cases replaced with the treated ground water.

(6) Where slurry cutoffs are used in conjunction with a cap, the wall-cap tie-in should facilitate construction and be of adequate thickness to prevent separation as a result of long-term settlement of the wall. Tie-in with an impervious layer beneath the wall is also important if ground-water cutoff is the objective.

(7) A slurry trench cutoff wall was designed and constructed to contain migration of contaminated ground water from the Lipari Landfill in Pitman, New Jersey, in October 1983. The trench was approximately 883.4 m (2,900 feet) long and 15.2 m (50 feet) deep. The bottom of the trench was keyed into a Kirkwood clay layer. The design drawing illustrating the position of the trench is presented in Figure 3-19. Depending on the grade and the position of the trench in relation to the batch-mixing operation performed in a clean area onsite, between 22.9 and 45.7 m (75 and 150 feet) of slurry trench could be constructed each day. The entire trench was constructed in two months.

c. Design and Construction Considerations.

(1) Slurry trenching must be preceded by thorough hydrogeologic and geotechnical investigations. A good hydrogeologic study will tell the designers the depth, rate, and direction of ground-water flow, and the chemical characteristics of the water. A geotechnical investigation will provide information on soil characteristics such as permeability, amount of stratification, and depth to bedrock or an impervious layer. In addition, it will tell the nature and condition of the bedrock. When the slurry wall is intended to provide total water cutoff, rather than just to lower the water table, particular attention must be paid to the soil/rock interface.

(2) The type of equipment used to excavate a slurry trench depends primarily on the depth. Hydraulic backhoes can be used to excavate down to 16.8 m (55 feet). Beyond that depth, a clamshell shovel must be used. If it is necessary to install the slurry wall into hard bedrock, drilling or blasting may have to be used to excavate the rock. Special blasting techniques would be required to maintain the integrity of the bedrock.

(3) Backfilling of a trench is often accomplished with the equipment used to excavate the trench. A bulldozer can be used to mix the soil with the slurry alongside the trench as well as to backfill the upper portion of the trench. Care must be taken to ensure that no pockets of slurry are trapped during the backfilling, as these can greatly reduce the wall*s effectiveness and permanence.

(4) For maximum permeability reduction, the soil/bentonite mixture used for backfilling should contain 20 to 25 percent fines (soil particles that will pass a 0.075 mm (200-mesh) sieve). To ensure long-term permeability reduction, as much as 40 to 45 percent fines may be required. In the event the onsite soils are too coarse, imported fines or additional bentonite must be added.

(5) The bentonite must be completely hydrated and well mixed with the soil or cement before being placed into the trench.

d. Advantages and Disadvantages. The process outlined above includes a number of variables that can affect the long-term effectiveness of a slurry wall. The extent to which these variables, such as ground water, soil, and rock characteristics, can influence the integrity of a wall can usually be determined by a variety of preconstruction tests. From the results of these

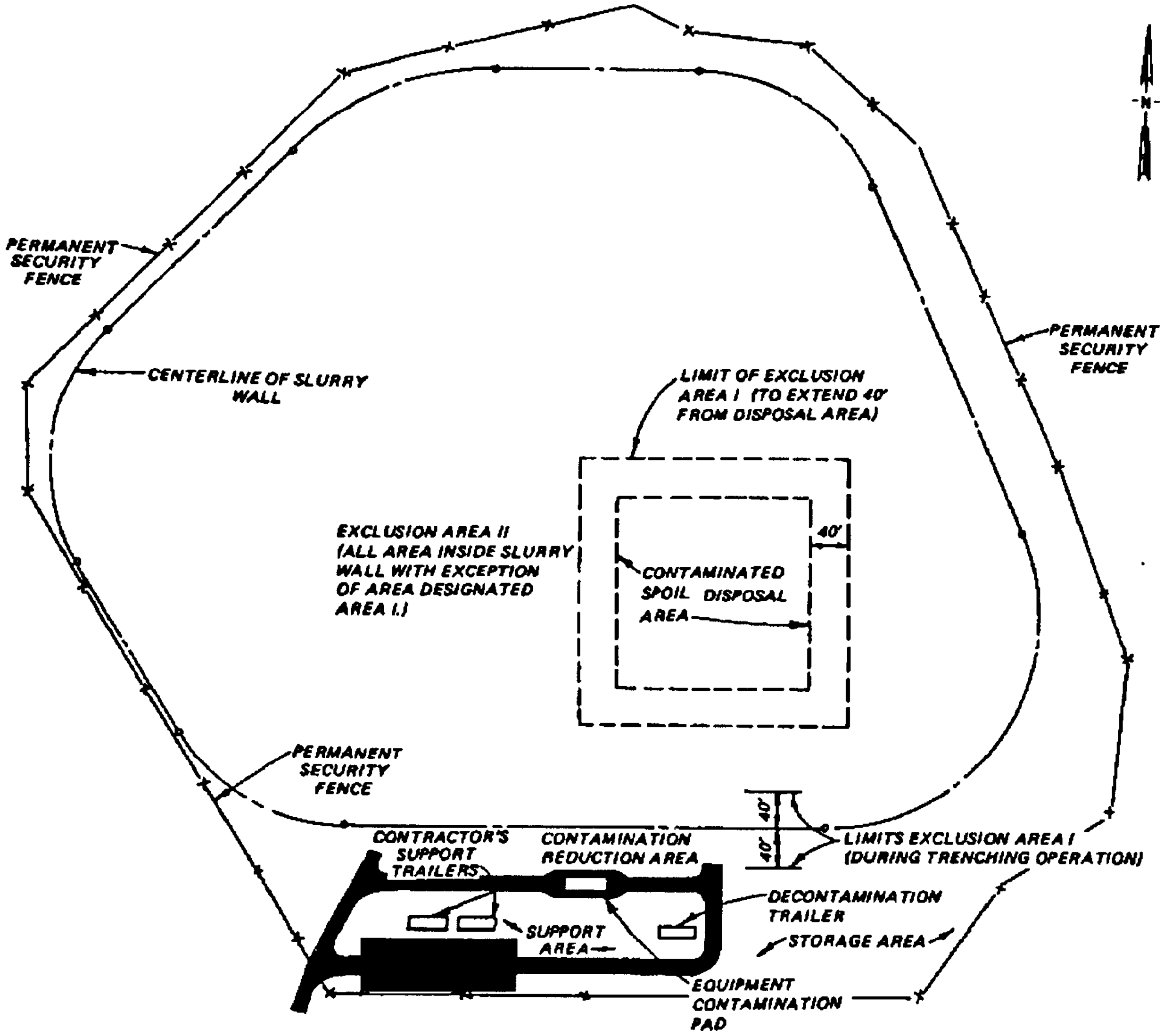


Figure 3-19. Design Drawing for Lipari Landfill Slurry-Trench Cutoff Wall

field and laboratory tests, more site deficiencies can be identified and corrected prior to construction. A properly designed and installed slurry wall can be expected to provide effective ground-water control for many decades with little or no maintenance. Advantages and disadvantages of slurry trenches are summarized below:

Advantages	Disadvantages
A long-term, economical method of ground-water control	Ground water or waste leachate may be incompatible with slurry material
No maintenance required over long term	Lack of near-surface impermeable layer, large boulders or underground caverns may make installation difficult or impractical
Materials inexpensive and available	
	Not practical with over 10 percent slope
Technology well proven	

3-17. Grout Curtains. Another method of ground-water control is the installation of a grout curtain. Grouting in general consists of the injection of one of a variety of special fluids or particulate grouts (Table 3-5) into the soil matrix under high pressure. The injection of the specific grout type is determined by conditions of soil permeability, soil grain size, chemistry of environment being grouted (soil and ground-water chemistry), and rate of ground-water flow. Grouting greatly reduces permeability and increases mechanical strength of the soil zone grouted. When carried out in the proper pattern and sequence, this process can result in a curtain or wall that can be an effective ground-water barrier. Because a grout curtain can be three times as costly as a slurry wall, it is rarely used when ground water has to be controlled in soil or loose overburden. The major use of curtain grouting is to seal voids in porous or fractured rock where other methods of ground-water control are impractical.

a. Description. The pressure injection of grout is as much an art as a science. The number of United States firms engaged in this practice is quite limited. The injection process itself involves drilling holes to the desired depth and injecting grout by the use of special equipment. In curtain grouting, a line of holes is drilled in single, double, or sometimes triple staggered rows (depending on site characteristics) and grouting is accomplished in descending stages with increasing pressure. The spacing of the injection holes is also site specific and is determined by the penetration radius of the grout out from the holes. Ideally, the grout injected in adjacent holes should touch (Figure 3-20) along the entire length of the hole. If this is done properly, a continuous, impervious barrier is formed (Figure 3-21).

b. Application.

(1) In general, grouts can be divided into two main categories- - suspension grouts and chemical grouts. Suspension grouts, as the name implies, contain finely divided particulate matter suspended in water. Chemical grouts, on the other hand, are true Newtonian fluids. Most of the grouting in the United States is done with suspension grouts, whereas about half of the grouting in Europe is done with chemicals. The principal grouts in use today are briefly described below.

Table 3-5. Significant Characteristics of Types of Grout

Type	Characteristic
Portland cement or particulate grouts	Appropriate for higher permeability (larger grained) soils
	Least expensive of all grouts when used properly
	Most widely used in grouting across the United States (90 percent of all grouting)
Chemical grouts	
Sodium silicate	Most widely used chemical grout
	At concentrations of 10-70 percent gives viscosity of 1.5-50 cP
	Resistant to deterioration by freezing or thawing
	Can reduce permeabilities in sands from 10^{-2} to 10^{-8} cm/sec
	Can be used in soils with up to 20 percent silt and clay at relatively low injection rates
	Portland cement can be used to enhance water cutoff
Acrylamide	Should be used with caution because of toxicity
	First organic polymer grout developed
	May be used in combination with other grouts such as silicates, bitumens, clay, or cement
	Can be used in finer soils than most grouts because low viscosities are possible (1 cP)
	Excellent gel time control due to constant viscosity from time of catalysis to set/gel time
	Unconfined compressive strengths of 344-1378 KPa (50-200 psi) in stabilized soils
	Gels are permanent below the water table or in soils approaching 100 percent humidity
	Vulnerable to freeze-thaw and wet-dry cycles, particularly where dry periods predominate and will fail mechanically
	Due to ease of handling (low viscosity), enables more efficient installation and is often cost-competitive with other grouts
Phenolic (Phenoplasts)	Rarely used due to high cost
	Should be used with <u>caution</u> in areas exposed to drinking water supplies, because of toxicity
	Low viscosity
	Can shrink (with impaired integrity) if excess (chemically unbound) water remains after setting; unconfined compressive strength of 344-1378 KPa (50-200 psi) in stabilized soils

(Continued)

Table 3-5. (Concluded)

Type	Characteristic
Urethane	Set through multistep polymerization Reaction sequence may be temporarily halted Additives can control gellation and foaming Range in viscosity from 20 to 200 cP Set time varies from minutes to hours Prepolymer is flammable
Urea-Formaldehyde	Rarely used due to high cost Will gel with an acid or neutral salt Gel time control is good Low viscosity Considered permanent (good stability) Solution toxic and corrosive Relatively inert and insoluble
Epoxy	In use since 1960 Useful in subaqueous applications Viscosity variable (molecular weight dependent) In general, set time difficult to regulate Good durability Resistant to acids, alkalis, and organic chemicals
Polyester	Useful only for specific applications Viscosity 250 to several thousand cP Set time hours to days Hydrolyzes in alkaline media Shrinks during curing Components are toxic and require special handling
Lignosulfonate	Rarely used due to high toxicity Lignin can cause skin problems and hexavalent chromium is highly toxic (both are contained in these materials) Cannot be used in conjunction with portland cement; pH*s conflict Ease of handling Loses integrity over time in moist soils Initial soil strengths of 344-1378 KPa (50-200 psi)

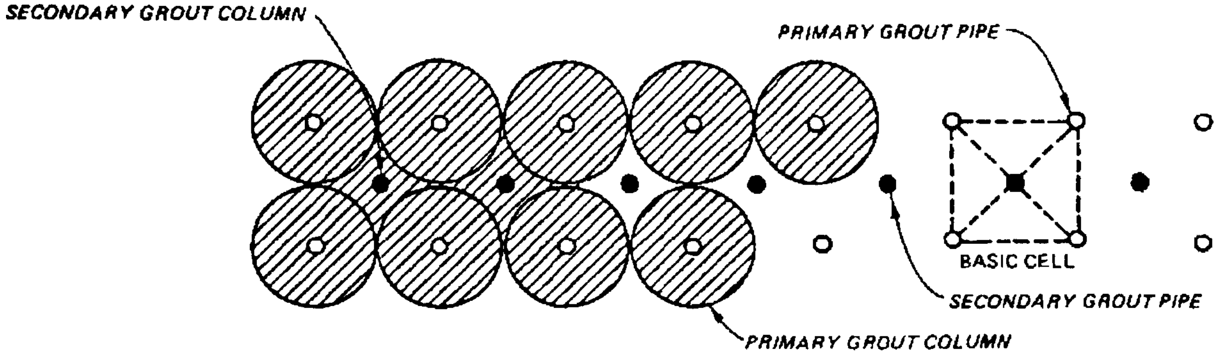


Figure 3-20. Grout Pipe Layout for Grout Curtain

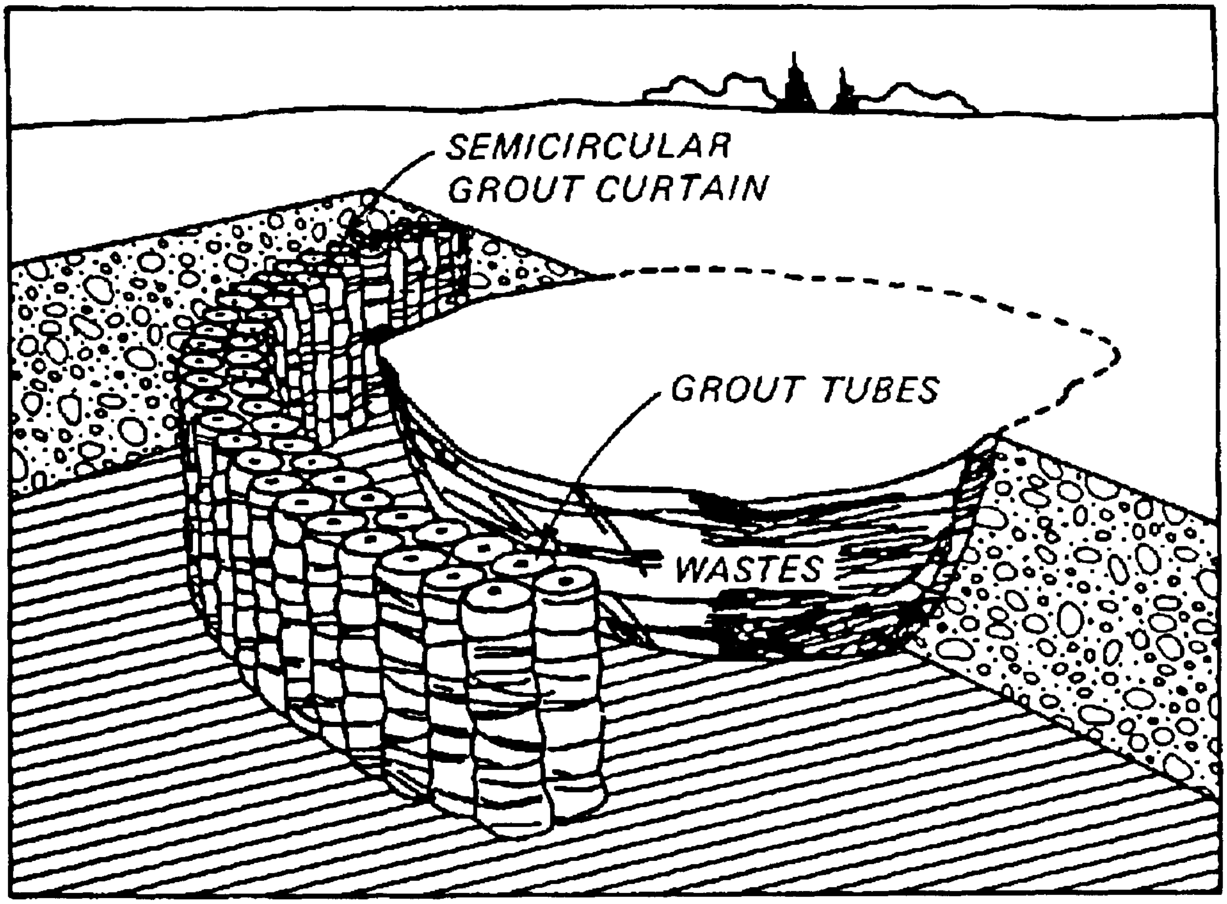


Figure 3-21. Semicircular Grout Curtain Around Waste Site

(2) Suspension grouts are for the most part either portland cement, bentonite, or a mixture of the two. Ultra-fine cement grouts are also available. Their primary use is in sealing voids in materials with rather high permeabilities, and they are often used as “pregrouts” with a second injection of a chemical grout used to seal the fine voids. If a suspension grout is injected into a medium that is too fine, filtration of the solids from the grout will occur, thus eliminating its effectiveness. Portland cement, when mixed with water, will set up into a crystal lattice in less than 2 hours. For grouting, a water-cement ratio of 0.6 or less is more effective. The smallest voids that can be effectively grouted are no smaller than three times the cement grain size. For this, it is clear that a more finely ground cement makes a more watertight grout. Portland cement is often used with a variety of additives that modify its behavior. Among these are clay, sand, fly ash, and chemical grouts.

(3) Of the clay minerals used for grouting, bentonite is by far the most common. Other locally available clays, especially those of marine or river origin, may be used but must be extensively tested and often chemically modified. Bentonite, however, because of its extremely small particle size (one micron or less), is the most injectable, and thus the best suited for grouting into materials with lower permeabilities. Medium- to fine-textured sands, with permeabilities of around 10^{-3}-10^{-4} cm/sec, can be sealed with a bentonite grout. Dry bentonite is mixed with water onsite at a rate of 5 to 25 percent by dry weight. In these ratios, bentonite will absorb large amounts of water and, with time, form a gel. This gel, although it imparts little if any structural strength, is an extremely effective water barrier.

(4) Placement of a grout curtain downgradient from or beneath a hazardous waste site requires consideration of the compatibility of the grout to waste leachate or other extremes of ground-water chemistry. Little information is available concerning the resistance of grouts to chemical attack. Should a case arise where grout must contact leachate or ground water of extreme, field tests should be performed to verify grout resistance.

(5) Quality control is a difficult issue since even small voids or breaks can greatly lessen the effectiveness of a grout curtain. By definition, a grout curtain is not amenable to inspection.

c. Design and Construction Considerations.

(1) Pressure grouting is a high technology endeavor. As with slurry trenching, extensive geotechnical and hydrologic testing must precede the placement of a grout curtain. Boring, pumping, and laboratory tests will determine whether or not a site is groutable and will provide the necessary ground-water, rock, and soil information to allow for the choice of the best-suited grout or grouts. They will further provide the designer with the information needed to plan the pattern and procedure for injection.

(2) For all grouts the closer the viscosity is to that of water (1.0 cP), the greater the penetration power. Grouts with a viscosity less than 2 cP, such as many of the chemical grouts, can penetrate strata with permeabilities less than 10^{-5} cm/sec. Higher viscosity grouts, like

particulate and some chemical grouts with a viscosity greater than 10 cP, can only penetrate coarse strata having permeabilities greater than 10^{-2} cm/sec. For suspension particulate grouts, the particle size will also influence the ability to penetrate voids.

(3) Short-term deterioration of the grout can be caused by rapid chemical degradation or by an incorrect setting time. The effect on setting time can be caused by a miscalculation of the grout formulation, dilution of the grout by ground water, or changes caused by chemicals contained within the grouted strata.

(4) Once a grout has set in the voids in the ground, it must be able to resist hydrostatic forces in the pores that would tend to displace it. This ability will depend on the mechanical strength of the grout and can be estimated by the grout*s shear strength. The shear strength of a grout will depend not only on its class, but also on its formulation. Thus, a class of grouts, such as silicates, can possess a wide range of mechanical strengths depending on the concentration and type of chemicals used in its formulation. The strength of the gel, then, can be adjusted, within limits, to the specific situation.

d. Advantages and Disadvantages.

(1) The advantage of grout curtain emplacement is the ability to inject grout through relatively small diameter drill holes at unlimited depths. The size of the pod or grouted column is a function of pore space volume and volume of grout injected. Grout can incorporate and/or penetrate porous materials in the vicinity of the injection well such as boulders or voids. Variable set times and low viscosities are also advantages.

(2) The major disadvantages of grouts are the limitations imposed by the permeability of the host material (soil or rock) and the uncertainty of complete cutoff, Specifically with particulate grouts only the most permeable units are groutable.

3-18. Sheet Pile Cutoff Walls. Sheet pile cutoff walls may be used to contain contaminated ground water, divert a contaminant plume to a treatment facility, and divert ground-water flow around a contaminated area. They constitute a permeable passive barrier composed of sheet piling permanently placed in the ground. Each section interlocks with an adjacent section by means of a ball/socket (bowl) union. The connection (union) may initially be a pathway for ground-water migration which may abate or cease if the ball/socket section is naturally or artificially filled with impermeable material. Sections of pilings are assembled before being driven into the ground (soil conditions permitting).

a. Description.

(1) Various sheet piling configurations are available. Application of specific configurations and fittings can be used for site-specific needs such as partitioning different sections of a waste-contaminated area or combination

of areas. Piling weight may vary from 1054 to 1820 Pa (22 to 38 lb/ft^2) depending upon the driving depth and soil materials.

(2) Keying in to a subsurface impermeable barrier is limited by depth to the barrier and composition of the barrier. Pile driving to a relatively shallow clay deposit and keying in to the clay without driving completely through the clay is relatively common in construction practices. However, keying in to a rock unit such as shale or other sedimentary unit is difficult. The physical tightness of such a bedrock/piling key is poor and may require additional sealing (grout, etc.). Pile testing and borings to an impermeable horizon can be used to determine the effectiveness of the barrier and piling interlock (ball/socket) damage.

b. Applications.

(1) As a remedial action at a hazardous waste site, sheet piling cutoff walls can be used to contain contaminated ground water. Piling driven to an impermeable layer can retain an existing contaminant(s) that may be released during cleanup actions.

(2) If ground-water flow rates and volume moving toward a hazardous waste site are sufficient to potentially transport a contaminant plume or impede site cleanup operations, a piling barrier can be used to divert the ground-water flow.

(3) Installation of sheet pilings at a hazardous waste site may present special problems related to buried tanks or drums that may be ruptured, unless care is taken to investigate the proposed piling alignment with magnetometers or other metal-locating devices. Drums at depth may not be detected and pose special problems.

c. Design and Construction.

(1) Maximum effective depth is considered to be 14.9 m (49 feet). Although under ideal conditions, pile sections have been driven up to depths of 29.9 m (98 feet).

(2) Steel sheet piling is most frequently used. Concrete and wood have also been used. Concrete is expensive but is attractive when exceptional strength is required, and, although less expensive, wood is relatively ineffective as a water barrier.

(3) Sheet piles are typically used in soils that are loosely packed, and predominantly sand and gravel in nature. A penetration resistance of 13 to 33 blows/m (4 to 10 blows/foot) for medium- to fine-grained sand is recommended. Cobbles and boulders can hinder pile placement.

(4) Piling lifetime depends on waste characteristics and pile material. For steel piles pH is of particular importance. A pile life up to 40 years (depending on other leachate characteristics) can be expected where pH ranges between 5.8 and 7.8. A pH as low as 2.3 can shorten the lifetime to 7 years or less.

d. Advantages and Disadvantages.

(1) Sheet pilings require no excavation. Thus, the construction is relatively economical. In most cases, no maintenance is required. The disadvantages of sheet pilings are the lack of an effective seal between pilings and problems related to piling corrosion.

(2) At hazardous waste sites, corrosion of sheet pilings can be a severe problem. Many sites contain mineral acids that react readily with iron. Standard cathodic protection may not be effective if local concentrations of acid materials are present. Any reaction of metal with acid can produce hydrogen gas that may diffuse from the soil and create a fire or explosion hazard at the surface.

3-19. Membranes and Synthetic Sheet Curtains. Membranes and other synthetic materials have been used extensively as pond and lagoon liners. The impervious nature of the liner and its general resistance to corrosive chemicals have been proven to exceed the qualities typical of clay liner material used in landfills. The key factor in the use of membrane liners is to produce an effective seal between adjacent sheets of membrane.

a. Description. Synthetic membrane materials (PVC, butyl rubber, polyethylene) may be used in a manner similar to clay or sheet pile cutoff walls. The membrane can be inserted in a slit or a V-shaped trench to facilitate anchoring at the top of the trench. Membrane liners require some special handling for effective use. Membrane materials are usually not laid with any stress on the membrane. All seams are heat- or solvent-welded using manufacturer-approved techniques to ensure the seams are as strong as the material itself.

b. Applications. Membrane curtains can be used in applications similar to grout curtains and sheet piling. The membrane can be placed in a trench surrounding or upgradient (ground water) from the specific site, thereby enclosing the contaminant or diverting the ground-water flow. Placing a membrane liner in a slurry trench application has also been tried on a limited basis.

c. Compatibility. Compatibility of the membrane material with contaminated ground water or soil should be considered before emplacement of the membrane.

d. Design and Construction. Emplacement of the liner in conventional style requires a trench of sufficient size and slope that crews can lay the liner and transverse the liner with sealing equipment. The trench needs to be excavated to an impervious zone wherein the membrane is keyed in and sealed to prevent leakage at the membrane bottom. In conditions of contaminated, unstable, or saturated soils, special safety and construction practices must be established. Lowering a prepared liner into a narrow vertical trench is not feasible. The narrow trench in most cases will not be able to remain open without caving debris interfering with keying in conditions. Suspending the lines may cause stretching or tearing.

e. Advantages and Disadvantages.

(1) The membrane provides an effective barrier if it can be emplaced without puncture or imperfect sealing. Sealing is a difficult process that requires material handling and manipulation not afforded by trench emplacement. Keying the membrane adequately to the impervious layer is also difficult. The key zone must be disturbed and membrane material may not be conducive to adhering to concrete or other sealing material.

(2) Installation of liners is also restricted to climatic conditions. Liner membranes generally should not be installed at temperatures colder than about 45 °F. Soil temperature as well as atmospheric temperatures affect the flexibility as well as sealing character of the membrane. Adverse moisture conditions also may inhibit successful sealing of seams.

3-20. Combination Barrier/Pumping Systems. Barrier and pumping systems can be used in combination to ensure containment of contaminated ground water. When used in combination, the general approach is to use the barrier system to minimize the quantity of ground water that must be pumped and treated. The most common application of a combination barrier/pumping system is the use of a circumferential slurry wall, keyed into an underlying aquiclude, combined with an interior pumping system to maintain an inward hydraulic gradient. Design criteria are similar to those previously discussed for the individual systems.

3-21. Subsurface Drains and Drainage Ditches.

a. Background.

(1) Subsurface French drains are trenches filled with gravel that are used to manage surface or ground-water flows in shallow subsurface materials. At most hazardous waste sites, standard French drains are of limited use because close control of ground-water flow is required, and care must be exercised in preventing contaminated water from reaching lower aquifers.

(2) Well-designed underdrains that can intercept ground water flowing into a waste site have been helpful in reducing the water treatment problem where extraction systems are employed. Where the water table is relatively shallow (30 feet below the surface or less), a waste site can be isolated by trenching down into the water table and introducing a barrier and a vertical permeable layer with a drain at the bottom. This system acts to intercept small springs or seepage that may enter a buried waste pit. By diverting the ground water before it enters the site, the growth of the pollution plume exiting the site is reduced without pumping.

(3) When applicable, the barrier/underdrain system is a permanent low-cost remedial option. It requires small maintenance efforts to ensure the drains are clear. The intercepted ground water is usually tested periodically to ensure that no pollutant is discharged. The only disadvantages observed with this system relate to possible movement of contaminant through the ground-water barrier and into the drains. If this occurs, all of the discharge from the underdrains may require treatment before discharge. This

problem can be minimized by having the system built in unconnected segments with separate outfalls.

b. Applications.

(1) Subsurface drains can be used to intercept leachate or infiltrating water in any clay or silty clay soil where the permeability is not adequate to maintain sufficient flow and at sites where the leachate is not too viscous or gummy to prevent flow to the drains. Other conditions, such as a deep frost zone, may also restrict the use of underdrains in certain soils.

(2) Drainage ditches can be an integral part of a leachate collection system in that they may be used as collectors for surface water runoff, collectors leading from subsurface drains, or as interceptor drains.

(3) Surface drainage may be essential for flat or gently rolling landfills underlain by impermeable soils where subsurface drainage may be impractical or uneconomical.

(4) Open ditches may be used as interceptor drains to collect lateral surface seepage, thus preventing it from percolating into ground water or flowing laterally to an area that should be protected. The choice between using an open drain or subsurface drain depends upon the slope of the flow. For steep slopes, open drains are generally more desirable. An open ditch may be used in certain circumstances to intercept subsurface collectors and carry the leachate to its ultimate disposal.

(5) Drains or trenches may be useful in collecting contaminants floating on the ground-water surface. Where the ground water is shallow, and the slope adequate, drains may be more economical and effective than extraction wells.

c. Design and Construction Considerations.

(1) Subsurface drains.

(a) Subsurface leachate collection systems (Figure 3-22) have been proposed or constructed at several existing landfills. The drainage systems are generally constructed by excavating a trench and laying tile or pipe sections end to end in strings along the bottom. The trench is then backfilled with gravel or other envelope material to a designated thickness; the rest of the trench is then backfilled with soil. Often the gravel is lapped with geotextile fabric to prevent fine soil from entering the gravel and clogging the drain. The front view of a subsurface leachate collection system is illustrated in Figure 3-23.

(b) In some instances, gravel-packed wet wells may be used. Wells are constructed similarly to trenches.

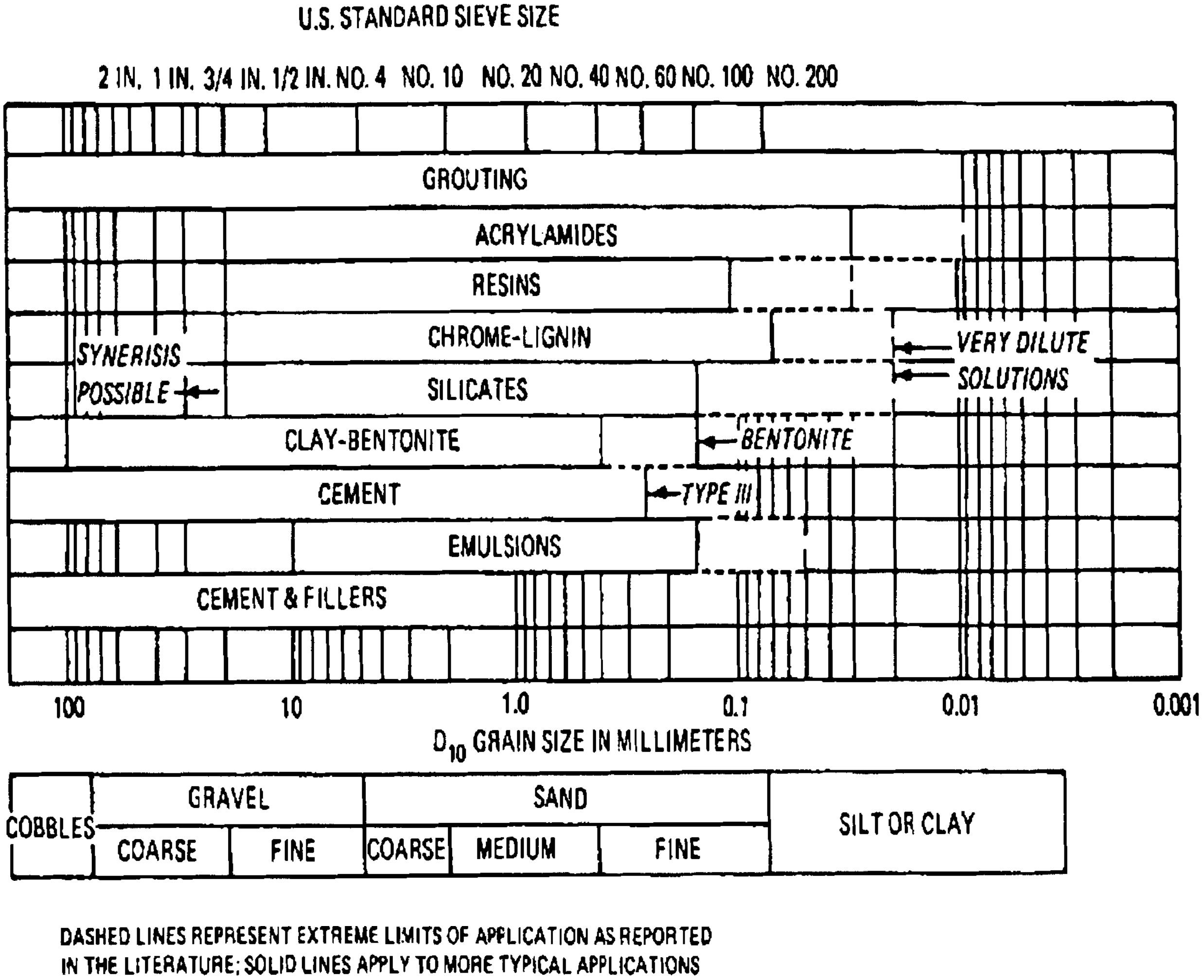


Figure 3-22. Subsurface Leachate Collection (Source: EPA 1979)

(c) An impermeable liner may be required on the downgradient end of the subsurface drain to prevent flow-through of intercepted and contaminated ground water if the surrounding materials have a moderate to high permeability.

(d) The major design problem for subsurface drains is to determine the optimum spacing, depth, and hydraulic capacity. Determination of these criteria is usually based on practical experience, experimental data, and calculations using drainage formula. Spacing between drain lines and wet wells depends upon the depth of the drain below the surface, the hydraulic conductivity of the soil, the amount of subsoil to be drained, and the potential for constructing underdrains beneath the landfill. Orientation of the trenches perpendicular to the flow lines would make spacing irrelevant, provided the trenches capture the flow at all required depths.

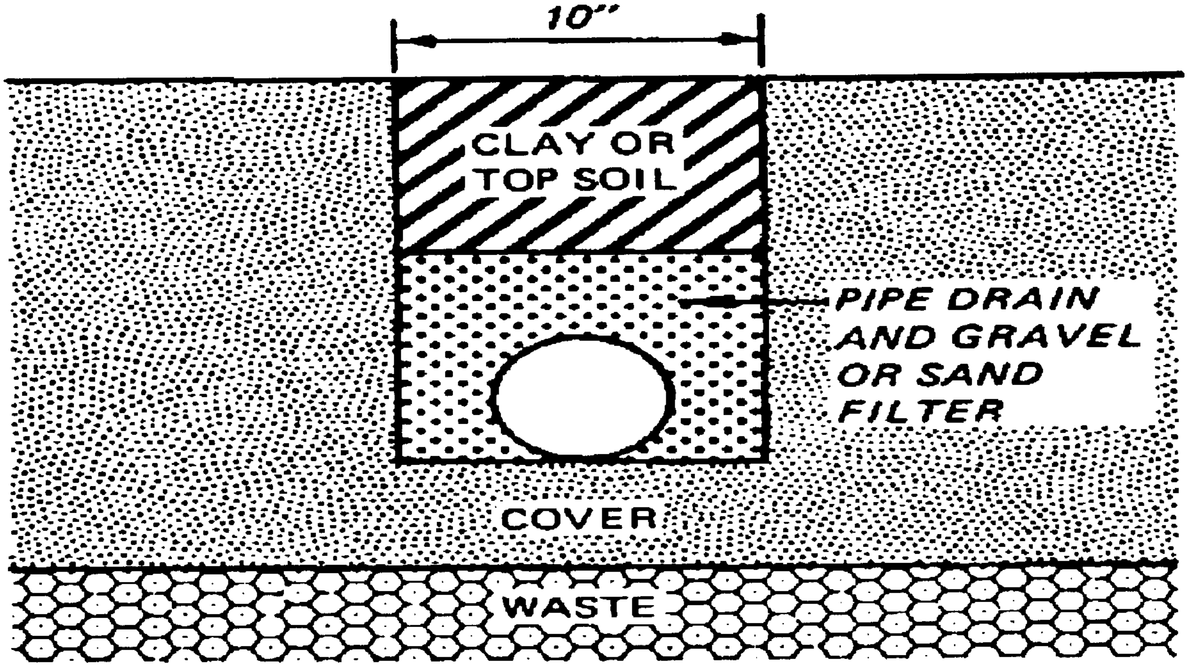


Figure 3-23. Typical Design Plan for Leachate Collection System

(e) Design equations that have been developed for flow to a drainage pipe indicate that a greater depth allows for wider spacing. These formulae are considered in relation to spacing. The simplest formula for estimating drain spacing assumes homogeneous soils and one-dimensional flow. Drain spacing can be estimated from Hooghoudt*s formula as follows:

$$S = \frac{4K}{Q}\left[(D + H)^2 - (D + h)^2\right] \qquad (3\text{-}1)$$

where

S = drain spacing, m (feet)

k = hydraulic conductivity, m/day (feet/day)

Q = design flow to the drain, m^3/day/m of ditch (cubic feet per day per foot

D = depth of flow layer beneath the drains, m (feet)

H = height of ground-water table above the plane through the drains and midway between two drains, m (feet)

h = height of water level in the drain, m (feet)

(f) The cone of depression observed around a well becomes a trough along the line of the drain. The spacing of the drains must be such that the water table at its highest point between drains intercepts all leachate-generating wastes, and does not interfere with plant growth or zone of aeration, if these factors play a part in proper operation of the fill.

(g) In actual practice, spacing of underdrains may be restricted by the boundaries of waste in such a way that the composite cones of depression of the drains do not completely overlap and some leachate escapes the collection system. This may occur where ideal spacing requires that underdrains be constructed beneath a waste site. Since the drain spacing is influenced by depth and hydraulic conductivity, it may be possible to increase spacing and still intercept all leachate by increasing drain depth and by adjusting envelope thickness to increase hydraulic conductivity so that underdrains beneath the site are not necessary.

(h) Horizontal drilling is now available without the need to jack or drill from a pit. This drilling technique allows drilling to start from the surface (at an oblique angle) and then turn horizontal at a certain depth. Though limited to depths of greater than about 6.1 m (20 feet), this technology shows promise for placing drains under landfills, lagoons, and tanks.

(i) Minimum grade or slope is determined on the basis of site conditions and size of the drains. Some designers wish to specify a minimum velocity rather than a minimum grade. It is generally desirable to have a slight slope in order to obtain a velocity sufficient to clean the drain during discharge and to speed up emptying of a drain after a discharge period. Slopes of about 0.1 percent can be obtained with present trench digging equipment accurate to within 1 centimeter of the prescribed depth.

(j) Drains have a relatively small area of inflow, causing an entrance resistance. Failures of tube drains are often due to the high resistance of approach of the envelope material and soil; the type of tube is usually less critical. Application of the proper envelope material in sufficient quantities can significantly reduce the effect of resistance. The most commonly used envelope materials include sand and fine gravel, and to a lesser extent straw, woodchips, and fiberglass. Recommendations for drain envelope thickness have been made by various agencies. The Bureau of Reclamation recommends a minimum thickness of 10 centimeters around the pipe, and the Soil Conservation Service recommends a minimum of 8 centimeters for agricultural drains. In actual practice, much thicker envelopes may be used to increase hydraulic conductivity. An 203 mm (8-inch-diameter) perforated pipe used for leachate collection at Love Canal is surrounded with about 0.61 m (2 feet) of gravel.

(k) After the trench is backfilled with the appropriate thickness of envelope material, it may be desirable to wrap the gravel with a fabric to prevent clogging of the gravel and drains with soil. One such available material is Typar, a strongly woven fabric that allows liquids to pass through but prevents soil from getting into the pipeline.

(1) The design and construction of leachate collection systems can be exemplified by the Love Canal (Figure 3-24). The heart of the collection system at Love Canal is a series of drains with 152 to 203 mm (6- to 8-inch-diameter) perforated, vitrified clay pipe backfilled with about 2 feet of gravel envelope. The ditches run roughly parallel along the north and south borders of the canal, as shown in Figure 3-24. The trenches are approximately 3.7 m (12 feet) below grade, dropping to a maximum of 4.6 m (15 feet). With a gradient of 0.5 percent, they empty leachate into precast concrete wet wells. Leachate is pumped from wet wells by vertical submersible pumps to an 203 mm (8-inch-diameter) gravity main, from which it descends into concrete holding tanks. Drains of different elevations are connected by manholes. To hasten dewatering from the canal, lateral trenches have also been dug between the canal boundaries and the main drainage system.

(2) Drainage ditches.

(a) Open ditches are on the order of 1.8 to 3.7 m (6 to 12 feet) deep. When they are connected to subsurface drains, they must be deep enough to intercept the underdrains.

(b) The water level in a ditch is determined by the purpose the ditch has to serve. Surface drains require sufficient freeboard when running at full capacity. The flow velocity should be kept within certain limits in view of scouring of the bed and side slopes and of sediment deposition. Important factors governing the desired flow velocity are soil type, type of channel,

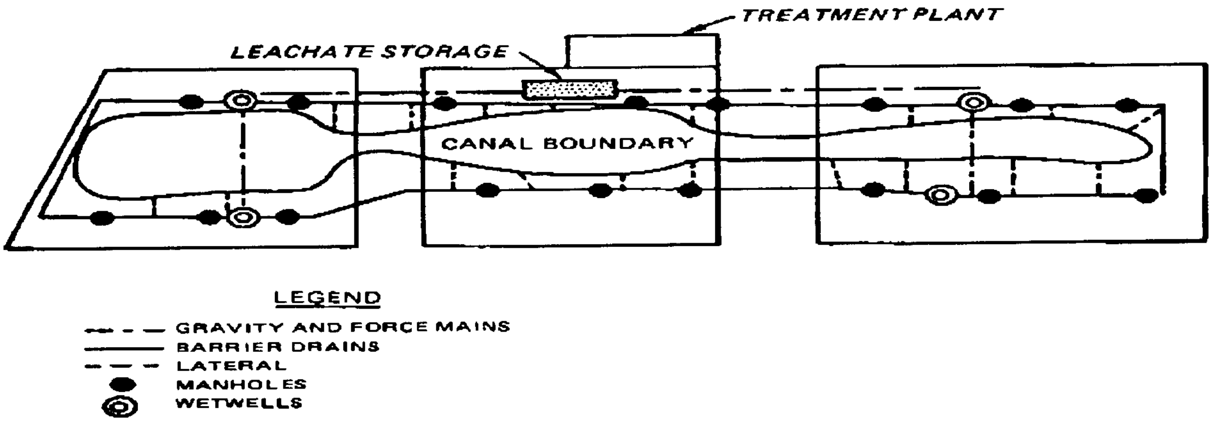


Figure 3-24. Leachate Collection System for Love Canal, Transverse View (Source: Glaubinger et al. 1979)

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well roughness, and sediment load. The size of the ditch necessary to carry the estimated quantity of water can be determined from the Manning velocity equation and is dependent upon the slope, depth, and shape of its cross section.

(c) The selection of side slopes is based on stability of soil and on the hazard of scour, taking into account possible ground-water pressures and vegetative cover. The stability of side slopes may be improved by tamping or rolling. Trapezoidal cross sections are generally most efficient. In fine-grained soils such as heavy clays, 1/2 to 1 slopes (0.15 to 0.3 m (0.5 foot to 1 foot vertical)) and 1-1/2 to 1 are common. In coarser textured soils, 1 to 1 or 2 to 1 may be advisable.

(d) Ditch bottoms at junctions should be at the same elevation to avoid drops that may cause scour. Right-angle junctions encourage local scour of the bank opposite the tributary ditch, and the smaller ditch should be designed to enter the larger at an angle of about 30 degrees. The scour will also occur at sharp changes in ditch alignment, so long radius curves should be used where change is necessary.

(e) An open ditch can be kept in efficient working condition by careful maintenance. A drain allowed to become obstructed by brush, weed growth, or sediment can no longer be efficient; it should be cleaned to its original depth when efficiency is curtailed.

d. Advantages and Disadvantages. The advantages and disadvantages of subsurface drains and drainage ditches are summarized below:

Advantages	Disadvantages
Subsurface Drains	
Operation costs are relatively cheap since flow to underdrains is by gravity	Not well suited to poorly permeable soils
Provides a means of collecting leachate without the use of impervious liners	In most instances it will not be feasible to situate underdrains beneath the site
Considerable flexibility is available for design of underdrains; spacing can be altered to some extent by adjusting depth or modifying envelope material	System requires continuous and careful monitoring to ensure adequate leachate collection
Systems fairly reliable, providing there is continuous monitoring	

(Continued)

Advantages	Disadvantages
Drainage Ditches	
Low construction and operating cost	Requires extensive maintenance to maintain operating efficiency
Useful for intercepting landfill side seepage and runoff	Generally not suited for deep disposal sites or impoundments
Useful for collecting leachate in poorly permeable soils where subsurface drains cannot be used	May interfere with use of land
Large welted perimeter allows for high rates of flow	May introduce need for additional safety/security measures

Section III. Surface Water Controls

3-22. Surface Water Diversion.

a. Background.

(1) A major consideration at any hazardous waste site is water management. Minimizing the amount of water moving through a site reduces the spread of potentially toxic materials and the requirements to treat leachate or drainage from the area. Many sites are in low-lying areas adjacent to natural watercourses. In some instances, it has been necessary to divert drainage around a landfill or reinforce or dike streambanks to prevent the waste from being washed into the stream and contaminating the water downstream. Run-on is generally controlled using ditching, channelization, or construction of berms and dikes.

(2) Run-on diversion can be implemented at a hazardous waste site by using many of the same remedies used to control run-on at a construction site. This remedial activity is applicable when it can be demonstrated that water is entering the disposal site from adjacent slopes or that streams moving across the site are contributing water to the site or washing wastes out of the site.

(3) Where minimizing ground-water infiltration is important to prevent the water table under the site from rising, lined trenches should be considered in drainage design. Lined trenches typically are constructed of concrete, shotcrete, asphaltic concrete, metal culvert (half sections), or synthetic membrane materials (polyvinylchloride or polyethylene).

(4) The data requirements for design of drainage systems on or around a hazardous waste system are similar to those required for construction drainage, including area to be drained, type of drain proposed, grade of the proposed drainway, and maximum capacity based on rainfall and snowmelt records. Additional considerations would be the lifetime of the system. Some systems will be required only until wastes can be excavated and transported;