30 Subsurface Drainage Design and Installation

Subsurface drainage systems remove excess groundwater below the ground surface. Perforated plastic drain tubes are placed between 1 and 2 m below the soil surface. The technique was originally called tile drainage because tile cylinders were laid end to end in a trench. Spacing and depth of drain tubes as well as lateral hydraulic conductivity of soil layers determine the rate of water removal from the field. Lateral hydraulic conductivity is generally measured with auger hole tests. Drainage can impact downstream water quality because it changes the timing of water and chemical leaching through the soil. Drainage planning and design require extensive analysis of hydrology, soil structure and texture, soil chemistry, crop rotations, field equipment, topography, waterways, and construction materials. The sizing of drainage pipes is based on the land slope and expected flow rate to pipes. Pipe layout and slope is a function of land slope and discharge location in the field. If the discharge waterway is higher than the drain outlet, then a sump and pump must be installed. Gravel envelopes or fabrics protect drain tubes from sedimentation.

Environmental Considerations

Drainage has an impact on the environment and is thus under increasing scrutiny by regulators and environmentalists.

The impact of the proposed drainage system on the community, landowner, neighbors, agricultural developments, natural resource conservation, biodiversity, wildlife habitat, water quality, economics, health, and social considerations are all be considered in the decision making and regulatory processes (NRCS Part 650 EFH 14, 2001).

Drainage water normally carries a high nitrate load because nitrate concentration is normally high in agricultural soils. However, the issue of whether subsurface drainage systems have a positive or negative effect on water pollution is a subject of debate. Fogiel and Belcher (1991) listed the following positive environmental impacts of subsurface drainage (EFH 14): reduced overland flow and erosion, reduced sediment transport and attached phosphorous and potassium off the farm, improved surface nutrient management, improved ability to monitor percolating flow, and reduction of nonpoint source pollution. The reason that erosion is reduced is that the soil generally has less water and infiltration is increased. The major disadvantage is increased discharge of nutrients and other chemicals in the soil to surface water bodies. For example, high nutrients in Mississippi River flow have caused eutrophication and dead zones in huge areas of the Gulf of Mexico. Much of this pollution comes from drainage water that is loaded with nitrate and other nutrients and agricultural chemicals from farms. Exacerbating this problem, many natural wetlands that used to flank the Mississippi River and purify the water before it entered the river have been removed by agricultural and urban development.

The NRCS recommends several techniques for the reduction of the impact of drained water from farmland on the environment. Install on-farm detention ponds or wetlands that reduce nitrate concentration in drainage water before it leaves the farm, retrofit drainage systems to reduce drainage during critical periods and manage the water table such that the nutrient load from subsurface drainage systems is reduced. Implement cropping systems that reduce nitrate losses. Improve fertilizer and animal manure management and timing.

Drainage System Planning

The first step in designing a drainage system is a general reconnaissance survey: needed items include maps, soil survey reports, a hand level, and a soil auger. Reconnaissance should begin with a walkover through the site soon after a heavy rainfall event in order to find drainage problems. Local wells and a few borings should be made in order to determine the depth to the water table. Wetlands areas

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should be delineated. Soils or vegetation types can indicate the presence of wetlands. Pacing off distances and a hand level can be used to determine the approximate slope of waterways and drainage paths. Surveying equipment can be used in locations where higher survey accuracy is needed. The NRCS (EFH 14, 2001) lists the following features that should be included in a reconnaissance survey.

- Location and extent of any wetlands.
- The areas in which crops show damage, as pointed out by the farmer, indicated by the aerial photograph, or noted in personal observations.
- Personal observations of unique landscape features, ecologically significant areas, land use patterns, operation (land management) aspects, and site visibility.
- Topography and size of the watershed area.
- Size, extent, and ownership of the area being considered for drainage.
- Location of the drainage outlet and its condition.
- Location, condition, and approximate size of existing waterways.
- Presence of cultural resources.
- Potential impacts outside the area being evaluated.
- General character of soil throughout the area needing drainage, including land capability, land use, crops and yields, and salinity or sodicity.
- High-water marks or damaging floods and dates of floods.
- Utilities, such as pipelines, roads, culverts, bridges, and irrigation facilities and their possible effect on the drainage system (see NEM part 503).
- Sources of excess water from upslope land or stream channel overflow and possible disposal areas and control methods.
- Condition of areas contributing outside water and possible treatment needed in these areas to reduce runoff or erosion.
- Condition of any existing drainage system and reasons for failure or inadequacy. Old subsurface drainage systems that have failed because of broken or collapsed sections may well be the cause of a wet area.
- Estimate of surveys needed.
- Type and availability of construction equipment.
- Feasibility.

Existing drainage pipelines are often difficult to find. Infrared remote sensing can detect the presence of existing subsurface drainage pipes by detecting the temperature of the soil. In general, the soil is warmer over subsurface drainage pipes. In addition to infrared maps, aerial photographs can show the natural drainage ways in a region.

Topographic information is important since flow is driven by gravity. The USBR recommends a scale of 1 in = 4,000 ft (2.54 cm = 1,200 m) topographic maps for reconnaissance studies and 1 in = 400 ft (2.54 cm = 120 m) for detailed design of drainage systems. A 2 m (5 ft) contour interval is recommended for preliminary studies, and a 0.6 m (2 ft) contour interval is recommended for drainage design. For large, nearly level areas, a 0.3 m (1 ft) contour interval is required. If land is relatively flat such as is common in surface irrigated agriculture, a topographic map is not adequate for planning drainage systems, and the path of the drain system must be surveyed. The NRCS recommends collecting survey information at 30–90 m (100–300 ft) intervals on flat land. The profile of existing ditch cross sections, details of utilities, and construction along ditches should also be provided to the drainage system designer.

The elevation of the drainage outlet can constrains the maximum slope of the drain pipe. The end of the drain can be no lower than the minimum elevation of the drainage outlet. If the potential drain slope in a field is unacceptable, then a sump may be required. Minimum drain depth at the upper end of the drain can be restricted by government regulations, the drainage design depth (Chap. 10), or by tillage practices. The combination of minimum depth of installation and a shallow outlet can severely restrict the slope on drainage lines. If drains are installed at a nearly level grade, then there is a possibility of air locks and sedimentation in the drainage pipeline. Dips fill with mud, and rises can have airlocks and prevent drainage. The USBR recommends that the minimum grade (slope) on a drain pipe should be 0.1 m/100 m. This is an extremely shallow grade and is susceptible to installation errors that may lead to air locks and blockages by siltation. In this case, extreme care must be taken during drainage installation to make sure that drains are installed to grade. If not installed to grade, causing the drain not flow, then the drains will need to be reinstalled at the expense of the installation company. This situation usually does not result in happy farmers, engineers, or contractors.

Laser levelers on modern trenching and drain pulling equipment provide elevation and direction control during drain installation. If laser equipment is not used, then surveyors mark elevations on stakes along the drain trench every 50 ft (15 m). A string is then tied at the marked elevations. Then a dogleg (upside down L) is held by a worker against the string and the bottom of the trench. This worker tells the trencher operator to raise or lower the depth of the trenching equipment as the trench is excavated.

Soils Analysis

Extensive soil hydraulic conductivity tests must be connected on the farm. A typical practice is to collect soil cores to 2 m depth every hectare. These can be used to develop hydraulic conductivity maps and soil profile maps for drainage design. Then, the methods presented in Chap. 31 can be used to determine the optimal drain spacing and depth.

A shallow hardpan or clay layer can influence drainage system design. If a drain is placed below an impermeable layer, then water may not be able to reach the drain.

Artesian water is a potential problem. If an aquifer is fed from below at sufficient pressure, then the capacity of the drainage system will need to be increased in order to drain the excess water from the field.

Pipe Network Layout and Elevations

Once the drain spacing is determined, a map of the drainage pipe layout can be drawn. Drains should follow the natural slope of the land if the field is relatively flat. A herringbone pattern or other geometries may be preferable depending on land slope and the outlet location. Elevation calculations and installation should begin at the outlet since that is the common point at which all branches meet.

Pipe Diameter

Drainage systems are designed to carry water from the field during the period of peak drainage. The design flow rate is often referred to as the drainage coefficient. The NRCS recommends that drain pipes should never flow under pressure because water flowing out of the pipe disturbs the envelope or soil around the drain. Drain pipes must be large enough to carry the peak flow during a storm or irrigation without becoming pressurized. The USBR bases the drainage coefficient on the rate that water flow to the drain and uses the following equation to calculate peak drainage requirement (design flow rate) for drains above an impermeable layer.

$$q_d = \frac{2\pi K m_0 D}{86,400L} \tag{30.1}$$

where

q_d = discharge from two sides per unit length of drain, m^3/sec/m,
m_0 = maximum height of water table above drain invert, m,
K = weighted average hydraulic conductivity of soil profile between maximum water table elevation, y_0, and impermeable layer.
D = average flow depth, d + $y_0/2$, m,
d = distance from drain to barrier, m,
L = drain spacing, m.

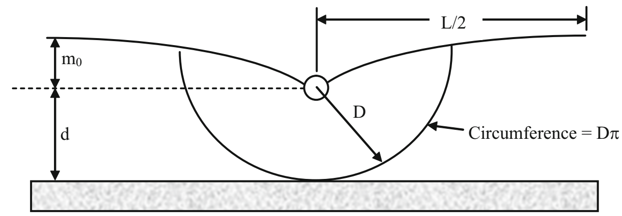


Fig. 30.1 Geometry for derivation of drainage coefficient

Equation 30.1 is derived from Darcy's law based on the geometry of Fig. 30.1 where the cross-sectional area of flow is Dπ, the energy difference is m_0, and the length is L/2.

$$q = KA\frac{\Delta H}{\Delta x} = KD\pi\frac{m_0}{L/2} \tag{30.2}$$

where

m_0 = energy difference, m,
L = distance between drains, m,
A = cross-sectional area of flow, Dπ, with D as a radius.

$$q_d = KD\pi\frac{m_o}{½} = \frac{2\pi K m_o D}{L} \tag{30.3}$$

Equation 30.3 is divided by 86,400 to convert flow rate from m^3/d/m to m^3/s/m.

$$q_d = \frac{2\pi K m_o D}{L}\left(\frac{m^3/m/\sec}{86,400\ m^3/m/day}\right) = \frac{2\pi K m_o D}{86,400\ L} \tag{30.4}$$

The drainage coefficient (Fig. 30.1 and Eq. 30.3) is not meant to represent the flow rate that occurs when the soil directly over the drain is saturated and water flows into the drain from above: In this case, the energy gradient is 1.0 rather than $m_0/(L/2)$.

The drainage coefficient can be expressed in units of mm/day by dividing by L, the distance between drains, and multiplying by 1,000 to convert from m/day to mm/day.

$$\begin{aligned} D_c &= \frac{q_d}{L} = \frac{2\pi K m_o D}{L^2}\left(\frac{1,000\ mm}{m}\right) \\ &= \frac{2,000\pi K m_o D}{L^2} = \left(\frac{mm}{day}\right) \end{aligned} \tag{30.5}$$

General drainage coefficients (Table 30.1) based on how quickly the soil must be dewatered have been developed by the NRCS (EFH 14, 2001) based on the constraint that surface depressions and the majority of the root zone should be drained within 24–48 hours after a storm.

Table 30.1 General drainage coefficients (Credit NRCS, EFH 14, 2001)

Soil	Field crops (grains, orchards, etc.)	Truck crops (vegetables)
Mineral	⅜ – ½ inch (8–12 mm)	½ – ¾ inch (12–18 mm)
Organic	½ – ¾ inch (12–18 mm)	¾ – 1½ inch (18–36 mm)

The USBR designs pipe drains that have no surface inlets to run full, and pipe drains that have surface inlets to run half full (larger pipe for fields with direct surface inlets to drains). Alternatively, the following adaption of the Manning equation calculates the minimum ID of corrugated plastic pipe drains with diameter less than 30 cm (Huffman et al. 2013) based on field area and drainage coefficient.

$$ID = 51.7(D_c{*}A{*}n)^{0.375}s^{-0.1875} \tag{30.6}$$

where

ID = inside drain diameter, mm,
D_c = drainage coefficient, mm/d,
A = drainage area, ha,
n = coefficient of roughness, 0.015 for corrugated plastic drain pipe,
s = drain slope, m/m.

Pipe flow rates as a function of drainage coefficient and drained area can be found in ASABE Standards. Pipe size as a function of flow rate, grade, and velocity is also found in ASABE Standards.

Example 30.1 Calculate the required diameter of a subsurface drain based on Eqs. 30.5 and 30.6 with the following parameters. Let Manning's n = 0.015.

Minimum depth to water table	0.48 m
Depth to impermeable layer	5 m
Drain depth:	2 m
Drain slope	s = 0.2 m/100 m
Hydraulic conductivity	K = 2.5 cm/hr
Drain spacing	L = 40 m
Length of drain pipe	L_d = 200 m
Maximum WT height above drains:	m_0 = 2 m − 0.48 m = 1.52 m
Distance from drains to impermeable layer	d = 5 m − 2 m = 3 m
Average depth of flow to drain	D = d + m_0/2 = 3 + 1.52/2 = 3.76 m
Hydraulic conductivity	K = 2.5 cm/hr = 0.6 m/day

Calculate drainage coefficient.

$$D_c = \frac{2{,}000\pi K m_o D}{L^2} = \frac{2{,}000\pi{*}0.6{*}1.52{*}3.76}{40^2}$$
$$= 13.5 \ mm/day$$

Calculate pipe diameter

$$ID = 51.7(D_c{*}A{*}n)^{0.375}s^{-0.1875}$$
$$= 51.7(13.5{*}200{*}40/10{,}000{*}0.015)^{0.375}{*}0.002^{-0.1875}$$
$$= 84 \ mm$$

The drain diameter, 84 mm, is between 3 and 4 inches diameter. Round up to the next largest manufactured size, 4 inches (102 mm ID and 114.5 mm OD).

Filters (Envelopes)

In many soils, a filter is required around the drain in order to prevent sedimentation of the drain by the base soil. Soils with low hydraulic conductivity do not tend to have problems with soil washing into the drain because the water does not flow fast enough to carry soil particles with it. In general, all soils with low clay content are considered problem soils with respect to sedimentation of drainage pipes (NRCS, EFH 14, 2001).

There are two primary types of envelope materials: (1) geotextile, and (2) sand and gravel. Organic materials, such as wood chips can be packed around the drains, but they may not be durable. In addition, organic materials may lead to slime formation in drains in some soils (NRCS, EFH 14, 2001). The soil textural triangle can be divided into sections that delineate base soils that need no filter, textile filters, or sand and gravel filters (Fig. 30.2).

Pulled drains can only use textile filters that are added to the drain during the manufacturing process. The filter is a sock around the drain tube that is pulled into the ground with the drain tube. The geotextile fabric may be constructed from polyester, nylon, polypropylene, polyamide, or polystyrene. These fabrics vary in mesh size, fiber size, and weight: no single fabric is suitable for all soils. The NRCS recommends that the flow capacity of the sock be 10 times that of the soil in order to avoid restricting flow to drain perforations. The recommended permittivity is 1 $m^3/(s * m^2 * m)$, which means one cubic meter per second should flow through a square m of fabric given a 1 m head differential from one side of the fabric to the other.

As large soil particles are stopped by the geotextile filter, they in turn become a filter and stop smaller particles from washing into the drain. In order to catch the larger particles, the following criteria is used by the NRCS. If less than 50 % of the soil particles pass the Number 200 sieve, then the apparent opening size (AOS) of the fabric should be the same size as the number 30 sieve (0.59 mm). On the other hand, if more than 50 % of the soil particles pass the number 200 sieve, then the apparent opening size of the fabric should be smaller (Number 50 sieve, 0.297 mm). For silty soils, sand and gravel envelopes are recommended (Fig. 30.2).

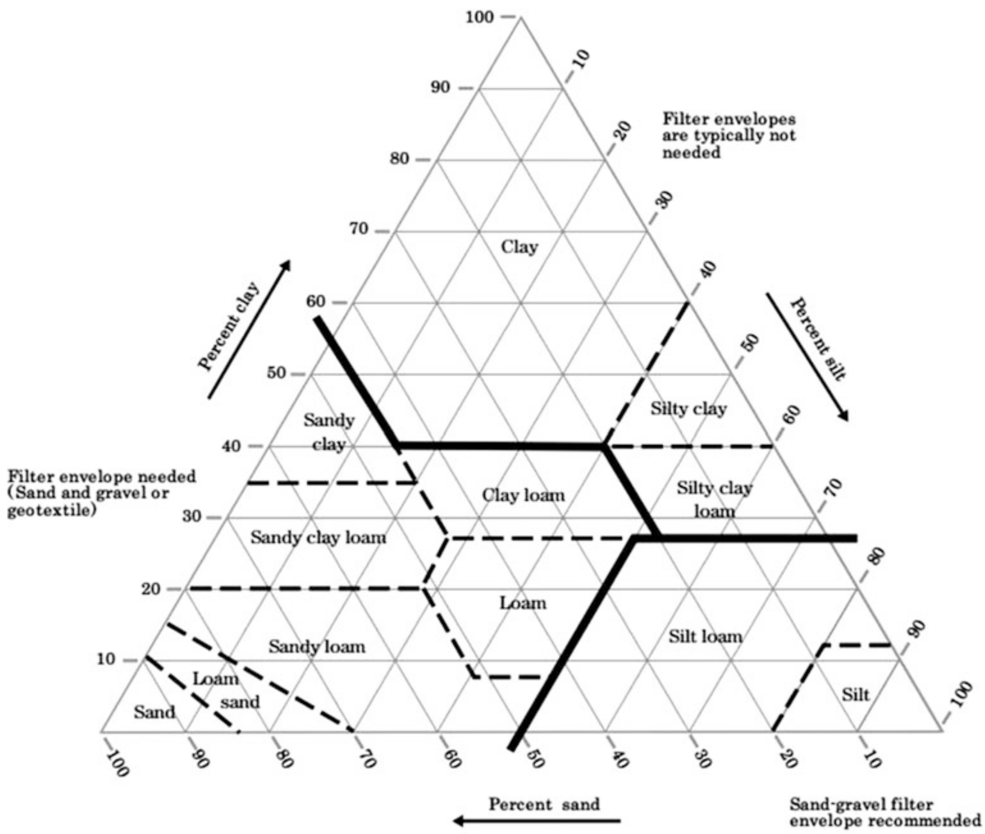


Fig. 30.2 Recommended filters for different soil textures (Credit NRCS, Part 650 Engineering Field Handbook, Chap. 14, 2001)

It is generally recommended that trenched drains have a sand and gravel filter envelope on all sides. The USBR Drainage Manual (1993) recommends that gravel envelopes should be designed with a 10 cm distance from the pipe to the surrounding soil; however, the NRCS recommends a minimum 7.5 cm (3 in) distance. Thus, a 4 in (10 cm) drain would be laid in a 25–30 cm width trench. Consult NRCS or USBR drainage manuals for further information on sand and gravel filter geometry. Sand and gravel filters increase hydraulic conductivity around the drain as well as prevent soil from washing into the drain. The envelope should be well graded, free of vegetable matter, clay and other deleterious substances that could change the hydraulic conductivity of the envelope: a well-graded envelope material has particles in all specified size ranges. Larger particles help increase conductivity and support the drain while smaller particles help reduce the movement of fines from the base material (original soil surrounding the trench) into the envelope material. Proper gradation usually requires machine sorting.

Velocity at the interface between the base material and the envelope must be low enough to prevent fine textured material from moving into the envelope. In order to meet the requirements for conductivity and filtration, there must an even distribution (gradual size gradation) of particle sizes within the envelope. If there is too much size difference between each particle size gradation in a filter, then the filter is called a gap graded filter. In this case, particle segregation may occur during placement (*NRCS NEH 633.2603*).

When sand and gravel filters are designed with the correct size gradation of particles, eroding soil is caught at the surface of the filter and these soil particles fill in developing cracks in the soil, causing subsequent flow to pass through soil pores (*NRCS NEH 633.2603*). This prevents the development of channeling or cracks in the soil and the resulting sedimentation of drains (*NRCS NEH 633.2603*). Envelope material requirements for silt-loam, sandy clay loam and loam base materials are more flexible than for fine sand and very fine sand because the finer textured soils (clays and loams) have a low velocity at the envelope – base material interface, and particles are not likely to be carried into the envelope.

The USBR recommends sampling with a soil auger every 180 m along trenches in order to characterize the base material. If the base material changes significantly along the trench system, then envelope gradation requirements should be changed.

The USBR uses two coefficients to assess envelope material gradation: coefficient of uniformity and coefficient of curvature. The coefficient of uniformity determines whether there is a sufficient range of sizes in the gravel or sand envelope material to prevent wash in of particles from the

Table 30.2 Gradation relationship between base material and diameters of envelope material

	Gradation limitations for envelope (diameter of particles, mm)										
	Lower limits, percent retained (i.e., $D_{10} \leftrightarrow 90$ %)						Upper limits, percent retained				
Base material, 40 % retained (diameter of particles, mm)	0	40	70	90	95	100	0	40	70	90	100
0.02–0.05 Silt	9.52	2.0	0.81	0.33	0.3	0.07	38.1	10.0	8.7	2.5	0.59
0.05–0.1 VFS	9.52	3.0	1.07	0.38	0.3	0.07	38.1	12.0	10.4	3.0	0.59
0.1–0.25 FS	9.52	4.0	1.30	0.40	0.3	0.07	38.1	15.0	13.1	3.8	0.59
0.25–1.0 Sand	9.52	5.0	1.45	0.42	0.3	0.07	38.1	20.0	17.3	5.0	0.59

base material. The coefficient of uniformity has two criteria: one for sand and another for gravel, where the minimum size of gravel (maximum size of sand) is 2 mm. The coefficient of curvature shows whether most of the change in size distribution occurs over a narrow range of sizes or gradually over the entire range. A coefficient of curvature between 1 and 3 reflects a relatively constant gradation of particle sizes.

Coefficient of uniformity (C_U): well graded if $C_U > 4$ for gravel and $C_U > 6$ for sand

$$C_U = D_{60}/D_{10} \tag{30.7}$$

Coefficient of curvature: between 1 and 3 for both gravel and sand

$$C_C = (D_{30})^2/(D_{10}*D_{60}). \tag{30.8}$$

where

D_x = Diameter (mm) where "x" is percent of particles smaller than the diameter.

For all envelopes, 100 % of the envelope material should pass the 38.1 mm sieve and 5 % or less should pass the 0.3 mm sieve. Based on experience and Eqs. 30.7 and 30.8, the USBR recommends the upper and lower limits of percent of particles that are smaller than the given sizes in Table 30.2.

For example, an envelope material in very fine sand (VFS) base material should have a sieve analysis with a gradation curve that lies between the upper and lower limits shown in Fig. 30.3. Each point on the curve is the percentage of material that is larger (is retained on the sieve) than the sieve. This percentage is the opposite of the D_x criterion $(100 - x)$. For example, at least 30 % of the material (D_{30}) should pass the 10.4 mm sieve, but no more than 30 % should pass the 1.07 mm sieve.

Example 30.2 Evaluate the C_C and C_U of the upper and lower gradation limits for very fine sand (VFS) base material in Fig. 30.3.

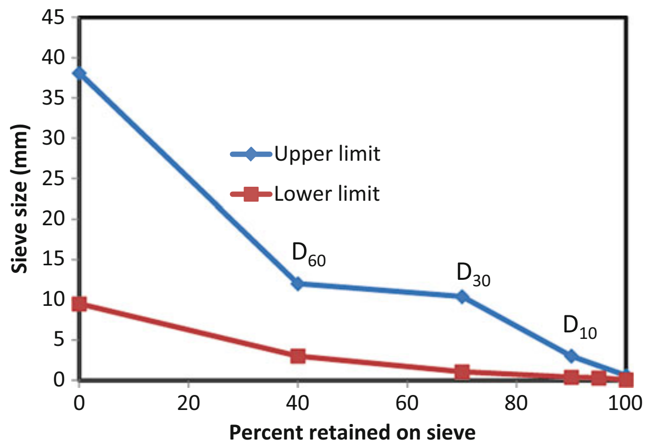


Fig. 30.3 Upper and lower gradation limits for very fine sand (VFS) base material

Upper Limit

$D_{60} = 12$ mm, $D_{30} = 10.4$ mm, $D_{10} = 3.0$ mm

$$C_u = \frac{D_{60}}{D_{10}} = \frac{12}{3} = 4 \quad C_c = \frac{(D_{30})^2}{D_{10}D_{60}} = \frac{10.4^2}{12*3} = 3$$

The minimum size of gravel is 2 mm; thus, almost all of the envelope material is gravel. The criterion for gravel gradation is that the C_u must be greater than 4, and the upper limit gradation C_u is exactly equal to 4. The coefficient of curvature is 3, the maximum acceptable level for both gravels and sands.

Lower Limit

$D_{60} = 3$ mm, $D_{30} = 1.07$ mm, $D_{10} = 0.38$ mm

$$C_u = \frac{D_{60}}{D_{10}} = \frac{3}{0.38} = 7.9 \quad C_c = \frac{(D_{30})^2}{D_{10}D_{60}} = \frac{1.07^2}{3*0.38} = 1$$

By definition, the larger size particles that are specified in the lower limit gradation are between the sizes of very coarse sand and very fine gravel. The criteria for sand gradation are that the C_u must be greater than six, and the lower limit gradation C_u is 7.9 – an acceptable value. The coefficient of

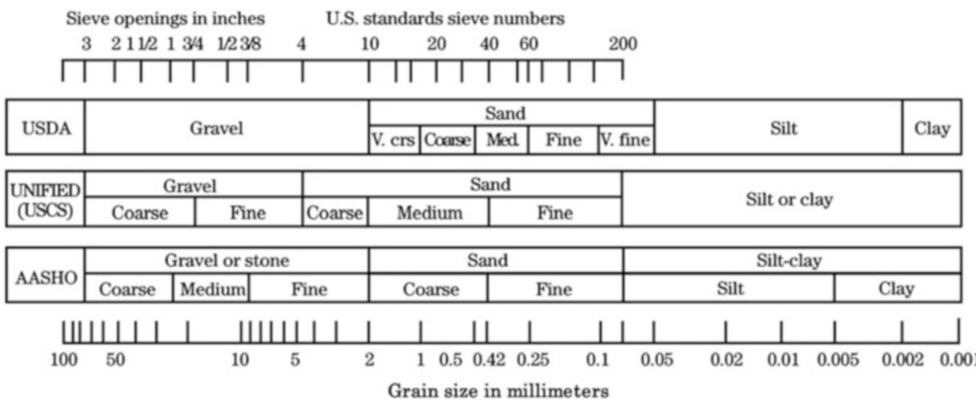


Fig. 30.4 Sieve sizes and associated particle grain diameters (Credit NRCS, Part 650 Engineering Field Handbook, Chap. 14, 2001)

curvature is 1.0, the minimum acceptable level for both gravels and sands.

Thus, both the coefficient of curvature and the coefficient of uniformity criteria are satisfied by the upper and lower limit curves on Fig. 30.3.

Envelope materials are evaluated with standard sieves. Standard sieve sizes as well as associated particle sizes are shown in Fig. 30.4.

The conductivity of the envelope material should be ten times greater than the hydraulic conductivity of the base material (USBR Drainage Manual) in order to not restrict the flow of water to drain openings; in general, if all particles in the envelope material are retained on the number 30 sieve (coarse sand), then the hydraulic conductivity of envelope should be adequate. In cases where it is suspected that the hydraulic conductivity is too low, the hydraulic conductivity of the material can be checked by filling a short piece of pipe with the envelope material and measuring the flow rate and energy difference between the two ends of the pipe. The procedure for this test is outlined in the USBR Drainage Manual.

The effectiveness of the envelope can be reduced by improper installation procedures. Care must be taken to avoid mixing the base material with the envelope during installation in saturated soil. If possible, the contractor should wait for a time of year when the water table is below the designed drain elevation. If this is impossible, then the soil may need to be dewatered before drainage installation if the base material is unstable. With trenchers that install pipe and backfill gravel in one operation, the risk of mixing base material with the envelope is less than in an open trench.

Based on conservation of energy, flow rate through the envelope material and into the drain is dependent in the energy difference between the outside of the envelope material and the interior of the drain and the envelope conductivity. The envelope dimensions (simplified as a circle) are shown in Fig. 30.5.

The average energy difference between the inside of the drain and the outside of the envelope for corrugated plastic drain pipe can be calculated with Eq. 30.9 (USBR), with the assumption that the water table intersects the upper surface of the envelope.

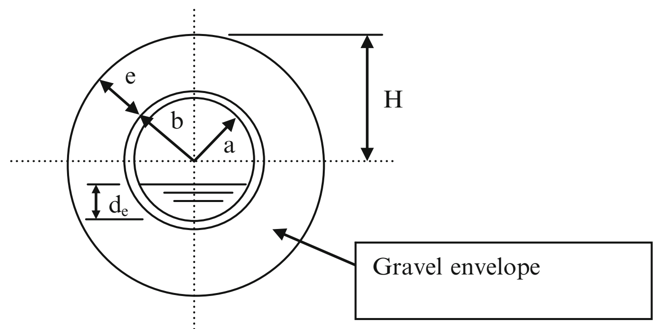


Fig. 30.5 Drainage envelope parameters

$$\overline{H} = H\left[1 - \frac{d_e}{160H}\left(22 + 29\frac{d_e}{a}\right)\right] \tag{30.9}$$

where

d_e = depth of flow in the drain, mm,
H = b + e (outside drain radius and width of envelope), mm,
a = inside drain radius, mm,
$\overline{H}$ = average energy difference between outside envelope and inside pipe, mm.

Calculation of the flow rate into the drain is then made with Eq. 30.10.

$$q_d = b\overline{H}K\phi \tag{30.10}$$

where

b = outside diameter of drain, m,
K = hydraulic conductivity of the envelope material, m/day,
q_d = flow rate into the drain, m^3/d/m,
ϕ = adjustment factor.

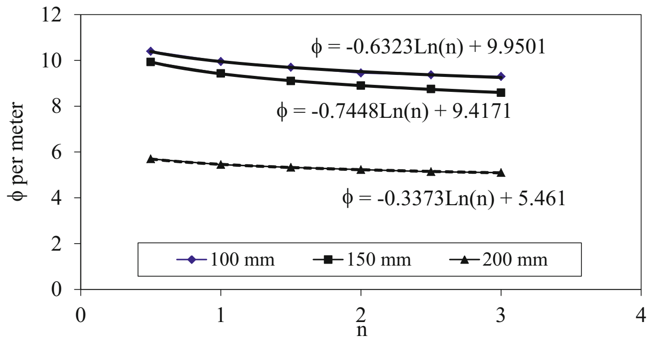


Fig. 30.6 n versus ϕ relationship

The term, ϕ, is found in Fig. 30.6 (Fig. 5.25 in the USBR drainage manual) for different sizes of drain pipe. Use of Fig. 30.6 requires the parameter n, which is equal to e/b.

$$n = e/b \tag{30.11}$$

If the drainage coefficient and the pipe diameter are already known based on drainage requirements as calculated above, then the only unknown parameters in Eqs. 30.9 and 30.10 are the width and conductivity of the envelope material.

Example 30.3 Calculate a minimum acceptable envelope width for Example 30.1 that will carry the required flow to the drain. The envelope material has a conductivity of 9.6 m/day, and the drain is running 3/4 full. The drainage coefficient is 13.5 mm/day. The outside pipe diameter is 114 .4 mm, and the internal diameter is 102 mm (4 inch pipe).

Required flow rate into the drain is the product of the drainage coefficient and the drain spacing.

$$q_d = D_c L = \left(\frac{13.5\ mm}{day}\right)\left(\frac{m}{1000\ mm}\right)(40\ m)$$
$$= 0.54\ m^3/day/m$$

Calculate a and b

$$a = 102/2 = 51\text{mm.}$$
$$b = 114.4/2 = 57.2\text{ mm}$$

Calculate d_e based on the assumption that the drain runs ¾ full.

$$d_e = 0.75{*}102\text{ mm} = 76.5\text{ mm}$$

Assume the envelope dimension, e, is 100 mm, in order to find initial n and ϕ values.

$$n = \frac{e}{b} = \frac{100\ mm}{57.2\ mm} = 1.75$$

$$\phi = -0.6323{*}\text{Ln}(n) + 9.9501$$
$$= -0.6323{*}\ \text{Ln}(1.75) + 9.9501 = 9.60$$

Calculate $\overline{H}$

$$\overline{H} = \frac{q_p}{bK\phi} = \frac{0.54}{0.0572{*}9.6{*}9.60} = 0.102\ m = 102\ mm$$

Calculate H (iterate to find answer)

$$H = \frac{\overline{H}}{\left[1 - \frac{d_e}{160H}\left(22 + 29\frac{d_e}{a}\right)\right]} = \frac{102}{\left[1 - \frac{76.5}{160H}\left(22 + 29\frac{76.5}{51}\right)\right]}$$
$$\Rightarrow 133\ mm$$

Calculate envelope dimension, e:

$$e = H - b = 133 - 57.2 = 76\text{ mm (3 inches).}$$

Example 30.4 Redo Example 30.3, but assume that envelope dimension, e, is 100 mm. Find minimum hydraulic conductivity of the envelope material. Assume that the water table intersects the top of the envelope material.

$$\overline{H} = H\left[1 - \frac{d_e}{160H}\left(22 + 29\frac{d_e}{a}\right)\right]$$
$$= 100\left[1 - \frac{76.5}{160{*}100}\left(22 + 29\frac{76.5}{51}\right)\right] = 69\ mm$$
$$K = \frac{q_p}{b\overline{H}\phi} = \frac{0.54}{0.0572{*}0.69{*}9.77} = 1.4\ m/day$$

The required hydraulic conductivity is six times less for the 100 mm width envelope material than for the 76 mm width envelope material. An economic decision may need to be made on whether to increase the size of the envelope or increase the conductivity of the envelope material. For example, if the gravel pit is near the job site, then it may be more economical to increase the envelope size than perform mechanical gradation of the envelope material.

In addition to the hazard of physical drain clogging by sediments, chemical or biological drain clogging can take place in certain soils. Iron or magnesium oxides can chemically react and seal the pores. Ochre is a red sludge produced by iron oxidizing bacteria. Sandy or peat soils with organic lenses are susceptible. If sewage sludge or cannery waste are applied to soils, then they can be an iron source. Ground water can have high ferrous iron concentration (>0.2 ppm). The ochre problem can take place just in the first few months after drain installation or it can be a long-term problem. Important factors that influence ochre formation are pH and temperature.

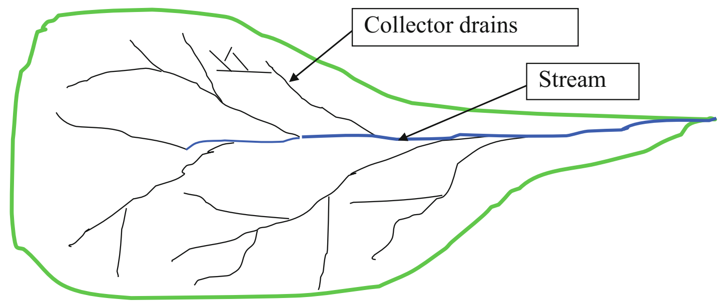


Fig. 30.7 Drains connecting low areas to river

If a gravel envelope is not used, then the bottom of the trench must support at least one quarter of the circumference of the drain pipe, in order to improve the structural strength of the drain. This can be accomplished by shaping the bottom of the trench at a 90^0 V angle. Maximum trench depths are based on no more than 20 % deflection of the drain by the overburden pressure + expected vehicle load (NRCS, EFH 14, 2001). Maximum depths range from 6 to 12 feet (2–4 m), depending on drain diameter and trench width

Field Drainage System Geometry

Three types of drainage patterns are shown in Figs. 30.7 and 30.8: random, herringbone, and parallel. In fields with undulating topography, a random pattern (actually not random but following the topography) is used to drain low areas into streams. In depressions, vertical open drain inlets can facilitate rapid drainage of ponded water after storms.

A herringbone pattern may be used if it provides advantageous slope to drains; for example, if the central collector drain is laid in the downslope direction, then a herringbone pattern can give a downslope orientation to the drains, and the drains can be laid at a constant depth in the soil rather than start shallow and end deep.

Drainage Structures

Drainage structures include surface inlets, junction boxes, silt traps, vents, and outlets. Direct surface inlets are common in regions with undulating topography and ponded depression areas. These inlets rapidly drain ponded water. However, they are not recommended by the NRCS. One of the primary hazards associated with surface inlets is drain siltation. If silt is a problem, then a blind surface inlet can be constructed, which includes highly porous material above the drain but no direct flow to the drain. Refer to NRCS design manual for drawings of these structures.

Junction boxes are required where two or more drains are joined together (Fig. 30.9). Junction boxes facilitate drain cleaning. Within the field, the junction box upper surface should be at least 18 in (45 cm) below the ground surface. Silt traps are similar to junction boxes except that the box bottom is far below the inlet and outlet. Silt traps are placed downstream from silt sources, such as an open inlet.

Plastic pipe has high tensile strength but very little resistance to collapse against an internal vacuum. However, corrugated drain pipe has higher resistance to collapse. An internal vacuum can develop if water drains rapidly from a downstream pipe while the upstream pipe has water moving more slowly down the pipe. This can occur where the drainage pipe changes from a flat slope to a steep slope. Placement of a vent (vertical pipe) at the point where slope changes from flat to steep can relieve internal vacuum and prevent collapse.

On the other hand, when pipe slope changes from steep to flat, pressure can build up in the pipe if a slug of water approaches the flat section. This is especially likely in the case of an open surface inlet. An air relief valve can be placed at these locations in order to allow air to breathe out of the pipe under high pressure. Vents and air relief valves should be placed along fence lines or other locations where they will not be in the way of farm equipment.

Drain outlets should corrugated metal pipe or other rigid pipe. The drain outlet should be protected from intrusion by rodents by a swinging gate or iron grating. Where surface outlets are submerged, the outlet should be protected by a swing gate. The outlet pipe should be fireproof if burning of weeds is expected. If surface water flows toward the outlet from above, then the drain outlet should be protected by a headwall or earth berm (NRCS, EFH 14, 2001).

Drainage Sumps and Pumps

If it is impossible to provide a gravity outlet for a drainage system, then a drainage sump and pump system may be required. A subsurface drainage sump (Fig. 30.10) can be constructed from stacked vertical, large diameter, concrete pipe culvert sections. A float valve with stop and start collars turns the pump on and off when the water level inside the sump rises and falls, respectively. It is better to spend extra money on a sump than deal with extremely shallow grades and risk siltation or air locks.

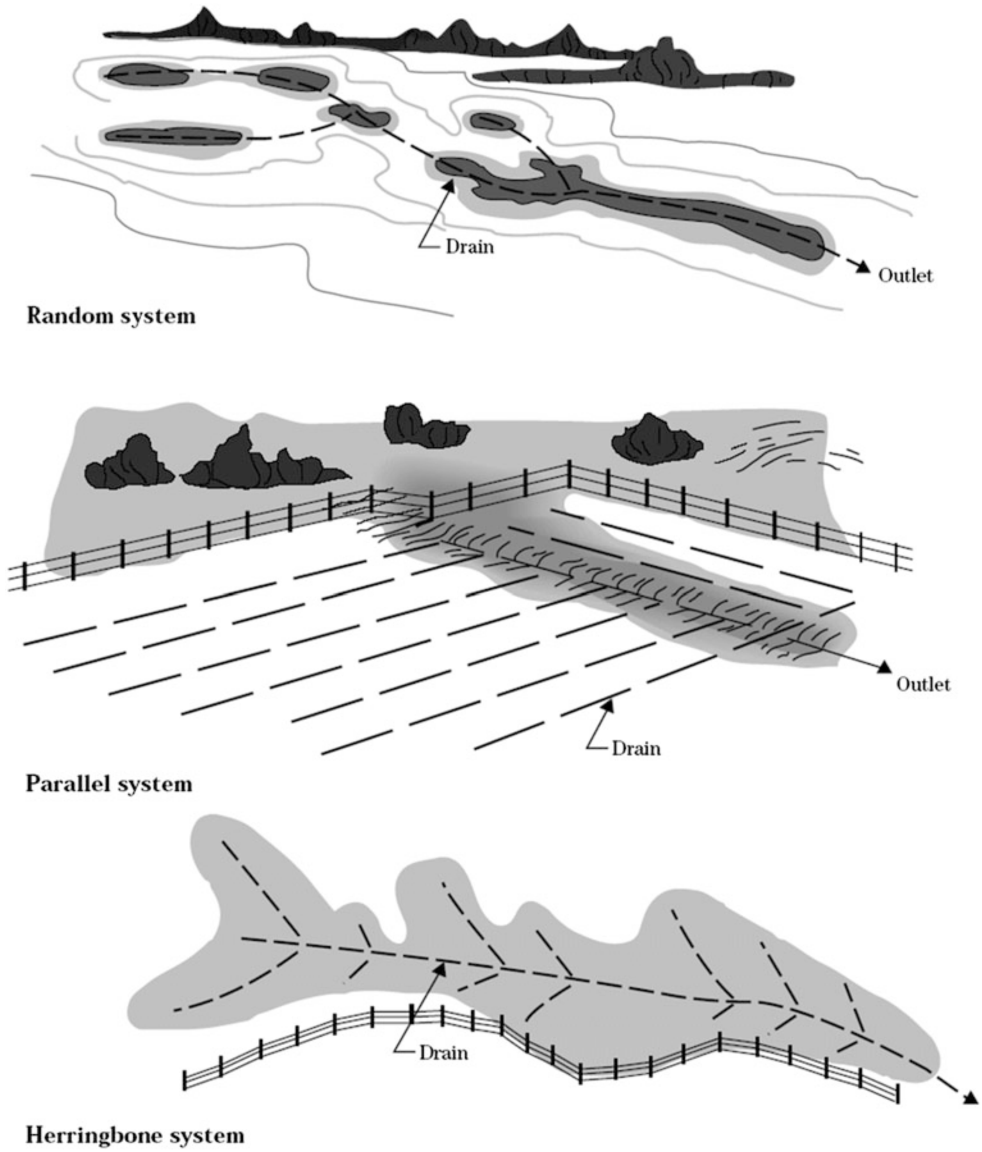


Fig. 30.8 Field subsurface drainage systems (Credit NRCS, Part 650 Engineering Field Handbook, Chap. 14, 2001)

The pump flow rate should be designed to meet the expected maximum drainage flow rate.

$$P = I \tag{30.12}$$

where

P = Pumping rate, LPM,
I = Drainage inflow rate, LPM,

During periods when the pump flow rate exceeds the drainage flow rate, the pump turns on when the water level in the sump reaches the start level and turns off when the water level reaches the stop level. The number of pump cycles per hour should not exceed 10; otherwise, the electrical efficiency of the pump decreases and the pump wears out quickly. The relationship between number of cycles, inflow and pumping rate and sump volume is given by the following equations.

$$\frac{60}{N} = \frac{S}{I} + \frac{S}{P - I} \tag{30.13}$$

where

N = number of cycles per hour
S = Storage volume, Liters.

The sump volume is based on the worst-case scenario: the maximum number of pump cycles per hour occurs when the inflow rate, I, is equal one-half of the pumping rate, P. If I = 0.5P is substituted into Eq. 30.13,

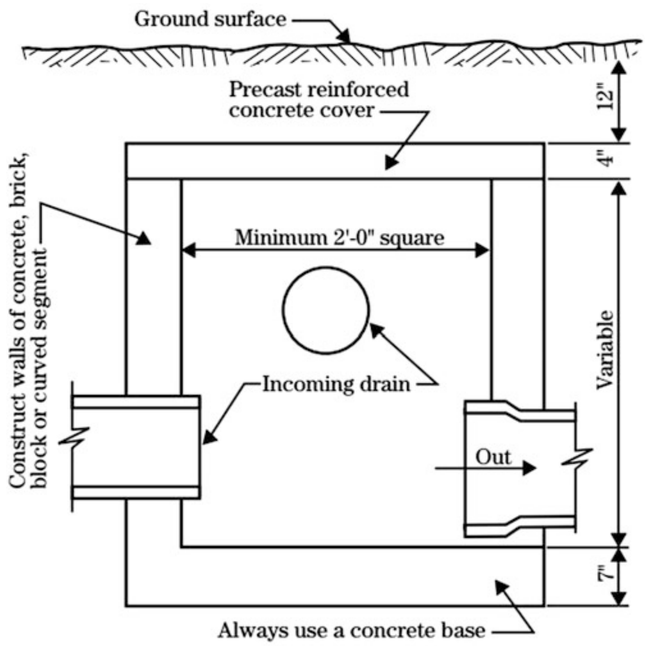


Fig. 30.9 Junction box (Credit NRCS, Part 650 Engineering Field Handbook, Chap. 14, 2001)

$$\frac{60}{N} = \frac{S}{I} + \frac{S}{P-I} = \frac{S}{0.5P} + \frac{S}{0.5P} = \frac{S}{P} \rightarrow S = \frac{60P}{N} \quad (30.14)$$

If the maximum number of cycles per hour is 10, then the sump storage volume should be (60/10) P = 6P.

Example 30.5 Design a drainage pump and sump for a maximum expected drainage rate of 200 LPM, and a design maximum number of cycles per hour of 5.

Pump flow rate = maximum drainage rate = 200 LPM.
Sump volume = 60 P / 5 = 12 (200) = 2,400 L = 2.4 m^3.

Measurement of Lateral Hydraulic Conductivity

Lateral hydraulic is measured in an auger hole. The hole is normally drilled below the water table. Water is pumped out of the hole, and then the rate that water rises in the hole is measured. The geometrical parameters in a standard auger hole test are shown in Fig. 30.11.

The auger hole should be drilled approximately 30 cm (1 ft) below the elevation of the water table at the expected elevation of the subsurface drain pipe. It may be necessary to wait until a large storm raises the water table to the necessary elevation above the drain elevation. If this is not possible, then there are auger hole tests for unsaturated soils.

- H = depth of hole below the ground water table (cm)
- r = radius of auger hole (cm)
- y = distance between ground water level and the average level of water in the hole (in) for the time interval t (s)
- Δy = rise of water (cm) in auger hole during Δt
- t = time interval (s)
- G = depth of the impermeable layer below the bottom of the hole (cm). Impermeable layer is defined as a layer that has the permeability of no more than a tenth of the permeability of the layers above.
- d = average depth of water in auger hole during test (cm)

The auger hole is evacuated with a small pump (double diaphragm or stirrup pump) or bail bucket (*NRCS EFH 14, 2001*). The level of water in the hole can be measured with a stick attached to a float or automatic depth sensor. The NRCS recommends a lightweight bamboo fishing rod with length markings attached to a cork or can (Fig. 30.12).

Ernst (1950) developed two equations for calculation of auger-hole hydraulic conductivity. The first equation is used if G is zero, and the bottom of the auger hole corresponds with the elevation of the top of the impermeable layer.

$$K_s = \frac{15,000(r^2)}{(H+10r)\left(2-\frac{y}{H}\right)y}\frac{\Delta y}{\Delta t} \quad (30.15)$$

where

K_s = hydraulic conductivity (cm/hr)

If the auger-hole is greater than 0.5H above the impermeable layer (G > 0.5H) then significant upward flow into the auger hole is expected and the following equation (Ernst 1950) is used.

$$K_s = \frac{16,667{*}r^2}{(H+20r)\left(2-\frac{y}{H}\right)y}\frac{\Delta y}{\Delta t} \quad (30.16)$$

The NRCS recommends the following for use of Eqs. 30.15 and 30.16. The hole diameter, 2r, should be between 6 and 14 cm. The static depth of water in the hole, H, should be greater than 25 cm and less than 200 cm. The average depth of water in the hole, y, should be greater than 0.2 H. The change in depth, Δy, should be less then ¼ y_0, the initial depth at the beginning of test.

During a conductivity test, the distance from the reference point to the water surface (Fig. 30.13) is measured over time. The difference between this distance (R) and the distance from the static water surface to the reference point (B) is plotted (Fig. 30.13) and is equal to Δy/Δt.

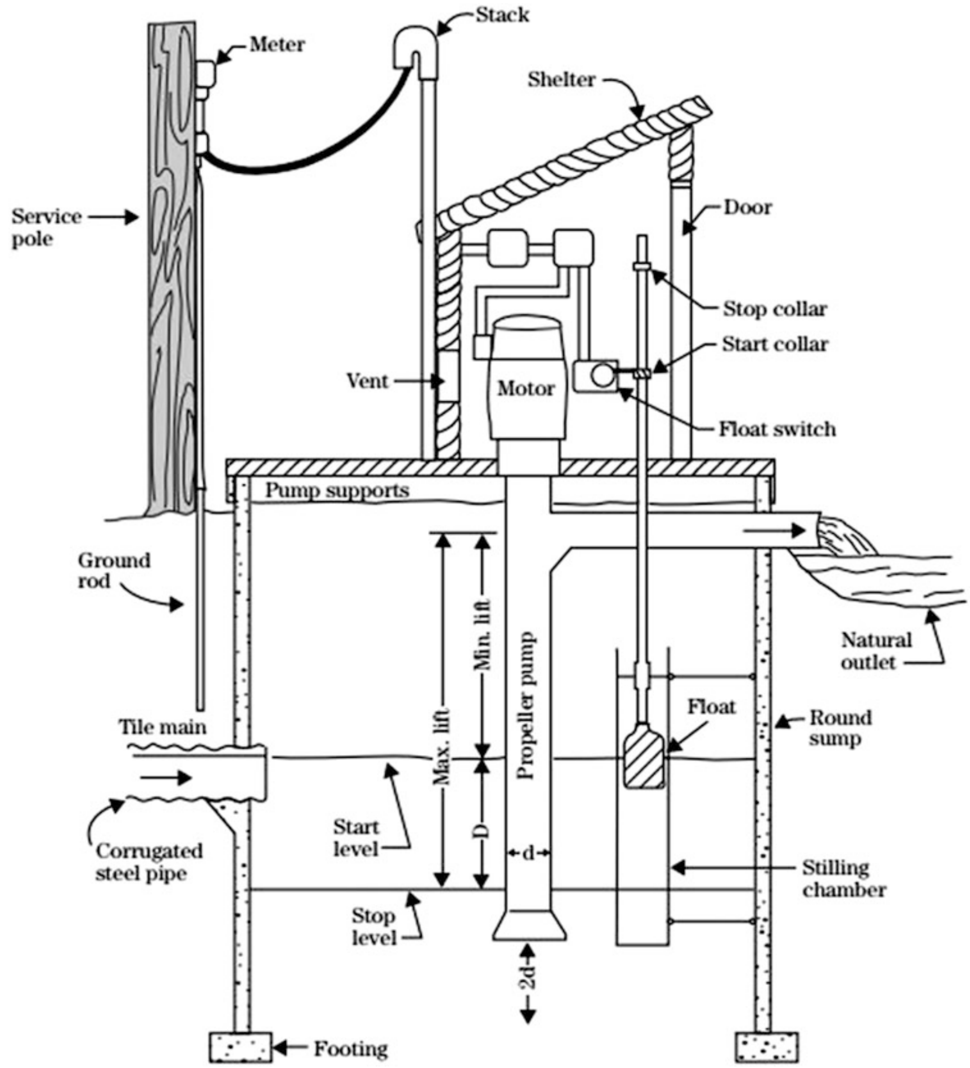


Fig. 30.10 Drainage pumping plant (Credit NRCS, Part 650 Engineering Field Handbook, Chap. 14, 2001)

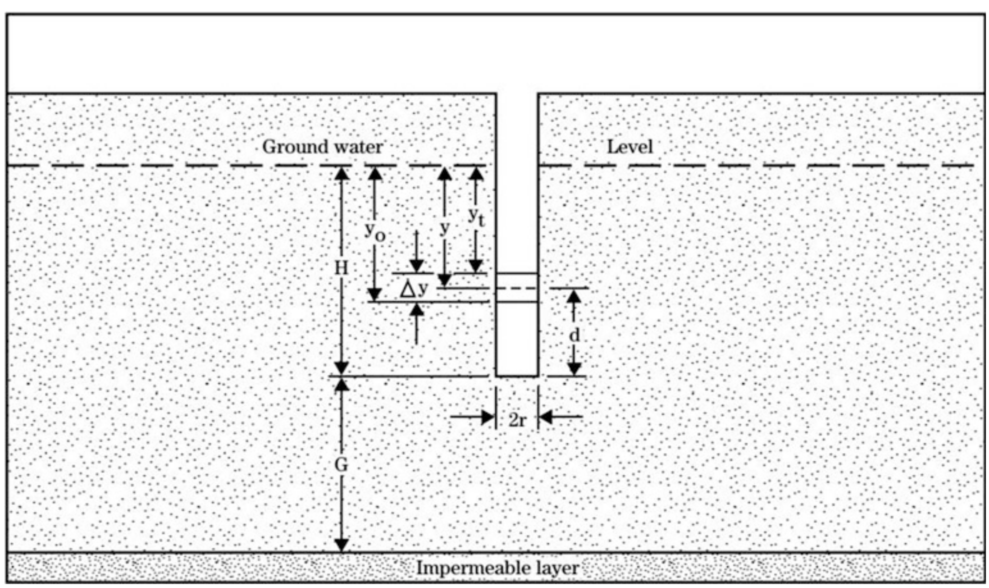


Fig. 30.11 Auger hole test parameters (Credit NRCS)

Example 30.6 Calculate hydraulic conductivity with Fig. 30.13 and the following parameters. The diameter of the auger hole is 10 cm, and the bottom of the auger-hole corresponds with the top of the impermeable layer.

Radius of auger-hole (5 cm = 2 in)	r	5 cm
Distance from bottom of auger hole to reference	D	236 cm
Distance from bottom of auger hole to static water table	H	127 cm
Distance from bottom of auger hole to average depth during test	d	41 cm
Change in elevation, R-B, during test	Δy	9.5 in = 24 cm
Length of test	Δt	150 sec

$$y = H - d = 127\ \text{cm} - 41\ \text{cm} = 86\ \text{cm}$$

$$K_s = \frac{15{,}000 * r^2}{(H + 10r)\left(2 - \frac{y}{H}\right)y}\ \frac{\Delta y}{\Delta t}$$

$$= \frac{15{,}000 * 5^2}{(127 + 10 * 5)\left(2 - \frac{86}{127}\right) * 86}\ \frac{24\ \ cm}{150\ \ \text{sec}} = 3.0\ \ cm/hr$$

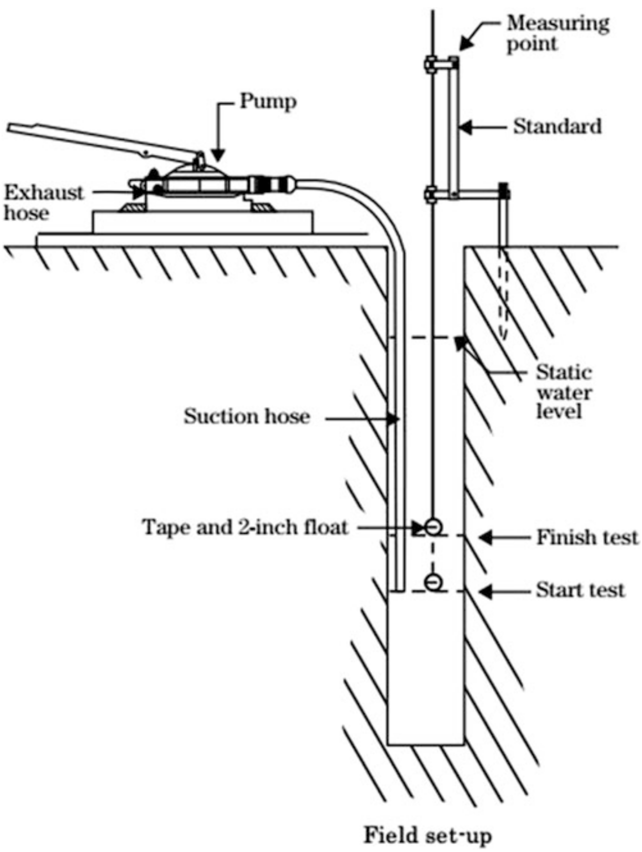


Fig. 30.12 Auger hole test equipment (Credit NRCS, Part 650 Engineering Field Handbook, Chap. 14, 2001)

Example 30.7 Calculate hydraulic conductivity based on the following measurements. The bottom of the auger hole is above the impermeable layer.

Radius of auger-hole (5 cm = 2 in)	r	5 cm
Distance from bottom of auger hole to static water table	H	102 cm
Distance from bottom of auger hole to average depth during test	y	30.5 cm
Change in elevation, R-B, during test	Δy	0.81 cm
Length of test	Δt	10 sec

The bottom of the auger-hole is greater than 0.5 H above the bottom of the impermeable layer, so use Eq. 30.16.

$$K_s = \frac{16{,}667 * r^2}{(H + 20r)\left(2 - \frac{y}{H}\right)y}\ \frac{\Delta y}{\Delta t}$$

$$= \frac{16{,}667 * 5^2}{(102 + 20 * 5)\left(2 - \frac{30.5}{102}\right) * 30.5}\ \frac{0.81\ \ cm}{10\ \ \text{sec}} = 3.2\ \ cm/hr$$

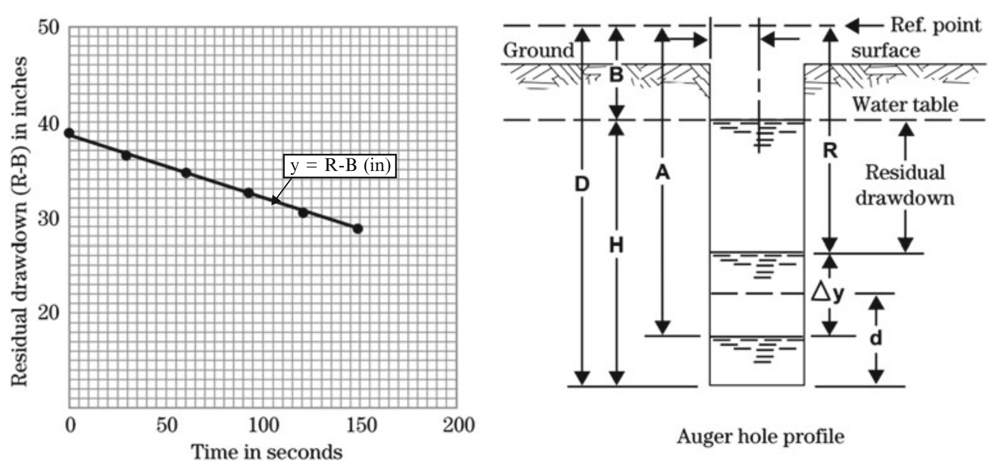
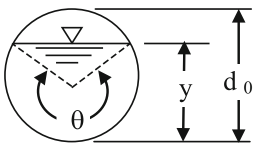


Fig. 30.13 Data for auger hole test. Y-axis is (R-B) in cm (Credit NRCS, Part 650 Engineering Field Handbook, Chap. 14, 2001)

Section	Area A	Wetted perimeter, P	Hydraulic radius R	Top width T
 Culvert	$\frac{1}{8}(\theta - \sin\theta)d_0^2$	$\frac{1}{2}(\theta)d_0$	$\frac{1}{4}\left(1 - \frac{\sin\theta}{\theta}\right)d_0$	$\left(\sin\frac{\theta}{2}\right)d_0$

If it is not possible to conduct auger-hole tests, an alternative technique is to use soil properties to estimate hydraulic conductivity. If soil texture is known, then conductivity can be calculated with the Hydraulic Properties Calculator referenced in Chap. 3.

Questions

1. List the positive and negative environmental aspects of subsurface drainage.
2. What measures are recommended by the NRCS to reduce the impact of drained water from farmland on the environment.
3. List the features that should be noted in a drainage reconnaissance survey.
4. Based on the geometry of Fig. 30.1 and the derivation of Eq. 30.1, are drains designed for the peak flow with the water table directly over the drain after a rainstorm?
5. Derive a drainage coefficient equation for flow with the water table directly over the drain. Compare the ratio of flow rates based on your equation and Eq. 30.4. Discuss why drains are not designed based on the flow rate that takes place when the water table is directly over the drain.
6. Derive Eq. 30.6 from Manning's equation assuming that the pipe is full and half full and determine whether the equation assumes that the drain is flowing half full of full.
7. A 5 ha area has a drainage coefficient of 19.1 mm/day. The drain slope is 0.3 %. Calculate the required drain size.
8. Calculate the required diameter of a subsurface drain for the following parameters.

Manning's n	0.017
Drain elevation above impermeable layer	3 m
Drain slope	s = 0.2 m/100 m
Hydraulic conductivity	K = 2 m/day
Drain spacing	L = 60 m
Length of drain pipe	L_d = 500 m
Maximum WT height above drains:	m_0 = 2 m − 0.48 m = 1 m

9. Can a geotextile filter be used in a loam soil? What mesh is recommended ?

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