CHAPTER 18
GROUNDWATER AND SEEPAGE

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18.1 INTRODUCTION

18.1.1 Purpose

The impact of groundwater on the construction, maintenance and long term performance of highways and highway structures should be considered on every project. Excessive and uncontrolled subsurface water has been responsible for large numbers of pavement failures, slope failures, and unsatisfactory projects. Subsurface drainage is essential for economical, long term performance of roads and highways.

This chapter discusses the impacts of groundwater on highway projects, identification of groundwater problems, and methods for control of subsurface and subpavement water. Procedures and criteria for subsurface drainage design are presented with emphasis on a multidisciplinary approach to groundwater problems with active interaction between the hydraulics, geotechnical and roadway engineer.

Photo 18.1

Photo 18.2

18.1.2 Sources of Groundwater

There are many sources of water that can enter the pavement subgrade. These include:

- Surface water infiltrating through porous or cracked pavements and unsealed joints, particularly through the longitudinal joint between concrete pavement and flexible asphalt shoulders;
- Lateral seepage from saturated median ditches, irrigation ditches;
- Shoulders, and irrigated landscape features;
- Capillary water rising from the underlying water table;
- Accumulated water vapor from temperature fluctuations and other atmospheric conditions;
- Poorly sealed irrigation culverts and siphons;
- Plugged culverts; and
- High groundwater table.

Most slope failures occur during heavy rainfall periods in combination with or shortly after snow melt. Sources of water contributing to slope instability include:

- Seepage from irrigation ditches and ponds above slopes;
- Interception of groundwater table in cut sections; and
- Rain and snow accumulation in slope scarps with subsequent infiltration and lubrication of active failure planes.

Subsurface drainage systems can be provided to remove or control groundwater from these sources and minimize impacts on highway projects.

18.1.3 Impacts of Groundwater on Highway Projects

Groundwater can have a considerable impact on the success of a highway construction project. If groundwater and seepage are not identified and adequately addressed it can significantly impair the following:

- Constructability;
- Pavement performance; and
- Slope stability.

Groundwater must also be considered in design and construction of drainage structures, wetlands mitigation sites, foundations, and retaining structures.

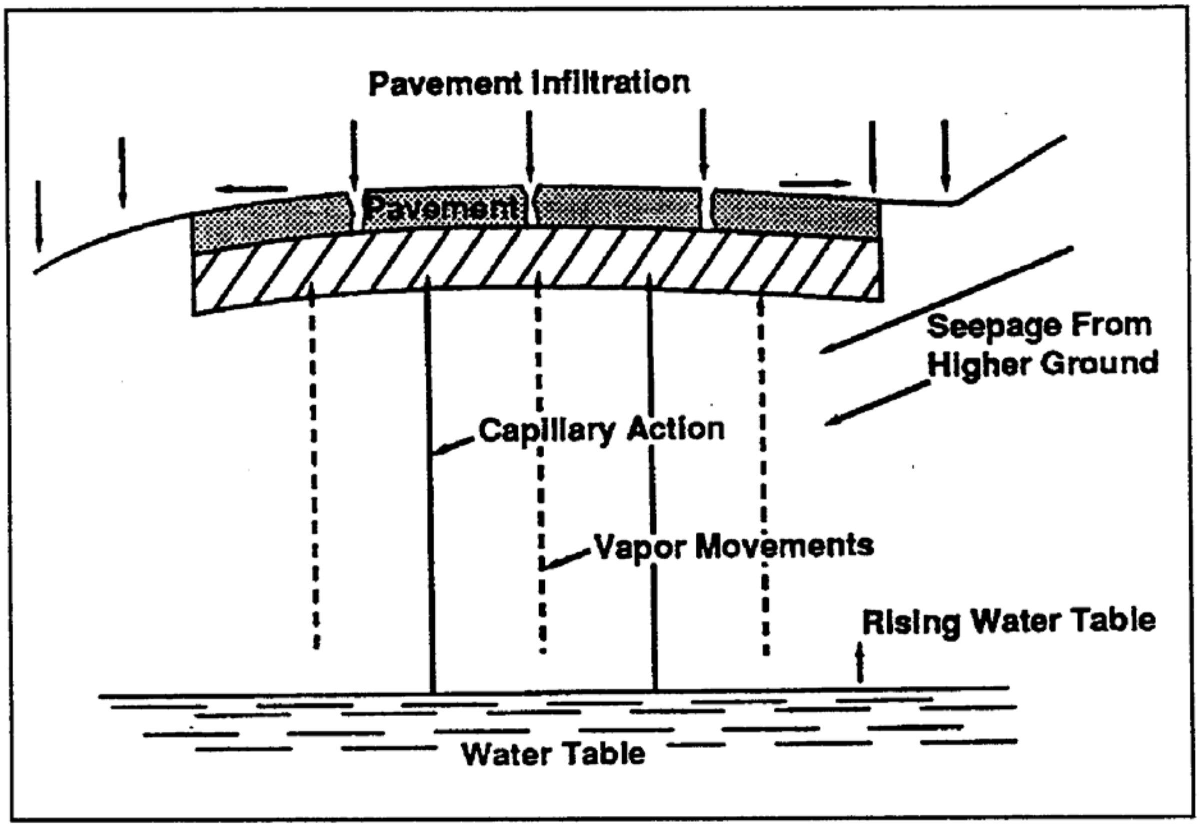


Figure 18.1 Sources of Subsurface Water in Pavements (FHWA, 1992)

18.2 PRELIMINARY INVESTIGATION

18.2.1 Identification of Subsurface Water

There is much variability and uncertainty in subsurface conditions, but in general, most subsurface drainage problems can be identified and designed for prior to construction.

The first step in addressing a groundwater problem is identifying that a problem exists. Field observations are essential to early identification of potential problems. If any of the following are observed during scoping or field reviews, subsurface drainage may be required:

- Distress or failure of existing pavement;
- Wet spots in pavement or subgrade material piping through cracks or joints;
- Undulating pavement surface;
- Unlined irrigation canals on slopes uphill of highway;
- Cattails or wetlands vegetation growing in borrow ditch or on slopes;
- Seepage from cut slopes or natural slopes;
- Evidence of slope instability such as scarps, old landslides, and trees at adverse angles.

If any of the above are identified, the Geotechnical Section or Hydraulics Unit should be contacted to assess the problem and determine if further analysis is warranted.

Maintenance personnel are an excellent source of information on surface and subsurface flow conditions and should be consulted.

18.2.2 Field Investigations

The validity of any analysis and design is dependent on the accuracy of data used in computations. Design of subsurface drainage features requires an accurate description of the soil characteristics and a thorough geologic evaluation. Information about groundwater occurrence and soils characteristics for the design of subsurface drainage structures often require extensive field investigation and a subsurface exploration program.

Field investigations and subsurface exploration programs are carried out by the Geotechnical Section. Soil borings and sometimes test pits are used to determine variation in subsurface conditions and water bearing capabilities of subsurface materials. Groundwater elevations are determined at the time of boring and through subsequent monitoring. Field investigations to determine groundwater problems should be carried out during the wet season. If the concern is seepage from irrigation ditches, monitoring should be performed during the irrigation season.

If data for seasonal or annual fluctuations in the groundwater elevation are needed, monitoring wells can be installed at the time of drilling and monitored until enough data is acquired. Groundwater monitoring can be essential for successful wetlands mitigation design.

Engineering properties of soils are determined by laboratory and field tests. Laboratory tests can be performed to determine soil grain size distribution, coefficient of permeability and frost susceptibility. Water and soil chemistry can be acquired to determine quality of groundwater and potential for corrosion or solute deposition in subsurface drainage systems.

18.3 ANALYSIS OF GROUNDWATER PROBLEMS

18.3.1 Introduction

The large variability in the properties of saturated soils is responsible for large variations in flow rates and seepage velocities. The analysis of subsurface flow requires a means of predicting flow rates and seepage velocities under different conditions.

It is important to make the best possible determination of the water bearing and carrying properties of a formation or soil mass. This will allow the best probability of designing subsurface drainage features that will perform as intended.

18.3.2 Darcy's Law

Darcy's law provides a means of calculating seepage flow rates and velocities in saturated soils. There are numerous practical applications of Darcy's law in the analysis of groundwater flow and design of subsurface drainage. It is commonly used to determine the capacity of underdrains and pavement drainage systems.

Darcy's law relates flow through porous media linearly to a proportionality constant, k, and the hydraulic gradient, i. Darcy's law is expressed in the following form:

$$Q = k\ i\ A \qquad \text{(Equation 18.1)}$$

where: Q = discharge through an area [volume/time]; k = coefficient of permeability (length/time); i = hydraulic gradient (ratio of change in water level and linear distance of fluid flow) (dimensionless); A = area through which flow occurs ($length^2$).

Darcy's law is valid within the range of steady state, laminar flow. This holds for flow in most naturally occurring deposits and man made fills. In highly permeable granular materials where turbulent flow may exist, validity of Darcy's law is questionable and it should be used with caution. Experience has shown Darcy's law to be valid for soils finer than coarse sand and gravel deposits with permeability up to 3,000ft/day.

18.3.3 Determination of Coefficient of Permeability

The coefficient of permeability, k in Darcy's law, is defined as the flow rate through a unit area with a unit hydraulic gradient. It indicates the capability of a material to carry water. Both soil and fluid properties affect the coefficient of permeability. Permeability is a function of soil particle size, soil void ratio, mineral composition, soil fabric, and degree of saturation. The coefficient of permeability is also a function of the fluid density and viscosity.

It is always preferred to determine permeability by direct methods in the laboratory or field. These methods include:

- Laboratory
  - Constant head test
  - Falling head test
- Field
  - Pump tests

Tests to determine the coefficient of permeability for fine grained soils can take a considerable time to perform, therefore permeability is sometimes determined indirectly from triaxial compression test results or from consolidation tests. Procedures for the above mentioned testing methods can be found in soil mechanics texts or laboratory manuals.

Although field or laboratory determinations of permeability are ideal, they can pose both great expense and difficulty. In practice it is often necessary to estimate soil or filter material permeability with empirical equations or charts that relate permeability to soil gradation.

The relationship between soil grain size and permeability can be used to estimate the permeability. Permeability of granular soils has been found to be proportional to grain size by Hazen's Formula:

$$k = C\,D_{10}^2 \qquad \text{(Equation 18.2)}$$

where: k = coefficient of permeability (in/sec); C = proportionality constant (C = 1 for coarse sands and gravel); D_{10} = effective grain size in inches (the particle diameter for which 10 percent of the soil mass passes in a sieve analysis).

It should be noted that the coefficient of permeability varies over many orders of magnitude depending on the soil properties. In natural deposits and some compacted soils permeability may be much greater in one direction than in the other. The coefficient of permeability for a soil is a very difficult value to determine and results obtained from these methods are approximations which should be used with discretion.

18.3.4 Flow Rate Determination

Subsurface flow rates of most highway seepage problems can usually be estimated with one of the following methods:

- Darcy's Law;

- Flow nets;
- Other empirical solutions as in permeable base and edgedrain design; and
- Two-dimensional computer seepage programs.

In cases that require a more regional analysis of groundwater flow, finite element or finite difference computer models should be employed. Descriptions of these methods are included in geotechnical texts and modeling manuals.

18.4 UNDERDRAINS

18.4.1 Introduction

Subsurface drains are effective in controlling groundwater problems when designed and constructed properly. Many pavement and slope failures can be prevented with effective drainage of subsurface water. Underdrains are used to intercept subsurface seepage before it enters the structural material supporting the pavement and are also used to draw down the water table.

Pipe underdrains consist of a perforated or slotted pipe placed near the bottom of a narrow trench backfilled with permeable backfill material. This backfill is typically wrapped in a filter fabric to prevent clogging of the drain from migration of fines into the permeable material. A french drain is an underdrain that consists of a trench backfilled with highly permeable material but without the perforated or slotted pipe.

Underdrains can be effectively used in the following situations:

- Longitudinal (parallel to roadway) underdrains can be used in regions of high groundwater to intercept subsurface water before it can reach and enter the materials supporting the pavement;
- In sloping terrain, where slope stability is not a problem, a trench may be excavated along the uphill side of the roadbed near the toe of cut slope;
- In areas where the ground is nearly level, longitudinal pipe underdrains may be necessary along both sides of the roadway bed near the toe of cut slope;
- Longitudinal underdrains are also placed along the toe of fills to intercept high groundwater;
- Transverse (perpendicular to roadway) underdrains are placed at a sag vertical or in cut sections at contact with an impervious layer;
- Transverse underdrains should also be placed at transitions from cut to fill to prevent saturation, settlement and instability in fill sections.

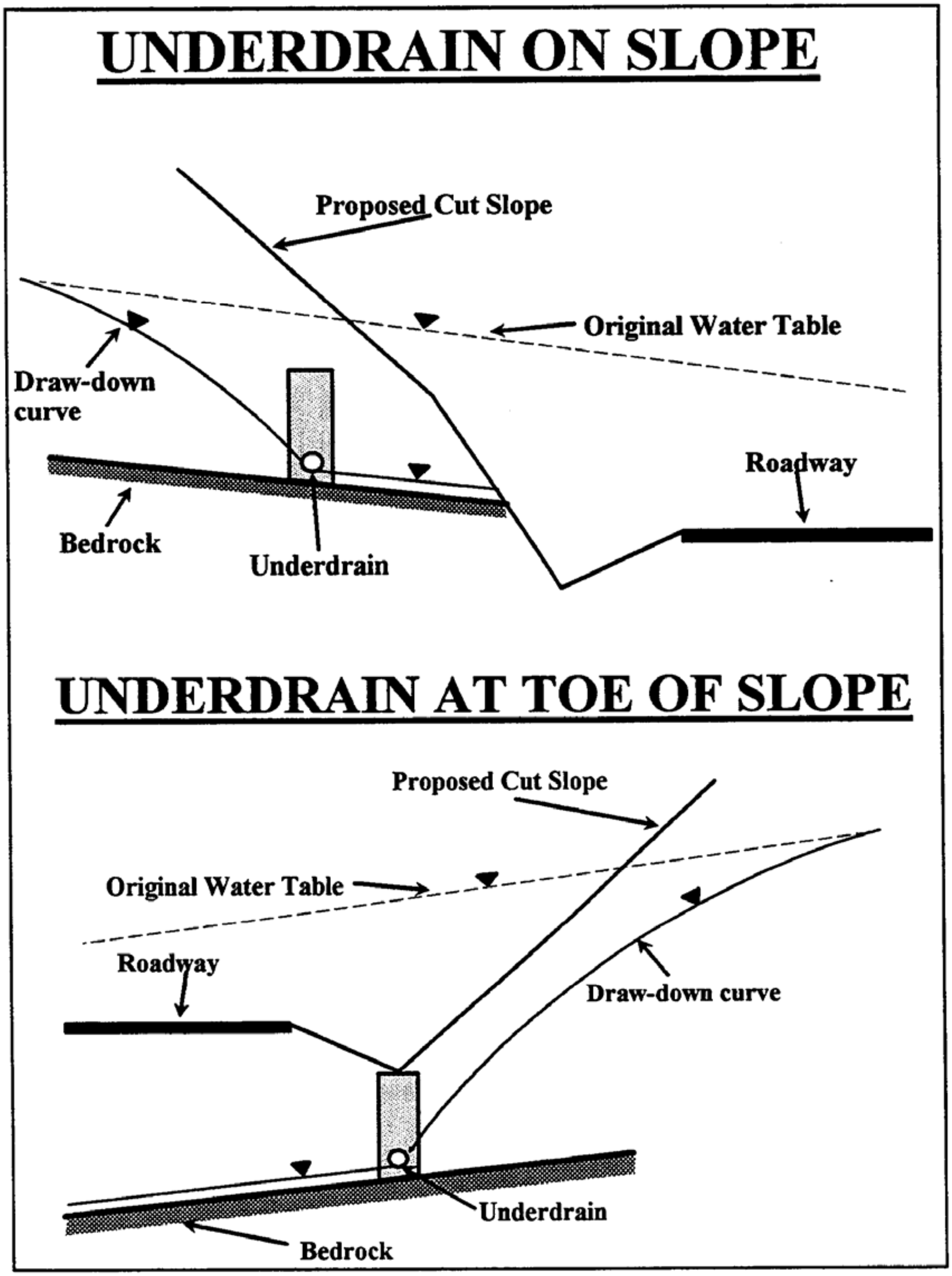


Figure 18.2 Intercepting groundwater with underdrains.

The location and depth of underdrains depends largely on the function intended and local geology. Whenever practical, an underdrain bottom should be placed at a depth below the impervious bedrock boundary below the aquifer. Constructed underdrains can exceed 10 foot depths and have been built successfully to depths exceeding 30 feet in Colorado. Deep underdrains require attention to worker safety and construction techniques.

Multiple underdrain installations are often constructed in a herringbone pattern. Such installations are well suited for collecting large quantities of groundwater, such as springs under roadbeds, and for stabilizing fill foundation areas.

Most of the components of underdrains are also integral components of other subsurface drains. Each component of a subsurface drainage system serves a particular function in ensuring that the drain performs as intended. Design of any subsurface drain should ensure a system that is cost effective, constructible, compatible with the surrounding soils, and that will provide adequate drainage throughout its design life. The following are the basic components of a subsurface drainage system:

- Filter/separator layer;
- Conducting drainage layer;
- Collector pipe;
- Outlet; and
- Appurtenances.

It is important for the engineer to understand the function and interaction of the basic components of subsurface drains. Site specific conditions must be considered and each component appropriately designed to ensure that the installed drain will perform as intended. A discussion of the function, interaction, and design criteria of each component is included in the following sections.

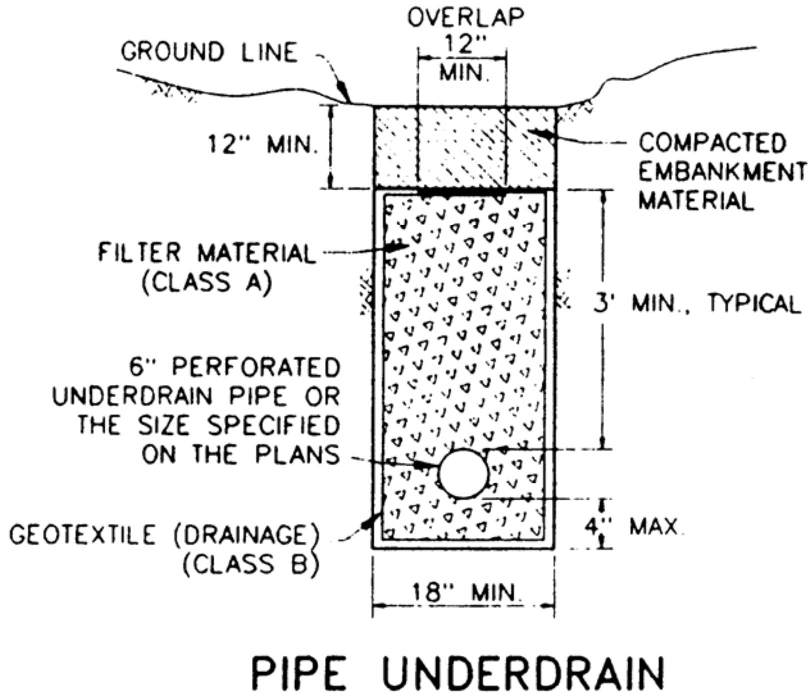
18.4.2 Filter Design

The most common mode of failure of subsurface drainage systems is clogging due to movement of fine soil from surrounding material into the drainage layer and material from the drainage layer into a collector pipe. The movement of fines into the drainage layers can be initiated both by erosion from seepage flow and pumping action caused by the repetitive loading of traffic. As such, the selection of compatible filter material can be the most critical aspect of subsurface drain design.

Filters provide two main functions in subsurface drains:

- Hold back erodible material from intruding the drainage layer and clogging the drain (prevent piping); and
- Allow free flow of water (the filter must be more permeable than the subgrade soil.).

In order to protect the drainage layer from intrusion of fines the filter must satisfy certain design criteria to prevent intrusion and clogging. Either granular material or geotextiles can be used as a filter.



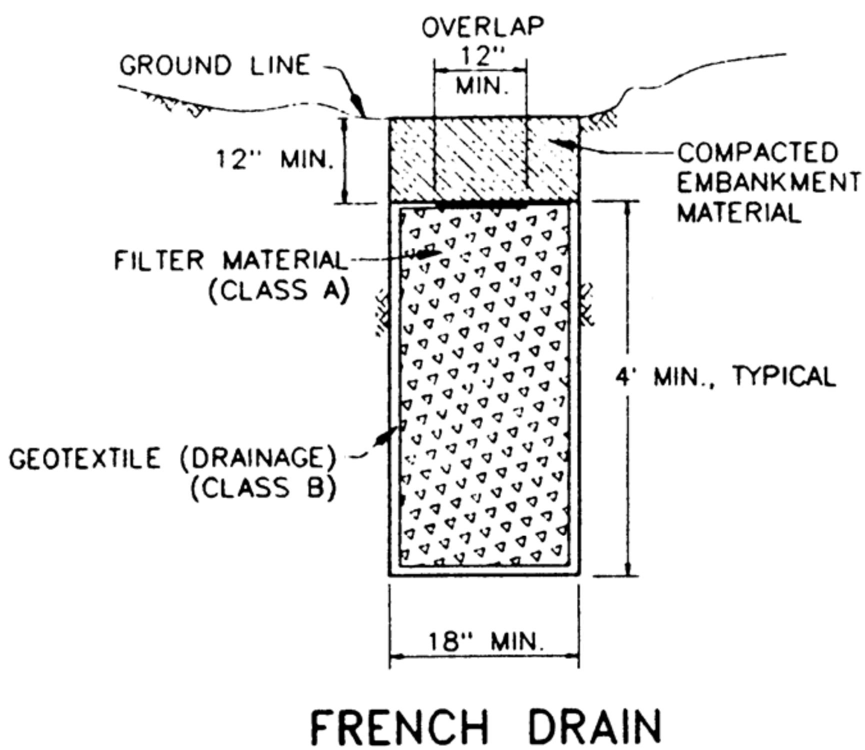


Figure 18.3 Typical underdrains (CDOT M-Standard 605-1).

Granular Filter Design

There are numerous sets of criteria used for granular filter design. CDOT has adopted that developed by the USBR and used by the FHWA. The filter must meet the requirements for the filter/soil interface as listed below:

1. Filtration Criteria

$$D_{15}(\text{filter}) \leq 5\ D_{85}(\text{Soil}) \quad \text{(Equation 18.3)}$$

2. Uniformity Criteria

$$D_{50}(\text{filter}) \leq 25\ D_{50}(\text{soil}) \quad \text{(Equation 18.4)}$$

where: D_x = screen size in millimeters at which “x” percent of the particles, by weight, are smaller.

To ensure that the granular filter is well graded and stable, the following range in coefficient of uniformity (C_u) must also be met:

$$20 \leq C_u \leq 40 \quad \text{(Equation 18.5)}$$

where: $C_u = D_{60}(\text{filter}) / D_{10}(\text{filter})$

A granular filter should not have more than 5 % passing the No. 200 sieve. If a single layer of granular material will not satisfy the above filter criteria, one or more additional filter layers must be used. In addition to the piping and permeability criteria, the grain size curve for the subgrade and the various filter layers should be approximately parallel. Also, the granular filter should be both chemically and structurally stable.

Similarly, the filter/drainage layer interface must meet the same requirements to ensure that the filter material does not intrude and clog the permeable drainage material. The filter criteria applies between the subgrade material and the filter, between successive layers of filter material if more than one layer is used, and between the filter layer and drainage material internal to the subsurface drain. The same criteria as above is used with the drainage layer replacing the filter and the filter replacing the subgrade.

The minimum filter blanket thickness of 4 inches is recommended for drainage applications.

Geotextile Filter Design

Because of ease of installation and usefulness in providing filtration on vertical and sub-vertical trench walls, geotextiles are commonly used as filter material. Unfortunately there have been a number of documented instances of subsurface drain failures because of clogging of geotextile filters. These failures have been mainly due to lack of or improper design.

Selection of a geotextile requires analysis to ensure that the geotextile will be compatible with the soils surrounding it. It is both the hydraulic engineer's responsibility to design and specify the appropriate geotextile and the construction engineer’s responsibility to ensure that the correct material is supplied in the field. Generalized geotextile requirements should be used only on very small or non-critical installations. A detailed design and analysis should be performed for all other applications and site specific requirements should be provided in project special provisions. Geotextile design requires consideration of the materials:

- soil retention;
- permeability;
- susceptibility to clogging; and
- survivability.

Table 18.1. Summary of design criteria for selecting geotextiles (FHWA, 1992).

I. SOIL RETENTION CRITERIA

Less than 50% Passing No. 200 Sieve		
Steady-State Flow	**Dynamic Flow**	
	Can Move	Cannot Move
AOS $O_{95} \le B\ D_{85}$ i) $C_u \le 2$ or ≥ 8, $B = 1$ ii) $2 \le C_u \le 4$, $B = 0.5\ C_u$ iii) $4 \le C_u \le 8$, $B = 8/C_u$	$O_{95} \le D_{15}$	$O_{50} \le 0.5\ D_{85}$

Greater Than 50% Passing No. 200 Sieve		
Steady-State Flow		**Dynamic Flow**
Woven	Nonwoven	
$O_{95} \le D_{85}$	$O_{95} \le 1.8\ D_{85}$	$O_{50} \le 0.5\ D_{85}$
AOS No.(fabric) $\ge$ No.50 Sieve		

II. PERMEABILITY CRITERIA

A. Critical/Sever Applications	**B. Less Critical/Less Severe Applications** (with clean medium to coarse sands and gravels)
k (Fabric) $\ge$ 10 k (soil)	k (fabric) $\ge$ k (soil)

III. CLOGGING CRITERIA

A. Critical/ Severe Applications	**B. Less Critical/Less Severe Applications**
Select fabrics meeting Criteria I, II, IIIB, and perform soil/fabric filtration tests before specifying. Suggested performance test method: Gradient Ratio $\le$ 3.	1. Select fabric with maximum opening size possible (lowest AOS No.). 2. Effective Open Area Qualifiers: - Woven fabrics: Percent Open Area $\ge$ 4% - Nonwoven fabrics: Porosity $\ge$ 30% 3. Additional Qualifier (Optional): $O_{95} > 3\ D_{15}$ 4. Additional Qualifier (Optional): $O_{15} \ge 3D_{15}$

Criteria for selection of geotextiles for filter and drainage application have been developed which consider these factors. Table 18.1 provides a summary of design criteria for selecting geotextiles. A detailed discussion of design criteria for geotextiles is provided in Drainable Pavement Systems - Demo 87 (FHWA, 1992). In Table 18.1, A.O.S. is the apparent opening size of openings in the geotextile and is the U.S. standard sieve number closest to the geotextile opening size. A.O.S. is sometimes referred to as the effective opening size that can be expressed in millimeters as O_{95}. Coefficient B used in Table 18.1 is a parameter which relates the coefficient of uniformity to the effective opening size.

18.4.3 Drainage Layer Design

The drainage layer is provided to rapidly convey intercepted water into the collector pipe and to the outlet. Both the permeable material that is placed in underdrain trenches and the permeable base used to drain pavements are considered drainage layers.

The drainage layer consists of coarse aggregate with high permeability. This permeable aggregate should have considerably higher permeability than the material that will surround the drain. It is important that the designer determine the availability of aggregate sources for the drainage layer and the permeability of this material in the vicinity of the project. This information will aid the engineer in determining underdrain capacity, required cross sectional area and slope, and evaluate the need for a collector pipe. Capacity of the drainage layer is determined with Darcy's law (Equation 18.2).

Drainage material should have no more than two percent passing the No. 200 sieve. Special care should be taken to ensure that gradation and permeability specifications are met at the time of installation and that the drainage layer is not contaminated by fines during stockpiling at the site or degradation of the material during transport.

18.4.4 Collector Pipe Design

Collector pipes are typically perforated or slotted pipe that collect water from the drainage layer and convey it to the outlet. Material used for underdrain pipes include plastic and corrugated steel pipe. Pipe selection should be based on corrosion resistance requirements, cost and availability and should be determined on a site by site basis.

It is not necessary to place collector pipes in all underdrains installations. Frequently, the granular drainage layer will be permeable enough to provide sufficient conveyance and a collector pipe will not provide any improvement in long term performance. Although the additional material cost of the collector pipe may not be significant, labor associated with placement of the collector pipe, particularly under saturated conditions can greatly increase installation costs. Collector pipes should not be provided in underdrain installations on or adjacent to areas of active slope instability.

A collector pipe will greatly increase the underdrain capacity and at sites where drainage layer permeability or drain cross sectional area is insufficient to provide the required conveyance of subsurface flows, a collector pipe should be provided. This is often true in areas with very coarse in-situ soil where permeability is close to that of the drainage layer material. A pipe will be needed to ensure adequate conveyance to lower the water table. The engineer should understand that even laboratory evaluations of soil permeability are only rough estimates at best, and flow rates can be significantly underestimated. Placement of a collector pipe can provide some addition safety in critical applications.

The following criteria are recommended for collector pipe design and installation:

- Minimum slope recommended is 0.5% and should never be less than 0.2%;
- Minimum size for underdrains is 6 inches; for lengths greater than 500 feet, consider increasing size to 8 inches to minimize effects of sedimentation; and

- Perforations and slots should be small enough to ensure that drainage layer material will not enter the pipe. The maximum pipe opening should be greater than the D_{85}, of the drainage layer material.

Geocomposites are plastic drainage cores wrapped in geotextile filter fabric. They have been used as collector pipes in underdrain applications and can eliminate the need for drainage layers. Experience has shown that geocomposites are much more likely to fail from clogging and are difficult to maintain. They should never be used if greater than 15% of the surrounding material passes the No. 200 sieve.

18.4.5 Outlet Design

Outlets for pipe underdrains and subsurface drains must be provided to convey collected water to the surface drainage system. Pipe used for this purpose is non-perforated and backfilled with low permeability soil.

The location of outlets is often dictated by the topography and configuration of surface drainage features. Design and analysis must take this into consideration. The following criteria are recommended in subsurface drain outlet design:

- Outlet pipe size must always be greater than or equal to the collector pipe size;
- Outlets must always be provided at less than 1,000 ft intervals;
- Outlets into ditches and storm drains should be at elevations greater than the 10-year flood level;
- Outlets should be protected with rodent screens to prevent small animals from entering the system;
- Outlets should be provided with headwalls that protect against damage from maintenance activities, animals and traffic; and
- Outlet markers must be provided at subsurface drain outlets to assist in location for maintenance and inspection.

The outlet system must be maintained to ensure performance through the life of the facility. Blockage of the outlet can occur from vegetation, siltation, animal activity or maintenance activities. Only through regular maintenance and inspection of the outlet can the functioning of the subsurface drain be verified and problems rectified. Subsurface drain outlets should be inspected annually and after unusual precipitation events.

In addition to the outlets themselves, outlet markers must be kept in good condition.

18.4.6 Appurtenances

It is important that access be provided to underdrains to facilitate inspection and maintenance of the system with periodic high pressure flushing. Clean-outs should be provided at 300 ft intervals, at grade changes and at changes in alignment. Clean-out risers should be protected from the same hazards as outlets.

18.5 DRAINABLE PAVEMENT SYSTEMS

18.5.1 Introduction

Water in pavement subgrade has long been recognized as a primary cause of premature pavement distress, deterioration and failure. When present in subgrade or base coarse for any length of time, water has been shown to weaken both concrete and asphalt pavements. Every year approximately $15 billion in damage

(Cedergren, 1988) occurs on undrained or poorly drained pavement in the U.S. To minimize the detrimental effects of water in pavement subgrades the following must be accomplished:

- Minimize the water entering the pavement structure; and
- Provide rapid drainage for water that does enter.

The first priority in mitigating the detrimental effects of water in the subgrade is to prevent it from entering. It is essential that all joints and cracks in pavements are sealed to prevent infiltration from the roadway surface. All borrow and median ditches must be graded to ensure positive drainage and prevent infiltration into the subgrade from ponding water. Underdrains, as discussed in Section 18.4, are often used to intercept seepage before it enters the subgrade and lower groundwater levels that could reduce the pavement life.

The second means of mitigation against water damage to pavement structures is providing drainage away from the pavement (Figure 18.4). Drainable pavement systems have been developed to do this. Although they will provide drainage for water from subsurface sources, subpavement drainage systems are primarily intended to collect water that infiltrates into the pavement structure through the pavement itself.

18.5.2 Permeable Base and Edgedrains

Drainable pavement systems are an effective means of removing water from the subgrade and prolonging the life of pavements. It has been found that by installing subpavement drainage systems, the life of asphalt pavements can be prolonged by up to 33% and the life of rigid concrete pavements can be extended by up to 50%.

A subgrade drainage system is composed of:

- A permeable base composed of coarse aggregate with high permeability to provide rapid drainage away from the pavement and provide additional support for the pavement structure and construction operation. A permeable base performs the same function as a drainage layer discussed in Section 18.4.
- A separator layer (filter layer) to prevent fine subgrade particles from entering and clogging the permeable base and edgedrain.
- A longitudinal edgedrain to rapidly convey water collected in the permeable base away from the roadbed. It has the same components and configuration as pipe underdrain discussed in Section 18.4.

18.5.3 Design Approach

Subpavement drainage systems must be designed to both convey all of the water which infiltrates into the pavement through and away from the pavement structure and drain that water in as short a time period as possible. It requires hydraulic calculations to predict the following flow conditions:

- The rate of infiltration into the pavement for the design storm (usually the 2-year 24-hour rainfall);
- The discharge rate from the permeable base into the edgedrain system; and
- The flow rate in the pipe edgedrain.

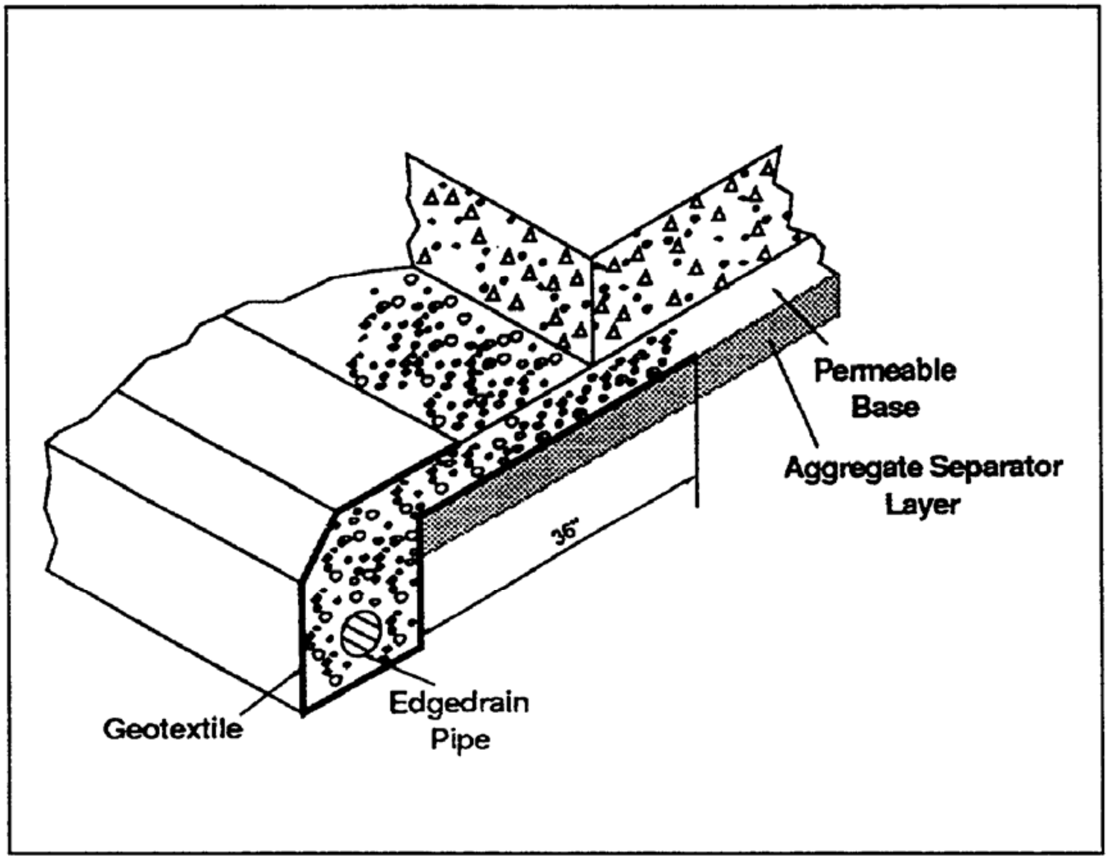


Figure 18.4. Typical pavement drainage system (FHWA, 1992)

These hydraulic calculations can then be used to design the drainable pavement system and determine the requirements for each system component. The following must be determined:

- Longitudinal and lateral extent of permeable base coarse;
- Permeable base coarse permeability;
- Permeable base coarse thickness;
- Cross slope of permeable base coarse;
- Filter/Separator requirements;
- Perforated edgedrain pipe size;
- Edgedrain slope;
- Outlet pipe interval; and
- Outlet pipe location.

Each of these drain components should be sized to ensure that the entire system is adequate to remove all of the water infiltrated during the design storm. It should also be designed to ensure removal at least 50% of the water within the system, from fully saturated conditions, in the first one hour after a rainfall event.

Drainable pavement systems are complex hydraulic features and should be designed by the Hydraulics Engineer. Design methodology should be consistent with those provided in Demonstration Project 87 - Drainable Pavement Systems (FHWA-SA-92-008) (FHWA, 1992).

18.5.4 Design Criteria

The following criteria are recommended for the design and construction of pavement drainage systems:

Permeable base

- A minimum permeability of 1,000 ft/day is recommended for the permeable base. The permeable base should be composed of angular crushed aggregate with 100% passing the 1 1/2 inch sieve and less than 2% passing the No. 16 sieve;
- The permeable base should have a minimum thickness of 4 inches; and
- If construction activity is expected on the base before paving, the base should be stabilization.

Edgedrains

- Minimum slope recommended is 0.5% and should never be less than 0.2%;
- Minimum size for edgedrain pipe is 4 inches; for lengths greater than 250 feet, minimum size should be 6 inches;
- If subgrade soil has greater than 15% passing the No. 200 sieve, geocomposite edgedrains will not be used; and
- An edgedrain should be provided across and perpendicular to the roadway at sag vertical and superelevation transitions.

Separator Layer

- Separator layer can be either a granular or geotextile filter and must meet the filter criteria provided in Section 18.4.2; and
- A 6 inch layer of aggregate base coarse is often adequate for use as a separator layer. Granular filter requirements should be checked.

Outlet pipe

- Outlet pipes should be on a slope of greater than 3% if possible;
- Outlet spacing should not exceed 300 ft; and
- In addition, the outlet pipe should meet the same design criteria as the underdrain outlet pipe discussed in Section 18.4.5.

18.5.5 Criteria For Using Pavement Drainage Systems

Pavement drainage systems can be a very effective means of prolonging the life of new and existing pavement but because of the additional initial cost, an evaluation of cost effectiveness should be made. An economic evaluation that considers the reduction in maintenance costs and extended service of the pavement with drainage is essential in determining if the subpavement drainage system is justified.

The following conditions should be used as criteria in determining if subgrade saturation will occur and a pavement drainage system should be considered:

- Distress or failure of existing pavement due to presence of subsurface water;
- Water table is in close proximity to pavement;

- Subgrade soils have permeability less than 1 ft/day, Typically, silts and clays;
- Subgrade soils are frost susceptible (typically silts - a discussion of frost susceptibility is provided in section 18.5.7);
- Presence of swelling soils in the subgrade;
- Pavement is located at a sag vertical or under a bridge structure;
- Pavement will have a wide typical section in low flat terrain;
- Pavement in cut sections; and

In addition, all new concrete pavements and asphalt pavements greater than 8 inches thick should be considered for permeable base and edgedrain systems.

18.5.6 Stabilized Permeable Base

The primary purpose of stabilizing permeable base is to provide a stable working platform during construction. If construction traffic is expected on the permeable base before paving, a stabilized base should be used. Stabilized bases must still be graded to permit permeabilities of greater than 1000 ft/day.

Permeable bases can be stabilized either with asphalt or portland cement. Asphalt content is recommended to be two percent to three percent in asphalt stabilized bases and cement content is recommended to be applied at a rate of two to three bags of Portland cement per cubic yard of aggregate.

18.5.7 Retrofit Edgedrains

Providing retrofit edgedrains at the shoulder of existing pavement has been used in a number of states in an attempt to prolong the life of existing concrete pavements. Results of using retrofit edgedrains have been mixed and it is questionable whether they have been cost effective.

Successful performances of retrofit edgedrains have been limited to pavements under 10 years old and with only minimum cracking and faulting. In some cases, however, the existing pavement and base may have deteriorated to the point that retrofitting an edgedrain system may have accelerated the deterioration of the pavement or base. Retrofit edgedrains were found to have been most successful in sandy soils. Because they are particularly prone to clogging, geocomposite edgedrains were found to have a poor record. Geocomposites should not be used on retrofit edgedrain projects except in sandy soils and when construction of a trench for a pipe edgedrain is prohibited.

18.5.8 Frost Action

Every year Colorado roads are subject to damage from what is known as spring break-up. Excessive moisture builds up in pavement subgrade during the winter months and causes localized pavement failures when pavement structures undergo a number of freeze-thaw cycles.

Frost damage is caused primarily by capillary water. Capillary water is moisture drawn upward from the water table by forces attributed to attraction between soil particles and water. Capillary rise is greatest in the winter months because flow is influenced by the temperature gradient. Capillary water will flow at an increased rate towards zones of cold temperature. This water freezes near the surface and forms ice lenses which can grow to the extent that they heave the pavement. These lenses melt when temperatures rise, increasing water content in the subgrade and reducing the strength of the pavement structure.

Frost susceptible soils are soils with a fabric that facilitates the drawing of water upwards and have sufficiently low permeability that they do not freely drain. Silts are the most susceptible to capillary action and frost damage. Coarse grained soils don't provide sufficient attraction to water molecules to create significant capillary rise and are permeable enough to drain rapidly before damage occurs. Clays are relatively impermeable and act as a barrier to capillary rise and subsequent frost action.

Measures to control frost damage in highway pavements include:

- Replacing frost susceptible soils with non-frost susceptible material to the depth of expected frost penetration;
- Removing or intercepting water before it enters the pavement structure;
- Protecting the pavement structure from freezing temperatures; and
- Lowering the water table.

Providing permeable base and edgedrain systems where frost susceptible soils are present should be considered in frost prone areas. They will act to drain moisture away from the pavement rapidly and the coarse grade of the permeable base will limit capillary rise. Styrofoam insulation, chemical additives and impervious membranes placed under the pavement have been successfully employed as mitigation against frost damage.

18.6 SLOPE STABILIZATION WITH DRAINAGE

18.6.1 Introduction

Slope stability is one of the most important considerations in highway design. Failure of highway cut or fill slopes can be extremely expensive and difficult to correct. Any widening or grade change should be evaluated by the Geotechnical Section to address the potential for slope instability.

Slope instability results when the slope's downward driving force exceeds the soil's resisting force. Most natural slopes are in equilibrium such that the soil strength is greater than the downward driving force. Changes in the force distribution can lead to slope failures.

Roadway fills above the slope or on the slope itself can increase the downward driving force. Roadway fills can also effectively dam subsurface water if the fill material is less permeable than the slope material. This too can increase the downward driving force by increasing seepage forces in the slope. The contact between the fill and the existing slope can be a zone of weakness and subsurface water can act to lubricate this contact and cause failures.

Roadway cuts can remove weight at the bottom of slopes and reduce stability. Cut slopes can also intercept groundwater tables and seepage through the slope face can cause surface erosion and sloughing.

Remedial measures that are used for slope stabilization can be divided into the following categories:

- Reducing the driving forces;
- Increasing the resisting forces; and
- Providing drainage (surface and subsurface)

Driving forces can be reduced by providing flatter slopes, reducing seepage forces and replacing slope material with light weight fill. Resisting forces can be increased by providing buttressing at the toe of slope.

Surface drainage to prevent infiltration into the slope is important. Ditches or irrigation channels on slopes should be lined when practical. Tension cracks should be filled in and slope scarps and depressions that could pond water should be contoured so they drain.

The following sections discuss several methods of subsurface drainage that can be used alone or in combination to improve stability of slopes.

18.6.2 Interceptor Drains

Underdrains

Deep underdrains can be used to lower groundwater levels in slopes and intercept seepage before it can reach the slope face. Interceptor drains are most effective when deep enough to intercept an impervious layer below the surface. Although interceptor drains as deep as 30 feet have been constructed in Colorado, construction techniques and worker safety should be considered before recommending an underdrain. Often other drainage methods will need to be considered when subsurface drainage is required at greater depths.

If continued movement of the slope is possible, perforated pipe in an underdrain is likely to rupture and fail. This may warrant using an aggregate drain without a collector pipe (french drain).

Interconnected Belled Caisson Drains

Interconnected belled caisson drains are usually used to lower groundwater levels on unstable slopes where depths restrict the use of underdrains.

A caisson drill rig is used to auger a line of large diameter holes. The bottom of each hole is belled such that each hole is interconnected. The belled caisson holes are filled with a coarse aggregate drainage material immediately after drilling. This is done one caisson at a time until the drain is complete. Vertical and horizontal control is essential to ensure that continuity and positive drainage is provided between adjacent bell sections. Caisson drains are outlet with non-perforated pipe that is stubbed into the last caisson bell. The outlet pipe is typically larger in diameter than underdrain outlet pipe because of the large flow capacity of these drains.

Interconnected belled caisson drains must be established in material which is firm enough to support them; usually shales. The use of this method is limited to those locations where this condition can be met.

18.6.3 Blanket Drains

A drainage blanket is a very permeable layer of material. It can be used to remove water from beneath pavement structures when applied as a permeable base or can be used effectively to control groundwater from cut slopes and beneath fills.

In slope stability applications drainage blankets improve slope stability by preventing a seepage surface from developing on the slope and by providing a buttressing effect. Drainage blankets are also used as an interface between embankment and soft foundations to provide drainage during foundation consolidation. Blanket drains often require a collection system and transverse pipe underdrains may be needed to outlet the blanket.

18.6.4 Horizontal Drains

Horizontal drains can be relatively inexpensive and effective in lowering groundwater levels and relieving stresses on slopes, sidehill fills and behind retaining structures. Their principle use is in slope stabilization applications.

A horizontal drain is a perforated or slotted pipe advanced into a slope with a special auger typically at 5 degrees above horizontal. The last 10 ft of pipe should be left unperforated to assure that water flows out. Filter material or filter fabric should be used if clogging is expected. This can greatly extend the life of the drain but is extremely difficult to install. Horizontal drains should be designed by the Geotechnical Section. They are commonly installed in fan-shaped arrays of several pipes emanating from a common point. Construction of horizontal drains can often be complicated depending on the drilling capabilities and techniques used. Soil conditions and moisture can affect stability of borings. Horizontal and vertical control are essential to ensure that the drains are installed as intended.

Regular maintenance and inspection of horizontal drain installations is critical to ensure effectiveness. Horizontal drains can clog from precipitation of metals, piping of fine particles and root penetration. Clogged drains can sometimes be cleaned with high pressure water systems. Drains installed in unstable soil slopes which continue to move after installation can fail. Steady discharge from the drain may cause dense vegetation to grow at the outlet which can conceal and plug the outlet if regular maintenance is not performed.

18.7 STRUCTURE AND FOUNDATION DRAINAGE

18.7.1 Retaining Wall and Slope Paving Drains

Retaining walls, bridge abutments and slope paving can often act as a barrier to groundwater flow. Groundwater levels will rise behind the structure, increasing lateral stresses against the structure and forcing the piping of material around the end of the wall.

Drainage measures behind retaining structures and abutments are absolutely necessary and an integral part of retaining wall design. Structure and foundation drainage will prolong design life by reducing hydrostatic pressures against the structure and reducing deterioration due to prolonged wet conditions. Both granular and geocomposite drains can be used. Both have been found to be effective in removing water and protecting against hydrostatic pressures behind walls. Details of subsurface drain applications behind retaining walls and abutments are provided in CDOT M- Standard 605- 1.

18.7.2 Wick Drains

Wick drains are used to accelerate the consolidation of soft and compressible soil materials, usually with surcharge loads. They are plastic cores wrapped in filter fabric and advanced through the soil to be consolidated with a mandrel. These soils are usually highly compressible but with adequate drainage can be made suitable for foundations.

Wick drains are installed to provide a shorter drainage path for pore water to escape from consolidating soils. Pore water under pressure due to embankment and surcharge loads will flow to the drain and be forced upward and away from the soil, speeding up the rate of consolidation.

Wick drain design is very specialized and requires a thorough understanding of the consolidation process. Wick drains should be designed by the Geotechnical Section.

18.7.3 Drop Structures and Culverts

Seepage forces and subsequent internal erosion of backfill and foundation material can cause failures of surface, drainage structures. Drainage structures provide an impervious surface along which hydrostatic uplift forces and groundwater percolation can occur. Culverts, rundowns and drop structures should be designed with components that minimize the destructive effects of subsurface flow.

Culverts in areas of high or fluctuating water tables should be fitted with cutoff collars at both the inlet and outlet. Intermediate cutoff collars should be considered for long culverts, greater than 100 feet in these areas. Cutoff collars will increase the path length of water percolating along the culvert and reduce seepage velocities and erosion, of backfill material. Special bedding and. structure backfill that will resist internal erosion forces should also be considered in seepage prone areas.

Drop structures and rundowns are particularly prone to the erosion of foundation material. Toe walls should always be provided with these structures to prevent erosion of foundation material and undermining at the end of the structure. If uplift force are expected a cutoff wall at the upper end of the drop should be provided. Intermediate cutoffs should also be considered in long drop structures or rundowns.

18.8 CONSTRUCTION CONSIDERATIONS

Not all groundwater problems can be identified during the design process. Often groundwater and seepage are encountered during construction. This can complicate and add delays and cost to the project if not appropriately addressed.

When this occurs, the Hydraulics Unit and Geotechnical Section should be contacted to assess the problem and provide support to the construction engineer. Most often they will be able to provide the construction engineer with timely and practical solutions to remedy the problem without adversely affecting the construction schedule or budget.

18.9 WATER QUALITY CONSIDERATIONS

Groundwater dischagre to the surface with subsurface drains must meet the same water quality requirements as surface water discharges. Caution must be exercised when using subsurface drains in areas with potentially contaminated groundwater. Contaminated groundwater should not be discharged into surface waters due to regulatory requirements and possible liability problems. The REM should be notified as early as possible when subsurface drains are being used in contaminated areas to ensure that adequate testing and field sampling has been performed and that the Department does not violate any water quality regulations or laws.

18.10 MAINTENANCE AND INSPECTION

Regular maintenance is often neglected but is essential to sustaining the operating capacity of a subsurface drainage system. Maintenance should involve both corrective and preventative measures and an inspection and maintenance plan should be implemented for all subsurface drainage systems.

Regular annual inspections shouls be performed to identify debris and flow impediments such as vegetation growth adjacent to outlets or mineral deposition and sediment accumulation within the system. Clean-outs should be inspected and outlet markers should be repaired or replaced when damaged or deteriorated.

Any evidence of operational problems such as prolonged standing surface water within the limits of the system are indications that corrective maintenance is required. If repair of an existing subsurface drainage system is required original materials and dimensions should be utilized to the extent possible.

High-pressure hydraulic cleaning should be performed annually for the first several years after construction. Regular inspection should help determine appropriate intervals for cleaning of a subsurface drainage system after that.

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