

18 Groundwater and Seepage

TABLE OF CONTENTS

18.1 INTRODUCTION 18-3

- 18.1.1 Purpose 18-3
- 18.1.2 Sources of Groundwater 18-3
- 18.1.3 Impacts of Groundwater on Highway Projects 18-4

18.2 PRELIMINARY INVESTIGATION 18-5

- 18.2.1 Identification of Subsurface Water 18-5
- 18.2.2 Field Investigations 18-6

18.3 ANALYSIS OF GROUNDWATER PROBLEMS 18-6

- 18.3.1 Introduction 18-6
- 18.3.2 Darcy's Law 18-6
- 18.3.3 Determination of the Coefficient of Permeability 18-7
- 18.3.4 Flow Rate Determination 18-7

18.4 UNDERDRAINS 18-8

- 18.4.1 Introduction 18-8
- 18.4.2 Filter Design 18-10
- 18.4.3 Drainage Layer Design 18-13
- 18.4.4 Collector Pipe Design 18-14
- 18.4.5 Outlet Design 18-14
- 18.4.6 Appurtenances 18-15

18.5 DRAINABLE PAVEMENT SYSTEMS 18-15

- 18.5.1 Introduction 18-15
- 18.5.2 Permeable Base and Edgedrains 18-16
- 18.5.3 Design Approach 18-16
- 18.5.4 Design Criteria 18-17
- 18.5.5 Criteria for Using Pavement Drainage Systems 18-18
- 18.5.6 Stabilized Permeable Base 18-18
- 18.5.7 Retrofit Edgedrains 18-19
- 18.5.8 Frost Action 18-19

18.6 SLOPE STABILIZATION WITH DRAINAGE 18-20

18.6.1 Introduction 18-20

18.6.2 Interceptor Drains 18-20

18.6.3 Blanket Drains 18-21

18.6.4 Horizontal Drains 18-21

18.7 STRUCTURE AND FOUNDATION DRAINAGE 18-22

18.7.1 Retaining Wall and Slope Paving Drains 18-22

18.7.2 Wick Drains 18-22

18.7.3 Drop Structures and Culverts 18-22

18.8 CONSTRUCTION CONSIDERATIONS 18-23

18.9 WATER QUALITY CONSIDERATIONS 18-23

18.10 MAINTENANCE AND INSPECTION 18-23

REFERENCES 18-24

18 Groundwater and Seepage

18.1 INTRODUCTION

18.1.1 Purpose

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

This chapter discusses the effects 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 interaction between the hydraulics, geotechnical and roadway engineers.



Photo 18.1

18.1.2 Sources of Groundwater

There are many sources of water that 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 and 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 the 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 their impacts on highway projects.



Photo 18.2

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, they can significantly impair 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.

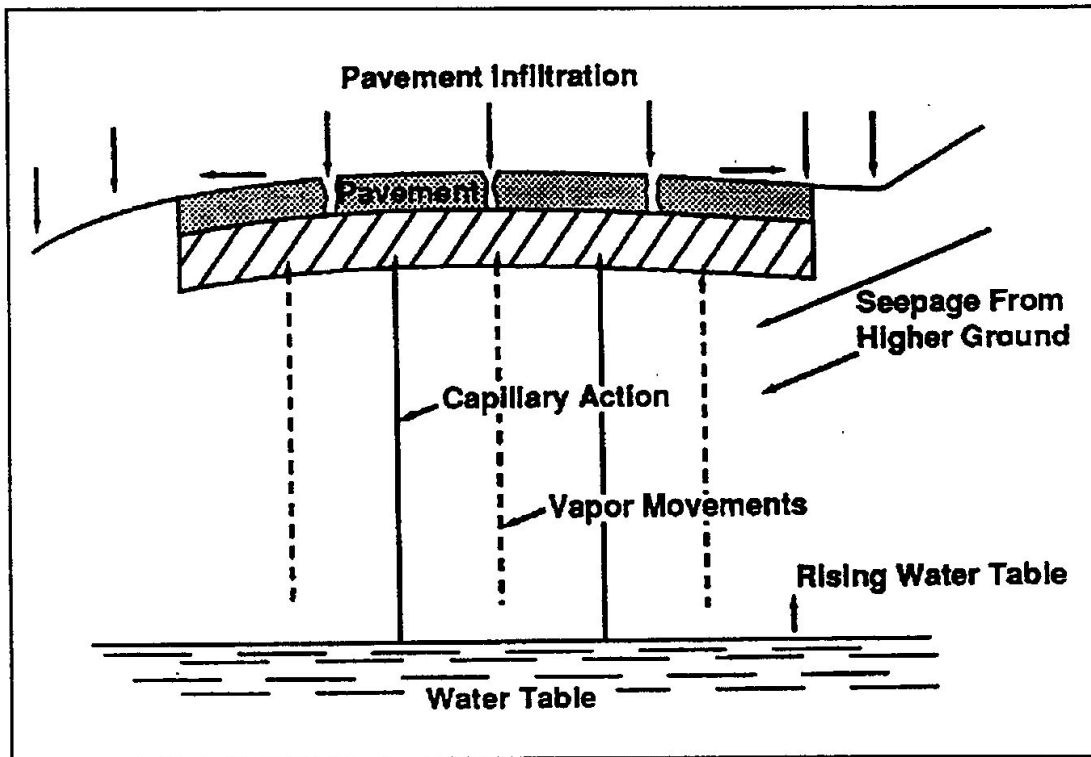


Figure 18.1 Sources of Subsurface Water in Pavements (FHWA, 1992)

18.2 PRELIMINARY INVESTIGATION

18.2.1 Identification of Subsurface Water

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

The first step in addressing a groundwater problem is recognizing 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 the highway;
- Cattails or wetland vegetation growing in a borrow ditch or on slopes;
- Seepage from cut or natural slopes;
- Evidence of slope instability such as scarps, old landslides, and trees at unusual angles.

If any of these are observed, the Region Geotechnical Section and/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 depends on the accuracy of the 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 soil characteristics for the design of subsurface drainage structures often requires extensive field investigation and a subsurface exploration program. These activities are carried out by the Region 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 is needed, monitoring wells can be installed and monitored until enough data is acquired. Groundwater monitoring also can be essential for successful design of wetland mitigation.

Engineering properties of soils are determined by laboratory and field tests. Laboratory tests determine soil grain-size distribution, coefficient of permeability, and frost susceptibility. Water and soil chemistry also can be analyzed 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 method for 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 maximizes the probability of designing subsurface drainage features that 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 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:

$$Q = k i A \quad (18.1)$$

where: Q = discharge through an area (volume/time); k = coefficient of permeability (length/time); i = hydraulic gradient, the ratio of change in water level and linear distance of fluid flow (dimensionless); A = area through which flow occurs (length²).

Darcy's law is valid within the range of steady-state, laminar flow. It is valid 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 3000 ft/day.

18.3.3 Determination of the 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 preferable to determine permeability by direct methods in the laboratory or field. These methods include:

- Laboratory - constant head test and falling head test; and
- Field - pump tests.

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

Although field or laboratory determinations of permeability are ideal, they are both expensive and difficult. 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 is related to grain size by Hazen's Formula:

$$k = C (D_{10})^2 \quad (18.2)$$

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 soil properties. In natural deposits and some compacted soils permeability may be much greater in one direction than in another. The coefficient of permeability for a soil is very difficult 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 for 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 used. 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 properly designed and constructed. Many pavement and slope failures can be prevented by 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. The 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 are effective 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 the cut slope;
- In areas where the ground is nearly level, longitudinal pipe underdrains may be constructed along both sides of the roadway bed, near the toe of the 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 curves, or in cut sections in contact with an impervious layer;
- Transverse underdrains can also be placed at transitions from cut to fill to prevent saturation, settlement, and instability in fill sections.

The location and depth of underdrains depend largely on the intended function and local geology. Whenever practical, the bottom of the underdrain should be placed at a depth below the impervious bedrock boundary which is below the aquifer. Underdrains can exceed depths of ten

feet and have successfully been built to depths exceeding 30 feet in Colorado. Deep underdrains require increased 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.

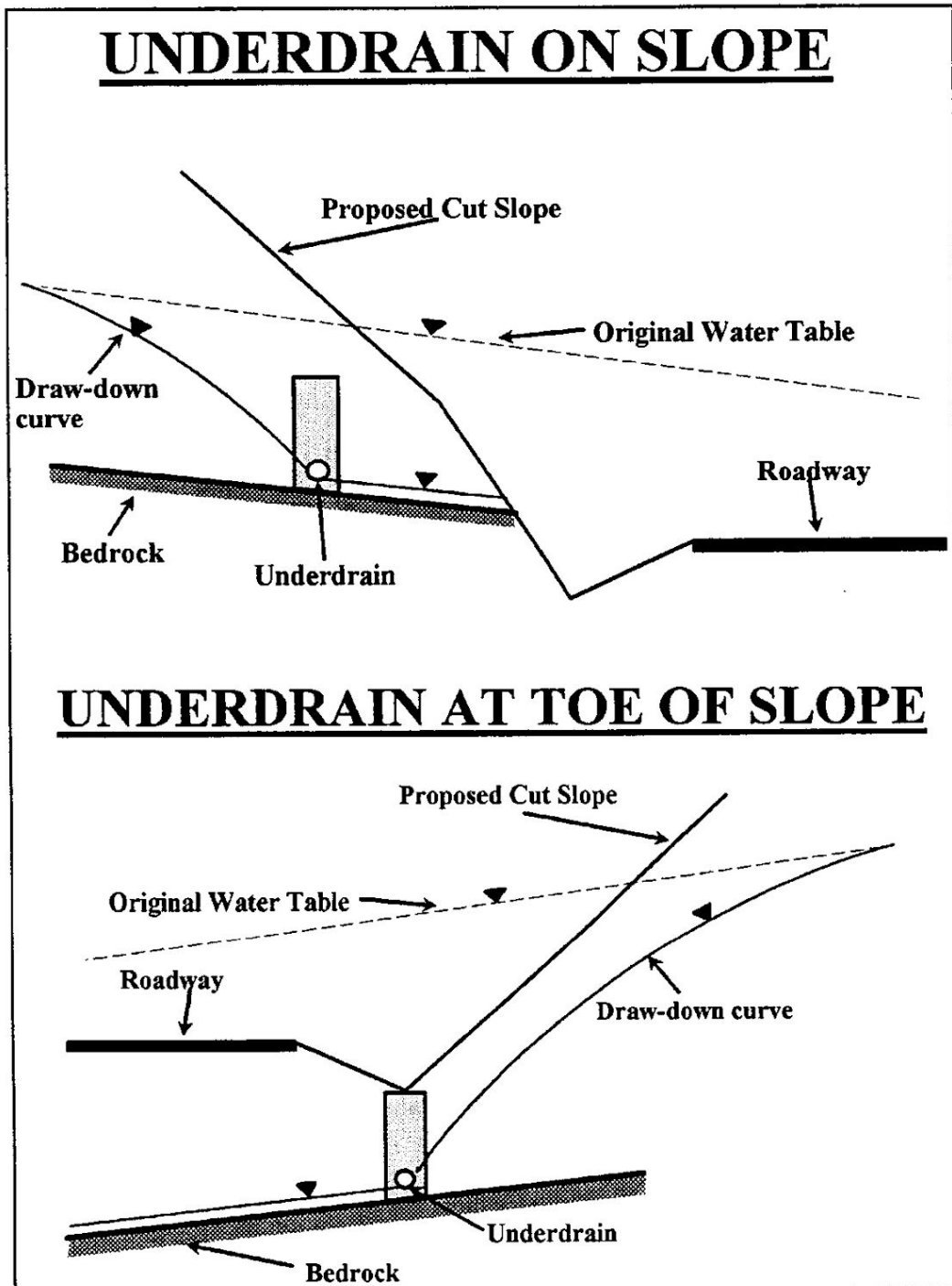


Figure 18.2 Intercepting groundwater with underdrains.

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 result in 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 basic components of a subsurface drainage system:

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

It is important for the designer 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 repetitive loading of traffic. As such, the selection of compatible filter material can be the most critical aspect of subsurface-drain design.

Filters serve two main functions in subsurface drains:

- Prevent erodible material from entering 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 by fines and clogging, the filter must satisfy certain design criteria. Either granular material or geotextiles can be used as a filter.

Granular Filter Design

There are numerous criteria used for granular filter design. CDOT has adopted criteria developed by the USBR and used by FHWA. A filter must meet the following requirements for the filter/soil interface:

1. Filtration Criteria

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

2. Uniformity Criteria

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

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

3. To ensure that the granular filter is well graded and stable, the coefficient of uniformity (C_u) must be within the range:

$$20 \leq C_u \leq 40 \quad (18.5)$$

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

A granular filter should not allow more than 5% passing the No. 200 sieve. If a single layer of filter material does not satisfy the above criteria, one or more additional filter layers must be used. In addition to 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 encroach and clog the permeable drainage material. The filter criteria apply between the subgrade material and filter, between successive layers of filter material if more than one layer is used, and between the filter layer and drainage material contained within the subsurface drain. The same criteria as above are used with the drainage layer replacing the filter, and the filter replacing the subgrade.

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

Geotextile Filter Design

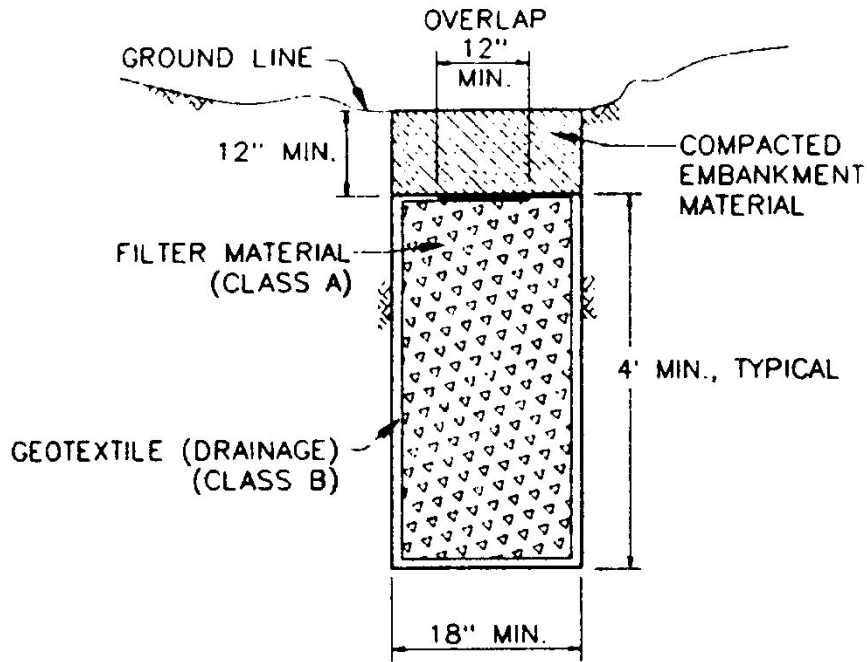
Geotextiles are commonly used as filter material on vertical and sub vertical trench walls because of ease of installation and effectiveness in providing filtration. However, there are many documented instances of subsurface-drain failures caused by clogging of geotextile filters. These failures have been due mainly to lack of, or improper design.

Selection of a geotextile requires careful analysis to ensure that it will be compatible with the surrounding soils. It is 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 and placed properly. 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 provided in project special provisions. Geotextile design requires consideration of the material's:

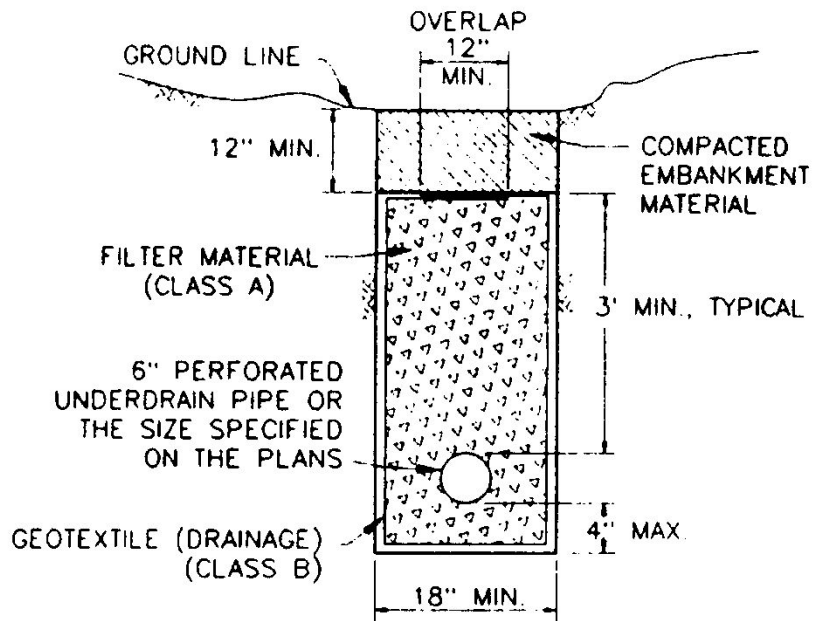
- Soil-retention characteristics;
- Permeability;
- Susceptibility to clogging; and
- Durability.

Criteria for selection of geotextiles for filter and drainage applications 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, *AOS* is the apparent size of openings in the geotextile. Use the U.S. standard sieve number closest to the geotextile opening size. *AOS*

is sometimes referred to as the effective opening size, expressed in millimeters as O_{95} . Coefficient B is a parameter relating the coefficient of uniformity to the effective opening size.



FRENCH DRAIN



PIPE UNDERDRAIN

Figure 18.3 Typical underdrains (CDOT M-Standard 605-1)**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	
$AOS O_{95} \leq B D_{85}$	Can Move	Cannot Move
$C_U \leq 2$ or $\geq 8B = 1$ $2 \leq C_U \leq 4B = 0.5C_U$ $4 \leq C_U \leq 8B = 8/C_U$	$O_{95} \leq D_{15}$	$O_{50} \leq 0.5D_{85}$

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

II. PERMEABILITY CRITERIA

A. Critical / Severe Applications	B. Less Critical / Less Severe Applications (with Clean Medium to Coarse Sands and Gravels)
$k \text{ (fabric)} \geq 10k \text{ (soil)}$	$k \text{ (fabric)} \geq k \text{ (soil)}$

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 ≤ 3	<ol style="list-style-type: none"> 1. Select fabric with maximum opening size possible (lowest AOS No.). 2. Effective Open Area Qualifiers: Woven fabrics: Percent Open Area $\geq 4\%$ Nonwoven fabrics: Porosity $\geq 30\%$ 3. Additional Qualifier (Optional): $O_{95} \geq 3D_{15}$ 4. Additional Qualifier (Optional): $O_{15} \geq 3D_{15}$

18.4.3 Drainage Layer Design

A drainage layer is provided to rapidly convey intercepted water into a 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 aggregate should have considerably higher permeability than the material that will surround the drain. It is important that the designer determine availability of aggregate sources for the drainage layer, and the permeability of soils in the project area. This information will aid the engineer in determining underdrain capacity, required cross-sectional area and slope, and in evaluating the need for a collector pipe. Capacity of the drainage layer is determined using Darcy's law (Equation 18.2).

Drainage material should allow no more than 2% passing the No. 200 sieve. Special care should be taken to ensure that gradation and permeability specifications are met during construction. The drainage layer must not be contaminated by fines during stockpiling at the site, and degradation of the material must not occur during transport. These requirements must be included in project special provisions to be monitored and enforced by the construction engineer.

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 an outlet. Materials used for collector 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 underdrain installations. Frequently, the granular drainage layer will be permeable enough to provide sufficient conveyance, and a collector pipe will not improve long-term performance. Although the additional material cost of the collector pipe may not be significant, labor associated with placement of the 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 capacity of the underdrain. At sites where drainage layer permeability or drain cross-sectional area is insufficient to provide 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 conveyance adequate to lower the water table. The engineer should understand that even laboratory evaluations of soil permeability are rough estimates at best, and flow rates can be significantly underestimated. Placement of a collector pipe can provide some additional safety in critical applications.

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

- The recommended minimum slope is 0.5%, and should never be less than 0.2%;
- The minimum diameter for underdrains is 6 inches. For lengths greater than 500 feet, consider increasing the minimum pipe 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 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.

However, geocomposites are much more likely to fail from clogging and are difficult to maintain. They should not 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 should be non-perforated and backfilled with low-permeability soil.

The location of outlets is often dictated by the topography and configuration of surface-drainage features. Analysis and design must consider this. The following criteria are recommended in design of subsurface drain outlets:

- Outlet pipe size must always be greater than, or equal to, the collector pipe size;
- Outlets must always be provided at intervals less than 1000 ft;
- Outlets directed to 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 to protect against damage from maintenance activities, animals, and traffic; and
- Outlet markers must be provided at all subsurface drain outlets to assist in locating them for maintenance and inspection.

An outlet system must be maintained to ensure optimum performance throughout the life of the facility. Blockage of an outlet can occur from vegetation, siltation, animal activity, or maintenance activities. Only by regular maintenance and inspection of the outlet can functioning of the subsurface drain be verified and problems rectified. Subsurface drain outlets should be inspected annually and after unusual precipitation events. Outlet markers also 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 is a primary cause of premature pavement distress, deterioration, and failure. When present in subgrade or base coarse for any length of time, water weakens both concrete and asphalt pavements. Every year more than \$15 billion in damage occurs on undrained or poorly-drained pavement in the United States. To minimize the detrimental effects of water in pavement subgrades, water entering the pavement structure must be minimized, and rapid drainage provided for water that does enter.

The first priority in mitigating the detrimental effects of water in 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 groundwater.

Drainable pavement systems direct water away from the pavement (Figure 18.4). In addition to draining water from subsurface sources, these sub-pavement drainage systems 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. By installing sub-pavement drainage systems the life of asphalt pavements can be prolonged as much as 33%, and the life of rigid concrete pavements can be extended as much as 50%.

A subgrade drainage system is composed of:

- A base of coarse aggregate with high permeability to provide rapid drainage away from the pavement, and additional support for pavement structure and construction operations. A permeable base performs the same function as a drainage layer, as 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 a pipe underdrain, discussed in Section 18.4.

18.5.3 Design Approach

Subpavement drainage systems must be designed both to convey all water which infiltrates the pavement away from the pavement structure, and to drain that water in a minimal time. Hydraulic calculations are required to predict the following flow conditions:

- The rate of infiltration through 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.

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

- Longitudinal and lateral extent of permeable base coarse;
- Permeability of the base coarse;
- Thickness of permeable base coarse;
- Cross slope of permeable base coarse;
- Filter/separator requirements;
- Size of perforated edgedrain;
- Edgedrain slope;
- Outlet pipe interval; and
- Outlet pipe locations.

Each of these drainage components must be sized to ensure the entire system removes all infiltrated water from the design storm. It should also be designed to ensure removal of at least 50% of the water within a fully-saturated system in the first hour after a rainfall event.

Drainable pavement systems are complex hydraulic features, and should be designed by a hydraulics engineer. Design methodology should be consistent with that found in *Demonstration Project 87 - Drainable Pavement Systems*, FHWA-SA-92-008 (1992).

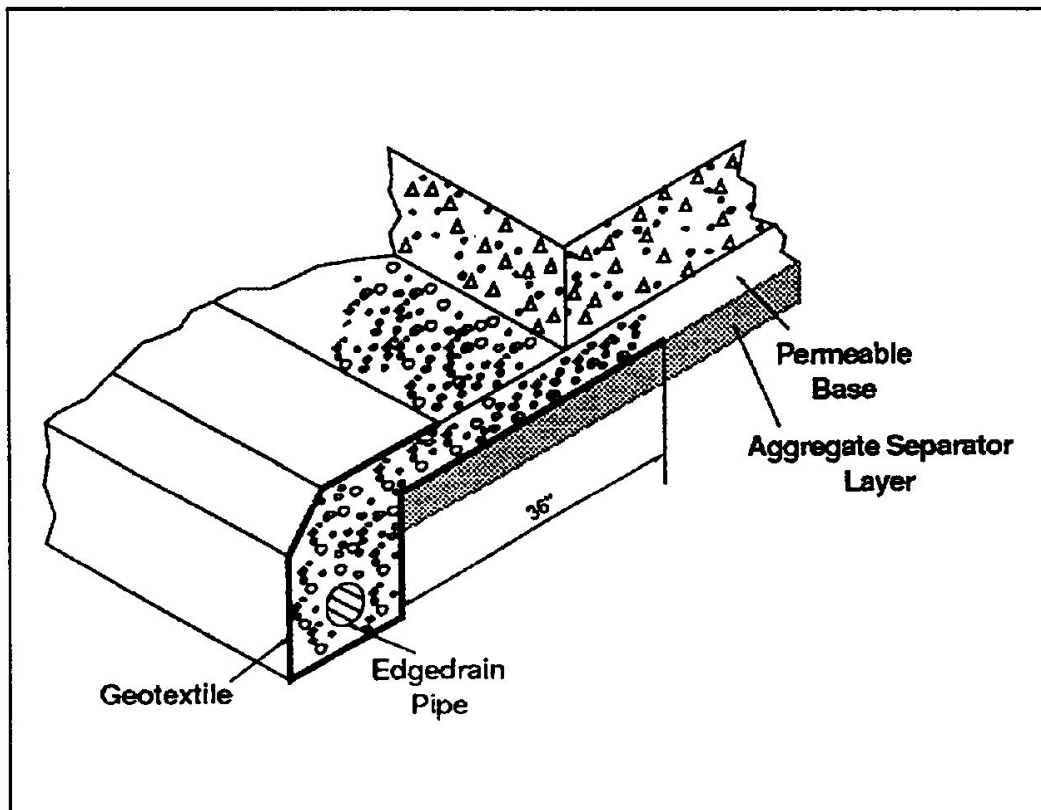


Figure 18.4 Typical pavement drainage system (FHWA, 1992)

18.5.4 Design Criteria

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

Permeable Base

- A minimum permeability of 1000 ft/day is recommended for permeable base. It should be composed of angular, crushed aggregate with 100% passing the 1.5-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 stabilized.

Edgedrains

- The minimum recommended slope is 0.5%, and should never be less than 0.2%;
- The minimum diameter of 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 must not be used; and

- An edgedrain should be provided across and perpendicular to the roadway at sag vertical curves and superelevation transitions.

Separator Layer

- A separator layer can be either granular material or geotextile filter, and must meet the filter criteria listed 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

- The slope of outlet pipes should be 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 underdrain outlet pipe, discussed in Section 18.4.5.

18.5.5 Criteria For Using Pavement Drainage Systems

Pavement drainage systems are effective for 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 considering reduced maintenance costs and extended service of the pavement is essential to determine if a 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 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 susceptible to frost (typically silts). A discussion of frost susceptibility is found in section 18.5.7;
- Presence of swelling soils in the subgrade;
- Pavement will be located at a sag vertical curve or under a bridge structure;
- Pavement will have a wide typical section in low, flat terrain; and
- Pavement in cut sections.

In addition, permeable base and edgedrain systems should be considered for all new concrete or asphalt pavement thicker than 8 inches.

18.5.6 Stabilized Permeable Base

The primary purpose of stabilized 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 be graded to allow permeability of greater than 1000 ft/day.

Permeable bases are stabilized either with asphalt or Portland cement. Asphalt content of 2% - 3% is recommended for asphalt-stabilized bases. Portland 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 attempts to prolong the life of existing concrete pavements. Results have been mixed, and it is questionable whether they are cost-effective.

Successful performance of retrofit edgedrains has been limited to pavements less than ten years old, with minimum cracking and faulting. In some cases, however, existing pavement and base have deteriorated to the point that retrofitting an edgedrain system accelerated deterioration of the pavement or base. Retrofit edgedrains have been most successfully used in sandy soils. Because they are prone to clogging, geocomposite edgedrains have a poor record of effectiveness. Geocomposites should not be used on retrofit edgedrains 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 winter months and causes localized pavement failures as pavement structures undergo freeze-thaw cycles.

Frost damage is primarily caused by capillary water. Capillary water is moisture drawn upward from the water table by forces of 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 toward zones of cold temperature. This water freezes near the surface and forms ice lenses, which can grow and 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 have a fabric that facilitates drawing water upwards, and sufficiently low permeability to not freely drain. Silts are the most susceptible to capillary action and frost damage. Coarse-grained soils do not 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 frost-resistant 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 areas prone to frost. They drain moisture away from pavement rapidly, and the coarse grade of the permeable base limits capillary rise. Styrofoam insulation, chemical additives, and impervious membranes placed under the pavement have been successfully used 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 difficult and expensive to correct. Any proposed widening or grade change should be evaluated for slope stability by the Region Geotechnical Section.

Slope instability results when the slope's downward driving force exceeds the soil's resisting force. Most natural slopes are stable with the soil strength 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 fill material is less permeable than the slope material. This also increases the downward driving force by increasing seepage forces in the slope. The contact surface between fill and an existing slope can be a zone of weakness, and subsurface water can lubricate this surface 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 for slope stabilization include reducing the driving forces, increasing the resisting forces, and providing surface and subsurface drainage.

Driving forces are reduced by providing flatter slopes, reducing seepage forces, and replacing slope material with lightweight fill. Resisting forces are increased by buttressing the toe of slope.

Surface drainage to prevent infiltration of 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 to drain.

The following sections discuss several methods of subsurface drainage used alone or in combination to improve slope stability.

18.6.2 Interceptor Drains

Underdrains

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

If continued movement of a slope is possible, perforated pipe in an underdrain is likely to rupture and fail. In this case, consider using an aggregate drain without a collector pipe (French drain).

Interconnected Belled-Caisson Drains

Interconnected belled-caisson drains are 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 the holes are interconnected. The belled-caisson holes are filled with 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. An outlet with non-perforated pipe 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 constructed in material firm enough to support them, usually shales. The use of this method is limited only to locations where this condition can be met.

18.6.3 Blanket Drains

A drainage blanket is a very permeable layer of material. It is 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, providing 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 are effective in lowering groundwater levels and relieving stresses on slopes, side-hill fills, and behind retaining structures. Their principle use is in slope-stabilization applications. Horizontal drains should be designed by the Region Geotechnical Section.

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 feet 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 are commonly installed in fan shaped arrays of several pipes emanating from a common point. Depending on the drilling capabilities and construction techniques used, installation of horizontal drains often is complicated. Soil conditions and moisture can affect stability of borings. Horizontal and vertical control are essential to ensure that drains are installed as intended.

Regular maintenance and inspection of horizontal drain installations is critical to ensure effectiveness. They 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 often act as a barrier to groundwater flow. Groundwater levels rise behind the structures, increasing lateral stresses against them and forcing piping of material around the ends of the obstruction.

Drainage measures behind retaining structures and abutments are absolutely necessary and an integral part of retaining-wall design. Structure and foundation drainage prolongs design life by reducing hydrostatic pressures against the structure, and reducing deterioration from prolonged wet conditions. Both granular and geocomposite drains can be used. Both are effective in removing water and protecting against hydrostatic pressures behind structures. 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 those with surcharge loads. These soils are usually highly compressible, but with adequate drainage can be made suitable for foundations. Wick drains are plastic cores wrapped in filter fabric, advanced through the soil and consolidated with a mandrel.

Wick drains provide a shorter drainage path for pore water to escape from consolidating soils. Pore water under pressure due to embankment and surcharge loads flows to the drain and is forced upward and away from the soil, increasing the rate of consolidation.

Wick drain design is very specialized and requires a thorough understanding of the consolidation process. They should be designed by the Region 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. These 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 table should be fitted with cutoff collars at both inlet and outlet. Intermediate cutoff collars should be considered for culverts longer than 100 feet in these areas. Cutoff collars increase the path length of water percolating along a culvert, reducing seepage velocities and erosion of backfill material. Special bedding and structure backfill resistant to internal erosion forces should also be considered in areas prone to seepage.

Drop structures and rundowns are particularly prone to 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 forces 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 unexpectedly encountered during construction. This will complicate the effort, and add delays and cost to the project if not appropriately addressed.

When this occurs, the Region Hydraulics Unit and Geotechnical Section should be contacted to assess the problem and support the construction Project Engineer. They often are able to quickly provide the engineer with practical solutions to the problem without adversely affecting the construction schedule or budget.

18.9 WATER QUALITY CONSIDERATIONS

Groundwater discharged to the surface by 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 must not be discharged into surface waters due to regulatory requirements, and may cause liability problems. The Region Environmental Manager must be notified as early as possible when subsurface drains are planned to be used in contaminated areas. This will ensure that adequate testing and field sampling are performed, and that the Department does not violate water-quality regulations or laws.

18.10 MAINTENANCE AND INSPECTION

Regular maintenance is essential to sustaining the operating capacity of a subsurface drainage system, but often neglected. 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 should 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. After that, regular inspection will help determine appropriate intervals for cleaning.

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