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DEVELOPMENT OF GUIDELINES FOR THE DESIGN OF SUBSURFACE DRAINAGE SYSTEMS FOR HIGHWAY PAVEMENT STRUCTURAL SECTIONS

CEDERGREN/KOA
A JOINT VENTURE
SACRAMENTO AND LONG BEACH,
CALIFORNIA

JUNE 1972

GUIDELINES FOR DESIGN

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16. Abstract

Design criteria and a design method for pavement subsurface drainage systems include inflow-outflow method of analysis, open graded drainage layers, collector drains, pipe outlets and markers. Design examples are given for embankment sections, cut sections and superelevated curves. Emphasis is on draining water that infiltrates the pavement structure from the surface through cracks, construction joints, and through permeable surfaces, medians and shoulders. A final section of the report covers general guidance for the design, construction and operation of subsurface drainage systems.

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PREFACE

These Guidelines were developed under Research and Development Contract FHWA-11-7852 issued by the Federal Highway Administration, Office of Research, Washington, D.C. to the Joint Venture of Cedergren/KOA.

This project has been accomplished in two phases. During Phase I, a thorough literature search was made of the past and present "State-of-the-Art" of protecting roads from the damaging effects of water with special emphasis on surface water. Extensive field surveys, reconnaissance, and interviews were also conducted and two test sites selected for Case Study to determine the magnitude of the problems being caused by undrained water in structural sections. During Phase II, seven additional Case Study sites were selected and investigated, the final report prepared, and these Guidelines developed.

The studies under the R&D contract have shown that with time, some pavements develop cracking and many others have opening of joints, thus precipitation can enter into the pavement structural section. Where this occurs, much of the damage and many of the premature failures can be blamed largely on excess water in the structural sections of highways.

Cost-effectiveness studies that were made in connection with this R&D study have demonstrated that pavements designed with subsurface drainage systems capable of rapidly draining excess water from structural sections generally have lower annual costs than undrained pavements.

These Guidelines present the methods of design of pavement subsurface drainage systems that will virtually eliminate exposure of pavement structural sections to excess water.

The procedures outlined in these Guidelines are proposed as an aid to Highway Engineers for design of pavements that, under certain conditions, should add many years of superior performance.

This guideline was prepared by the Joint Venture of Harry R. Cedergren, Consulting Engineer, Sacramento, California and Ken O'Brien & Associates, Consulting Engineers, Long Beach, California. This research and development study was authorized by the Federal Highway Administration under Contract No. FH-11-7852, dated June 26, 1970. The contents of this guideline reflect the views of Cedergren/KOA, A Joint Venture which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policy of the Department of Transportation. This guideline does not constitute a standard, specification or regulation.

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1 INTRODUCTION

The research and development studies performed to formulate these Guidelines have demonstrated that most modern highway pavement structural sections are slow draining systems, and heavy wheel impacts on these structural sections that contain free water or "excess water" are accelerating the damage and deterioration of the highways. Subsurface drains have generally been used to remove high ground water, inflows from springs, etc.; but seldom used specifically for the control of surface water that infiltrates into the highway pavement structural sections.

The purpose of these Guidelines is to show how to design drainage layers to rapidly drain entire roadbeds to reduce the periods of exposure of structural sections to excess water. The basic method considers subsurface drainage layers as conveyors of water and analyzes probable inflow rates from all known important sources (Refer to Figure No. 1). Seepage principles are then used to determine the required permeability and thickness of a subsurface drainage layer that will accommodate the anticipated flows.

Additional information on the many important aspects of subsurface drainage system design, damages caused by excess water in highway pavement structural sections, and related matters, is presented in considerable detail in the Final Report and Case Study Reports for the development of these Guidelines.

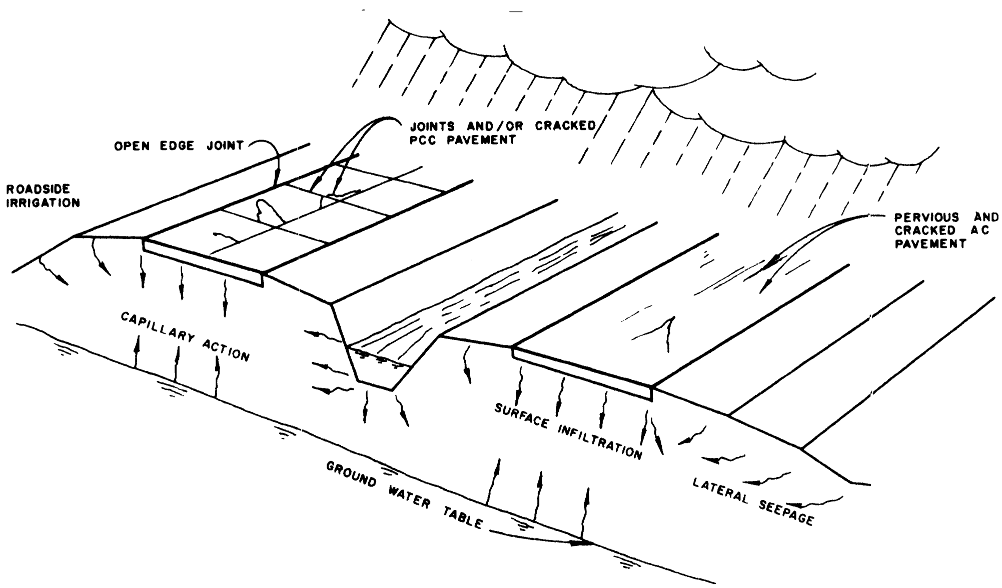

FIGURE NO. 1 - Sources of Water in Roadbeds

The purpose of subsurface drainage systems for highway pavement structural sections is to reduce damages caused by "excess water." Excess water is water which (1) creates a condition of internal flooding of the pavement structural section with free water available to produce hydrostatic pressures in cracks, voids, and other spaces; or (2) causes detrimental changes in the supporting characteristics of the structural layers.

To properly protect highway pavement structural sections, subsurface drains must be capable of removing the water as fast as it enters. Since the present "State-of-the-Art" of constructing roads does not guarantee watertightness of pavement surfaces for more than brief periods of time, subsurface drainage systems are needed for modern rigid and flexible highway pavements.

Surface water can enter into highway pavement structural sections through cracks or joints in rigid pavements; or through cracks, joints or the pavement surface in flexible pavements. Temperature changes, weathering, pavement deflection under traffic, and other actions can produce openings or highly permeable areas in road surfaces to permit water to enter pavement structural sections. Since all of the specific locations where water can enter structural sections cannot be predicted in advance, <u>subsurface drainage systems are needed for the full width of pavements that may be subjected to significant numbers of heavy wheel impacts while the sections contain excess water</u>. The foregoing is the basic concept of these Guidelines.

Subsurface drainage systems as advocated in these Guidelines consist of a layer of highly permeable open graded base placed immediately beneath paved areas requiring protection from excess water (Refer to Figure No. 2). The subsurface drainage systems must include pipe collector drains and outlets properly located to provide a permanent system that will prevent the accumulation of excess water in the structural section. The open graded base drainage layer must be protected from the possibility of becoming clogged during construction and the operational life of a pavement system. Subsurface drainage systems should not be considered as a panacea--maintenance of highway pavement surfaces by sealing of joints and cracks must be continued to minimize infiltration of surface water.

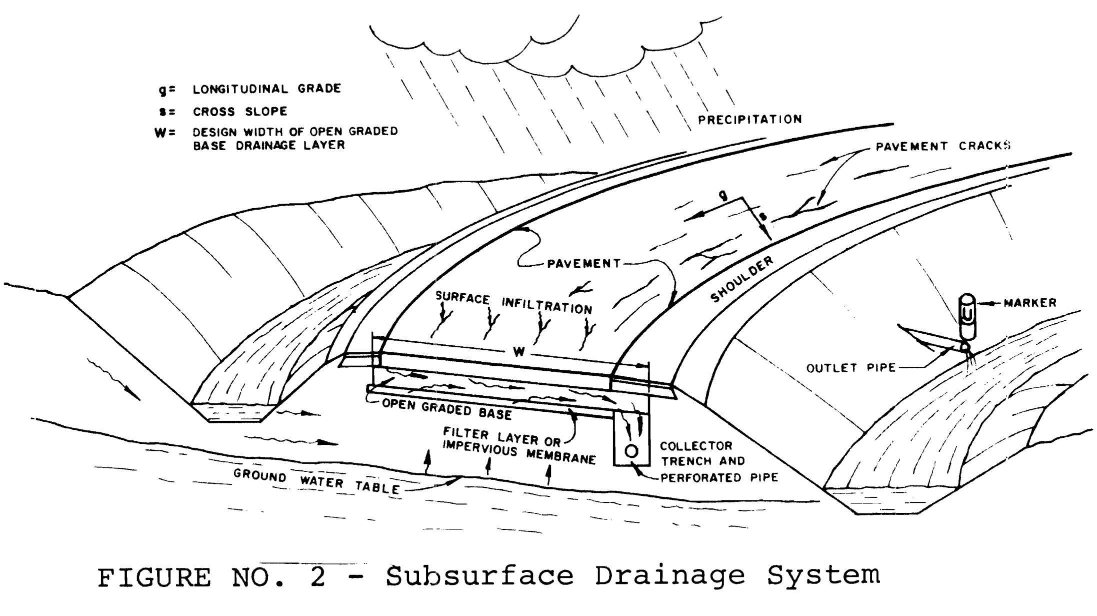

FIGURE NO. 2 - Subsurface Drainage System

Subsurface drainage systems should be provided for all important highway pavement structural sections unless economic feasibility studies indicate that they are not cost-effective, precipitation quantities and frequencies are so small that drainage is not needed, or heavy wheel load impacts per day are very small.

The recommended criteria (tentative) for determining the locations where subsurface drainage systems for highway pavement structural sections <u>may not be required</u> are as follows:

(1) Where the average annual precipitation is less than 10 inches.

(2) When the lateral drainage transmissibility of the base layer beneath the highway pavement surface is 100 times greater than the design infiltration rate (inches/hour). The design infiltration rate is 1/3 to 2/3 the 1 hour/1 year frequency precipitation.

(3) When the combined lateral drainage transmissibility of the base, and the vertical drainage capability of all underlying materials exceeds the design infiltration rate (inches/hour).

(4) When 250 or less 18,000-pound axle loads per day are predicted during the design life of rigid pavement systems.

Criteria (2) and (3) are not applicable where freezing of base, subbase and subgrade materials can occur. The average annual precipitation can be obtained from U. S. Government weather records. The 1 hour/1 year frequency precipitation rates for conterminous United States are shown on Figure No. 3. The lateral drainage capability can be determined by calculation and the permeability of subgrade can be determined by test. The number of 18,000-pound axle loads per day for rigid pavements can be forecasted by evaluating traffic data. No specified traffic volume of 18,000-pound axle loads can be indicated at this time for flexible pavements--a more detailed analysis should be made in accordance with the general procedures contained in the Final Report.

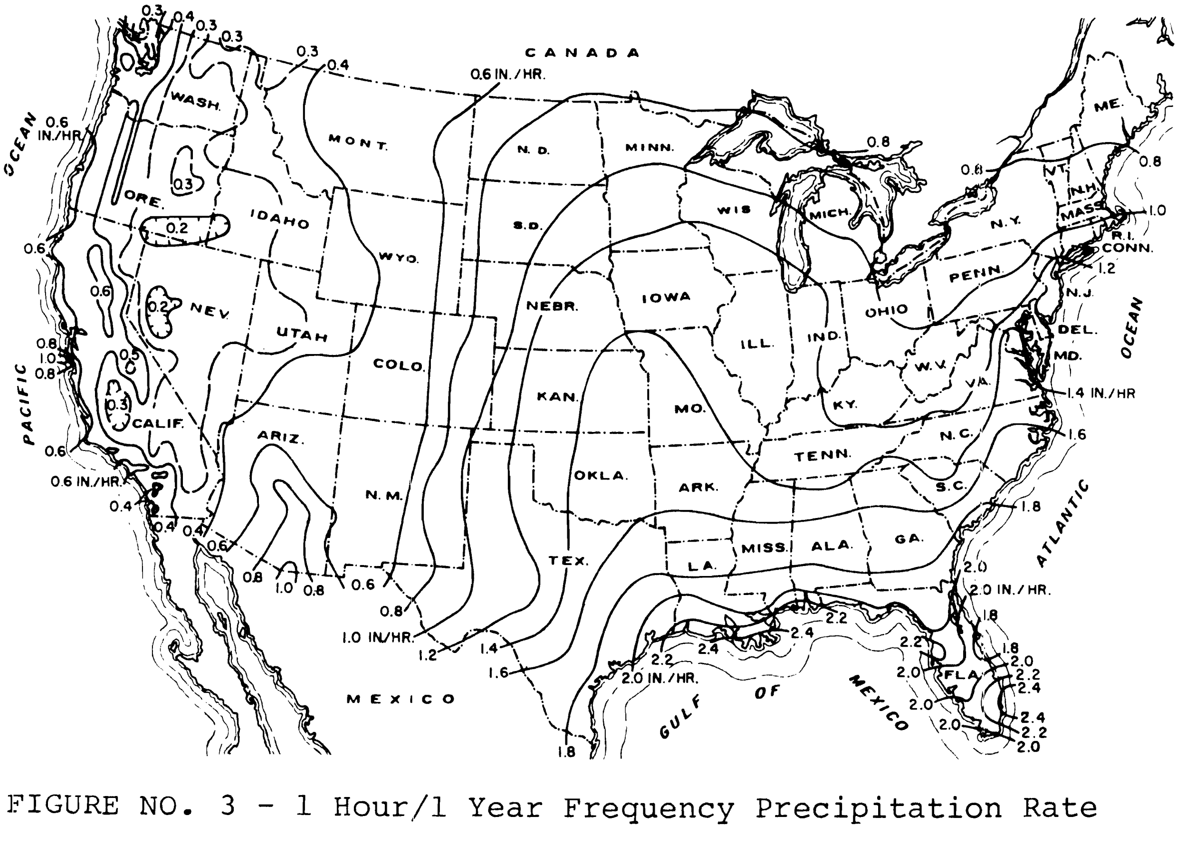

FIGURE NO. 3 - 1 Hour/1 Year Frequency Precipitation Rate

Very few roadbed sections including the subgrade will normally contain materials that have relatively high permeabilities; therefore, it is considered unlikely that the foregoing permeability criteria will apply to more than limited mileages of roads in the United States.

3 DESIGN CRITERIA FOR SUBSURFACE DRAINAGE SYSTEMS

Rapid drainage of pavement structural sections is essential and can be best achieved by placing a highly permeable drainage layer under the full width of the pavement surface. This type of system must include collector and outlet pipes. The drainage layer is an integral part of the structural section and is a substitute for a portion of the normally required base or subbase layers. Studies made in developing these Guidelines have indicated that in a majority of cases, roads designed with subsurface drainage systems as advocated by these Guidelines are more cost-effective than presently designed conventional pavement sections.

The basic components of a subsurface drainage system (Refer to Figure No. 2) are: (1) a highly permeable open graded base drainage layer, (2) filter layer or impervious membrane, (3) collector trench and perforated pipe, (4) outlet pipes, and (5) markers. In developing plans and specifications for pavement sections with subsurface drainage systems, care must be taken to visualize the three dimensional system, and to properly delineate the location and function of each component of the system. The important design and criteria for the main components are described in 3.1, 3.2, 3.3 and 3.4 following.

3.1 Subsurface Drainage Layers (Open Graded Bases or Subbases)

Subsurface drainage layers (open graded base) should be constructed immediately below the pavement surface (first layer) and should extend laterally 1 foot beneath the inside shoulder and at least 3 to 4 feet laterally beneath the outside shoulder. In the event shoulders are not paved, the top surface of the subsurface drainage layer must be protected from intrusion of fines by impermeable seals or filter layers.

Open graded bases utilized for subsurface drainage must be constructed of hard, durable aggregates and stabilized when necessary with an asphaltic binder. These types of bases have high permeabilities and can have excellent structural properties (stability) and often can be substituted "inch-for-inch" for currently accepted base course materials.

In some areas of the United States where suitable hard, durable aggregates of the sizes required to develop an open graded drainage layer are not economically available, it may prove advantageous to utilize very thin "mini" drainage layers. In such cases, open graded base layers as thin as 1-1/2 inches or 2 inches thick should be considered. However, the desirable minimum thickness of a subsurface drainage layer should be 3 inches, except in unusual situations. If thin subsurface drainage layers are used, especial care must be taken to prevent contamination of these layers to assure an effective drainage layer.

3.1.1 Discharge Capabilities of Open Graded Bases

Open graded bases or subbases to be used for subsurface drainage of pavement structural systems must be designed as conveyors of water. Total expected inflows must be estimated and shall include surface infiltration and any other significant sources of water. After estimating the inflow rate from annual precipitation and frequency records (the total of all inflows), the minimum required transmissibility of the open graded base can then be determined using Darcy's law or other suitable seepage analysis methods. The equation for Darcy's law ($Q = kiA$) can be written in the form:

$$Q/i = kA \qquad (1)$$

In equation 1, the transmissibility of the open graded base (kA) is equal to the discharge quantity (Q) divided by the hydraulic gradient (i) in the base. Any suitable combination of permeability (k) and thickness (A) will remove the anticipated flow (Q).

Charts and graphs giving potential outflow capabilities of open graded drainage layers are presented in Section 4. Several examples for the design of open graded subsurface drainage layers are presented in Section 5. Typical gradations and estimated permeability values for some filter and drain materials are given on Figure No. 4. These values illustrate the levels of permeability that are possible for a range of material gradations.

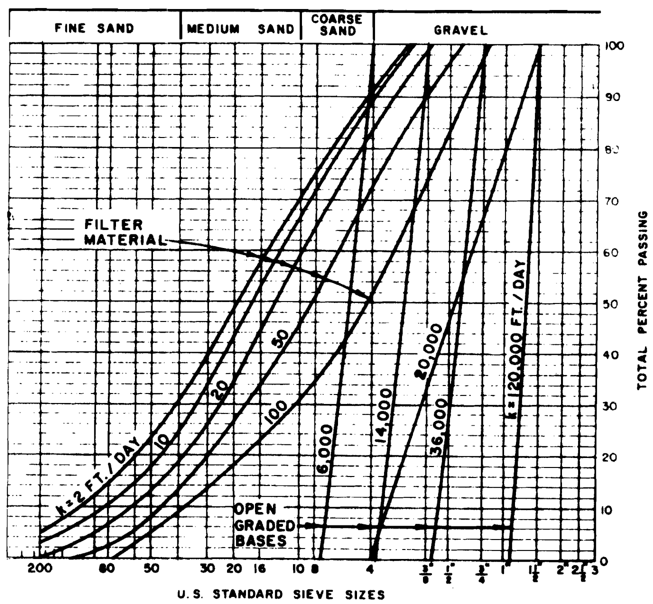

FIGURE NO. 4 - Typical Gradations and Permeabilities of Open Graded Bases and Filter Materials

3.1.2 Filter Protection of Open Graded Bases

Open graded bases serving as subsurface drainage layers must remain unclogged and highly permeable for the operational life of the road. Consequently, open graded bases must be protected against clogging both during construction and after the road is completed. Open graded bases should never be placed directly on sand, silt, clay or any other erodible subgrade or excessively fine subbase that can be carried into the base by seepage. The following filter criteria will provide a high degree of protection if gradation of open graded bases, filter layers, and adjacent finer materials are within the prescribed limits:

$$D_{15}(\text{soil}) \leqq \frac{D_{15}(\text{filter})}{5} \leqq D_{85}(\text{soil}) \qquad (2)$$

$$\frac{D_{50}(\text{filter})}{25} \leqq D_{50}(\text{soil}) \qquad (3)$$

$$\frac{D_{15}(\text{open graded base})}{5} \leqq D_{85}(\text{filter}) \qquad (4)$$

When an open graded base is "sandwiched" within the structural layers of a roadbed, clean well graded base and subbase materials will often meet the above filter requirements. Nevertheless, verification of the compatibility of materials with respect to filter criteria should always be made and the gradations of adjacent layers modified, if necessary, to ensure that no intrusion of finer material will occur.

Certain plastic fabrics can also be used as filters for open graded bases.[1] The suitability of a given filter fabric should be verified by test or be approved by a recognized U.S. Government or private laboratory. The choice between filter aggregate or filter fabric is a matter of economy and construction feasibility.

3.1.3 Protection of Sensitive Subgrades

In areas where highway pavements are constructed on highly expansive soils and geologic formations, fine grained materials of uniform gradation (i.e. loess), or other sensitive materials that undergo changes under prolonged exposure to water, it may be necessary to construct an impermeable seal beneath the subsurface drainage layer and around the collector trench backfill to prevent water from infiltrating into these sensitive materials. Several types of impermeable seals can be utilized to protect sensitive subgrades from moisture and include asphaltic materials and plastic membranes. In certain instances, lime can be utilized to stabilize the subgrade. The depth at which impermeable seals should be constructed will depend upon local conditions. Where an open graded base drainage layer is utilized, the impermeable seal can be placed directly beneath the base.

3.1.4 Specifications for Subsurface Drainage Layers

To ensure proper performance, specifications for subsurface drainage layers should include a requirement for permeability tests. Subsurface drainage layers should be constructed of aggregate materials of limited size range. In no case should open graded

[1] "Performance of Plastic Filter Cloths as a Replacement for Granular Filter Materials" by C. C. Calhoun, J. R. Compton and W. E. Strohm, WES, presented at HRB Annual Meeting, January 1971.

base sizes be smaller than No. 4 sieve since the smaller size materials greatly reduce permeability. The maximum size aggregate should be 3/4 to 1-1/2 inch. The range of size of open graded bases can be No. 4 to 3/8 inch, No. 4 to 1-1/2 inch, 3/8 to 3/4 inch, 3/8 to 1 inch, and 3/4 to 1 inch. These sizes are in the range of No. 467 through No. 67, ASTM D 448-54.

When required for stability, the open graded drainage layer can be stabilized with 2 to 4 percent asphalt cement, plant mixed.

The permeability of open graded drainage layers as tested in the laboratory should not be less than 10,000 feet per day in areas of highway construction with no frost penetration and 20,000 feet per day in areas with frost penetration to the depth of the drainage layer. Practical construction considerations dictate that design permeability values should never exceed one-third to one-half of the value obtained by tests. Figure No. 5 presents freezing indices for continental United States.

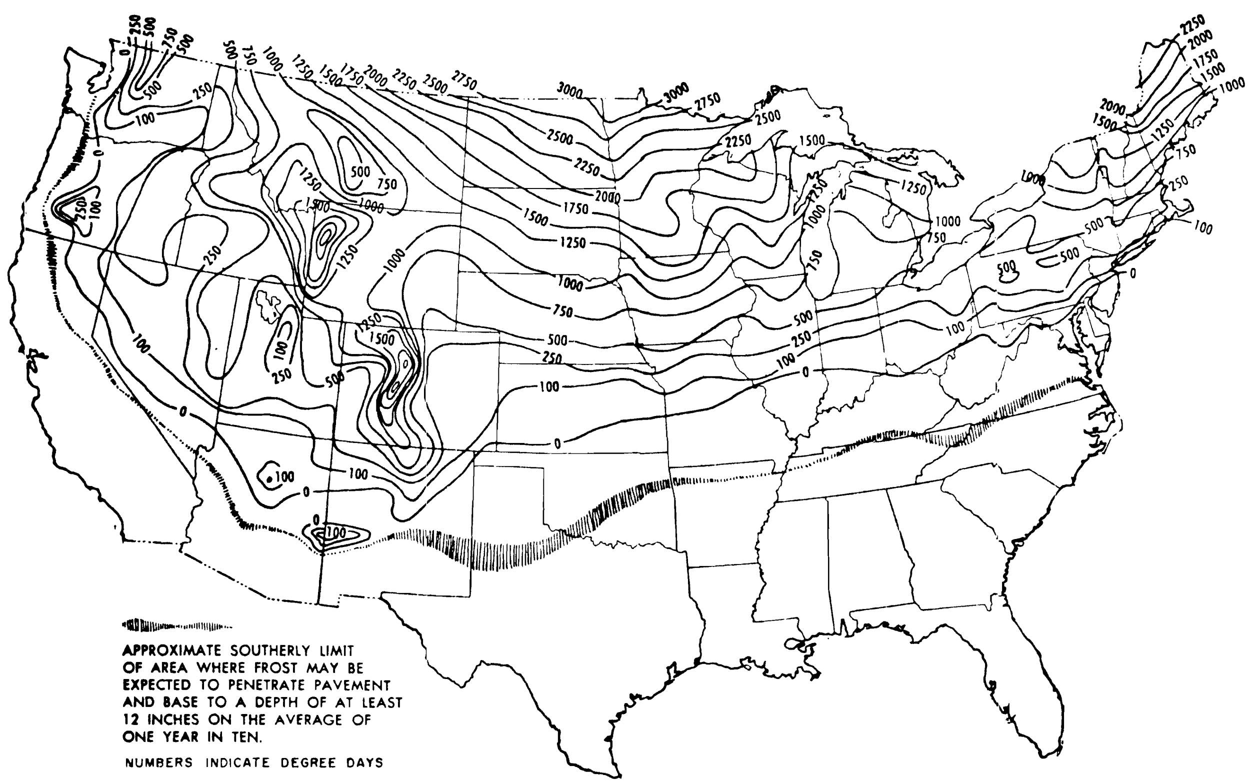

FIGURE NO. 5 - Freezing Indices for Continental United States

3.2 Collector Drains

Collector pipes for subsurface drainage layers should be installed at locations that will expedite the removal of water from these layers. If there is no ground water to be removed, collector pipes installed in shallow "V" trenches will suffice as indicated by Figure No. 6. Where frost penetration is a problem and where ground water must also be removed, collector pipes installed in rectangular trenches will be required. The rectangular trench drains should be of sufficient depth to maintain ground water at least 3 feet below the bottom of the structural section.

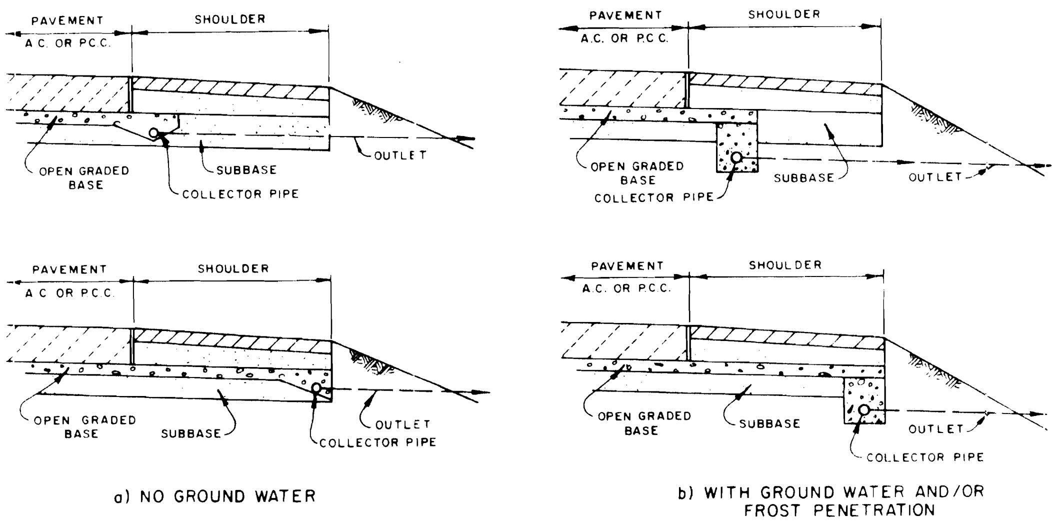

FIGURE NO. 6 - Typical Cross Sections of Subdrainage Systems

In flat terrain, longitudinal drains will generally be needed only along the lower edge of the traveled lanes. In steep terrain, cross drains may be required priodically to limit the maximum seepage path in subsurface drainage layers to less than 150 to 200 feet. For superelevated curves, collector drains should be installed along the lower side of the curve, and cross collector drains should be installed wherever required to prevent the "build-up" of a hydrostatic head in the drainage layer in excess of the overburden pressure. Refer to Figure No. 7. Road intersections and interchanges will also require special collector drain installations.

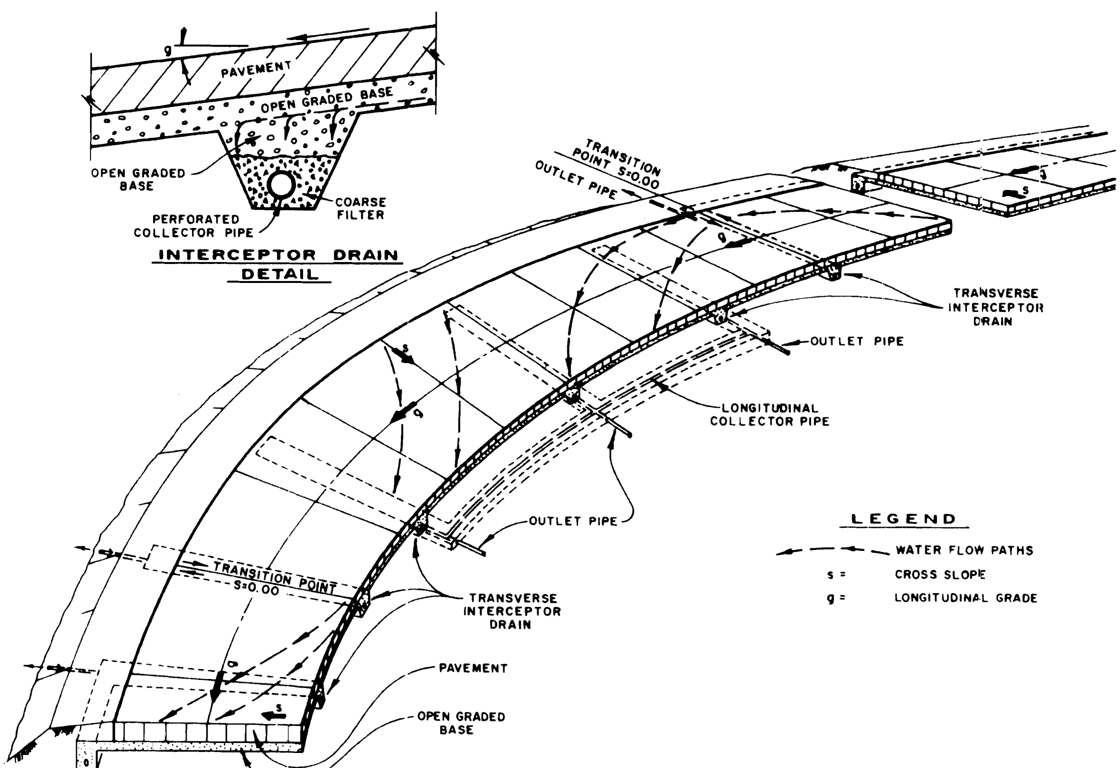

FIGURE NO. 7 - Transverse Drains Are Needed on Superelevated Curves

In general, collector pipes should be no smaller than 3 inches in diameter and no larger than 8 inches in diameter.

The minimum width of collector drain trenches is dictated by the practicalities of construction. Collector drain trenches must be of sufficient width to permit the collector pipe to be completely enveloped with a minimum of 6 inches of carefully placed permeable filter material.

Collector pipes should be installed at sufficient depths to: 1) protect the pipe from crushing; 2) exceed the frost penetration depth; 3) intercept lateral ground water flow, when present; and 4) lower the water table to at least 3 feet below the pavement structural section in areas of high ground water. Published procedures[2] are available for dimensioning the trenches for 3) and 4) above.

The gradation of backfill aggregates for collector trenches should comply with the filter criteria given in 3.1.2. The permeability of the trench backfill material must be at least several hundred feet per day to permit the drainage inflows to reach the collector pipe without restriction. In many instances, the backfill material size will be 1/8 to 1/4 inch diameter or coarser. Where trenches are excavated into erodible soils and pea gravel or coarser backfill is required, filter fabric can be used to provide protection against clogging of the backfill by intrusion of fines from the sides and bottom of the trench.

The backfill materials enveloping the perforated collector pipe must comply with the following criteria to prevent intrusion of material into the pipe:

$$D_{85}\text{(filter)} > \text{Diameter of Perforations} \qquad (5)$$

$$D_{85}\text{(filter)} > 1.2 \text{ Times the Slot Width}$$

Placement of filter and drain materials must be carefully controlled in order to preserve the drainage characteristics of the backfill. Placement methods must not permit segregation of particles by size, and degradation or contamination should be prohibited. Laboratory permeability tests of the collector trench backfill should be conducted as part of the quality control program to ensure proper drain performance. Materials not having the required permeabilities should be replaced.

Collector pipes, perforated or slotted, should be placed in the trench on a bedding of backfill drain or filter material at least 2 inches thick, with slots or perforations in the bottom half of the pipe. To provide a self-cleaning action so that sedimentation will be at a minimum, longitudinal pipe gradients should always be in the direction of flow and no individual section shall be laid on a reverse slope.

Collector pipes should be inspected immediately prior to their installation to verify that they have not been damaged during transit, handling and storage. After installation, when backfilling

[2]Seepage, Drainage and Flow Nets by Harry R. Cedergren; Road Research Laboratory Report LR-110; HRB Proceedings, Volume 23, 1943; HRB Proceedings, Volume 31, 1952; and ASCE Journal TE-4, November 1969, No. 6912.

operations are completed, a cleaning device should be pulled through the collector pipes to test the waterway continuity.

The type of collector pipe to be utilized depends on several factors such as pH and chemical characteristics of embankment, backfill, and subgrade materials. Where ground water or lateral seepage is to be accommodated by the collector system, the material of the collector pipe must be resistant to deterioration that could be caused by the chemical composition of the water.

3.3 Pipe Outlets

Pipe outlets must be provided at locations and intervals dictated by design considerations. The outlets must be located to ensure that the subsurface drainage system will be completely free draining for the entire life of the highway pavement section. Outlets should be provided at the sag of every vertical curve. The spacing of outlets should be determined by hydraulic computation of discharge capacities of the pipe sizes utilized. The location of outlets may frequently be restricted by the adjacent land elevations and contours, and the geometrics of the highway. However, for most subsurface drainage systems, gravity drainage of outlet pipes should be obtainable by proper engineering analysis. In rare instances, pumping may be an economic option for removal of the water.

The open end of the outlet pipe should be at least 12 inches above the flow line of the roadside ditch and be protected against damage or the intrusion of foreign matter. The area in proximity to the outlet should have a splash block or should be paved and the adjoining earth surface sterilized to prevent growth of weeds. The trench for the outlet pipe should be backfilled with material of low permeability or provided with a cutoff wall or diaphragm to prevent piping.

3.4 Markers

A marker should be installed at each collector pipe outlet location consisting of a treated wooden post, 6 to 8 inches in diameter and approximately 36 to 42 inches long, imbedded to a depth of 18 or 20 inches with an identification sign affixed that is visible from the traveled way.

Other types of markers, such as light gage steel posts, may be specified in areas subjected to extended periods of frost; however, these types of markers require maintenance and replacement because they are easily damaged.

4 INFLOW-OUTFLOW METHOD OF ANALYSIS

4.1 General

The basic method of designing a subsurface drainage system for a highway pavement structural section is to estimate all significant inflows into the structural section and to determine the design permeability and optimum thickness of the drainage layer. If surface water is the only source of water into the structural section, the use of a stabilized open graded base will generally be cost-effective because there will be merely a substitution "inch-for-inch" of open graded base for currently accepted base material. Stabilized open graded bases can have strength properties comparable to currently accepted base course materials. However, where large amounts of surface and subsurface water must be drained, the thickness of the open graded drainage layer (base) may in some cases exceed that required for the support of highway pavement loads.

Although there are a number of possible sources of water that can enter into highway pavement structural sections, surface infiltration is often the major source. Ground water is the second major source. Since methods for lowering ground water, collecting flows from springs, etc. are well understood, the main emphasis in these Guidelines is on surface water inflows.

The amount of water that can enter through the pavement surface is usually the <u>lesser</u> of the rate supplied by precipitation or the rate permitted by the average or <u>global</u> permeability of the paved areas. The average or global permeability is the intrinsic permeability of the pavement surface material that includes joints, cracks, and any other discontinuities or lapses in watertightness of the surfacing that permits water to enter. Little is known about numerical values of global permeability, although numerous investigators have tested the permeability of various types of pavement at different ages. Tests on new and old asphalt concrete pavement surfaces have indicated a wide range of permeabilities, from 0.002 inch/hour to over 150 inches/hour.[3] Because of the deteriorating effects of aging and traffic, any attempts to assign global permeabilities to pavements should realistically represent conditions as can be expected to develop after pavements have been in use a significant number of years.

Until better knowledge becomes available regarding the effective permeabilities of pavement systems, it is recommended that the surface infiltration rate be predicated on a <u>design precipitation rate</u>. This is the basis utilized for the method outlined in these Guidelines for design of subsurface drainage systems.

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[3]Tests performed by: Breen, University of Connecticut; Kari and Santucci, American Bitumuls & Asphalt Co., California Research Corp.; and Van Ganfe & Brull, Centre de Recherches Routieres, Belgium.

4.2 Inflow Analysis

4.2.1 Surface Infiltration

The selected design precipitation rate should be exceeded for only a small portion of the time each year. This determination requires an evaluation of precipitation rate for a given climatic area. The rate recommended in these Guidelines is the 1 hour/1 year frequency precipitation rate, which can be obtained from National Oceanic and Atmospheric Administration (National Weather Service) Technical Paper No. 40.

Since it is expected that not all of the surface precipitation will enter into structural sections, the design precipitation rate (1 hour/1 year frequency - Refer to Figure No. 3) should be adjusted to a realistic infiltration intensity by multiplying by a coefficient of between 0.50 and 0.67 for portland cement concrete pavements and 0.33 to 0.50 for asphaltic concrete pavements. On this assumption, the following criterion is recommended for determining inflow rates from surface precipitation: Design Infiltration Rate = I = 1 hour/1 year precipitation multiplied by 0.33 to 0.67. Design of the subsurface drainage layer with an outflow capability to accommodate the design infiltration rate will protect the roads from excess water about 99 percent of the time.

4.2.2 Ground Water and Other Inflows

Estimates of inflows from ground water and other seepage inflows should be determined by using flow net analysis techniques or Darcy's law. Examples of these types of calculation methods are given in technical publications.[2] Realistic estimates of inflows from any anticipated sources can usually be made by Darcy's law ($Q = kiA$), whenever reasonable values can be assigned to k, the average or effective permeability of a formation or layer through which water is entering; i, the effective hydraulic gradient in the direction of flow; and A, the cross-sectional area through which water is flowing.

4.2.3 Design Inflow Rate

The design inflow rate to be used in designing a subsurface drainage layer should be the sum of surface infiltration and all other significant inflows (ground water, seepage, etc.) that is converted to an equivalent rate in inches/hour.

4.3 Outflow Analysis

As previously indicated, Darcy's law ($Q = kiA$) can be expressed in the form $Q/i = kA$. The transmissibility (kA) of a subsurface drainage layer must be at least equal to the discharge rate (Q) divided by the hydraulic gradient (i) in the drainage layer. Outflow capabilities of drainage layers are dependent on the permeability of the materials, thickness and the available hydraulic gradient. The longitudinal grade and the cross slope of the pavement section determine the available hydraulic gradient.

An illustration of the use of Darcy's law to determine outflow capabilities of various types of drainage layer or aggregates is indicated on Figure No. 8.

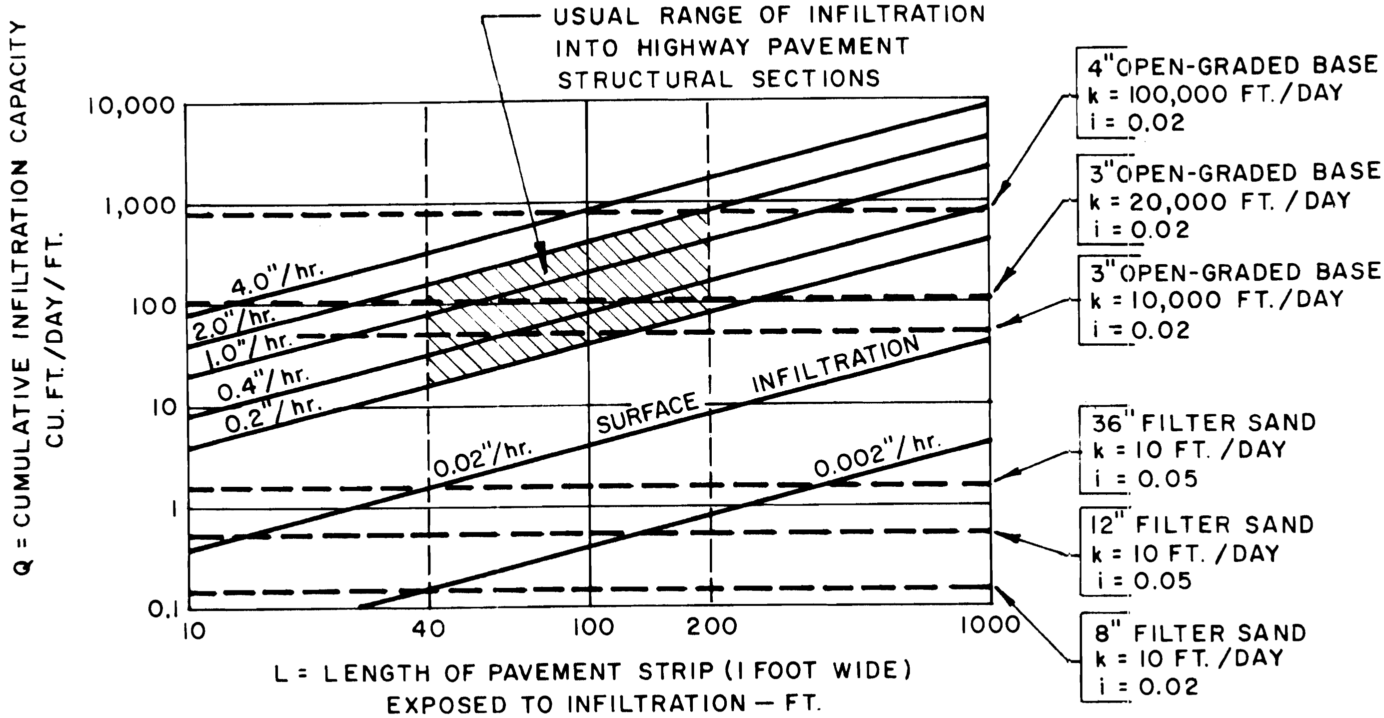


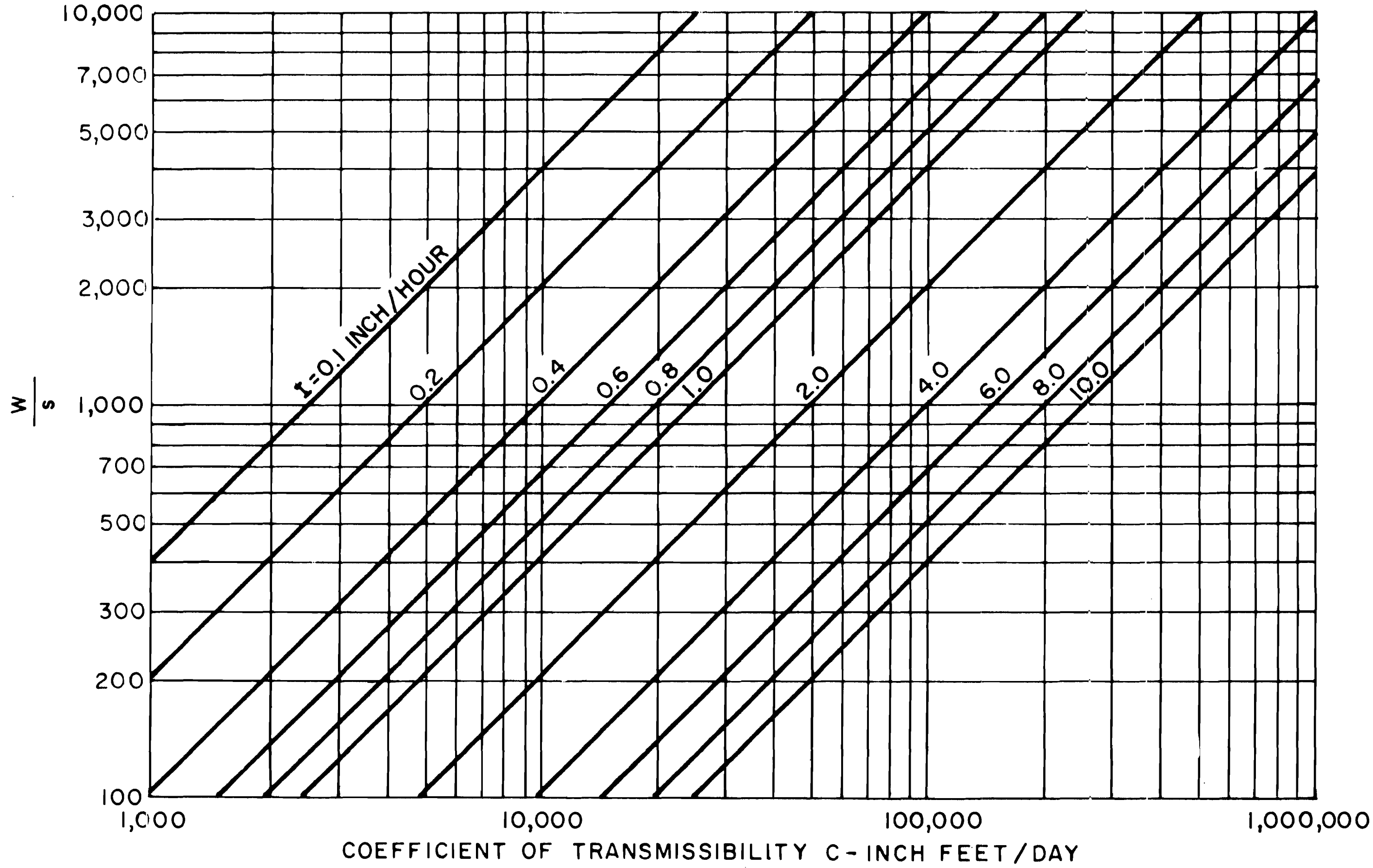
FIGURE NO. 8 - Outflow Capabilities of Drainage Layers

The outflow capabilities of drainage layers of different thicknesses and permeability are indicated by horizontal lines on the chart. The length of pavement strip 1 foot wide exposed to surface infiltration is shown as the abscissa, the quantity of cumulative infiltration as the ordinate, with various rates of infiltration intensity plotted as diagonal lines. A 3-inch thick layer of open graded base with a permeability (k) = 20,000 feet/day can remove surface infiltration of over 1 inch/hour for a 40-foot length of pavement strip. This chart illustrates the need for the rational design of subsurface drainage systems.

The geometric factors that must be known before a subsurface drainage system can be designed are: the cross slope of the drainage layer (s), the width of the drainage layer (W), and the longitudinal grade (g) of the road (Refer to Figure No. 2). These three factors are generally established prior to the determination of the need for subsurface drainage. In almost all cases, (W) and (g) cannot be changed, whereas there may be some latitude to change (s), if necessary.

FORM A has been developed to calculate the design of subsurface drainage layers using formulas. FORM A is included as the last page of these Guidelines.

Figure No. 9 is a chart that a designer can utilize to determine required thickness of a subsurface drainage layer (open graded base) or the permeability of the drainage layer. This chart can be used in lieu of Formula No. 1 on FORM A.



$C = k_b \cdot t_b$

k_b = PERMEABILITY OF DRAINAGE LAYER - FEET/DAY

t_b = THICKNESS OF DRAINAGE LAYER - INCHES

W = TOTAL WIDTH OF DRAINAGE LAYER - FEET

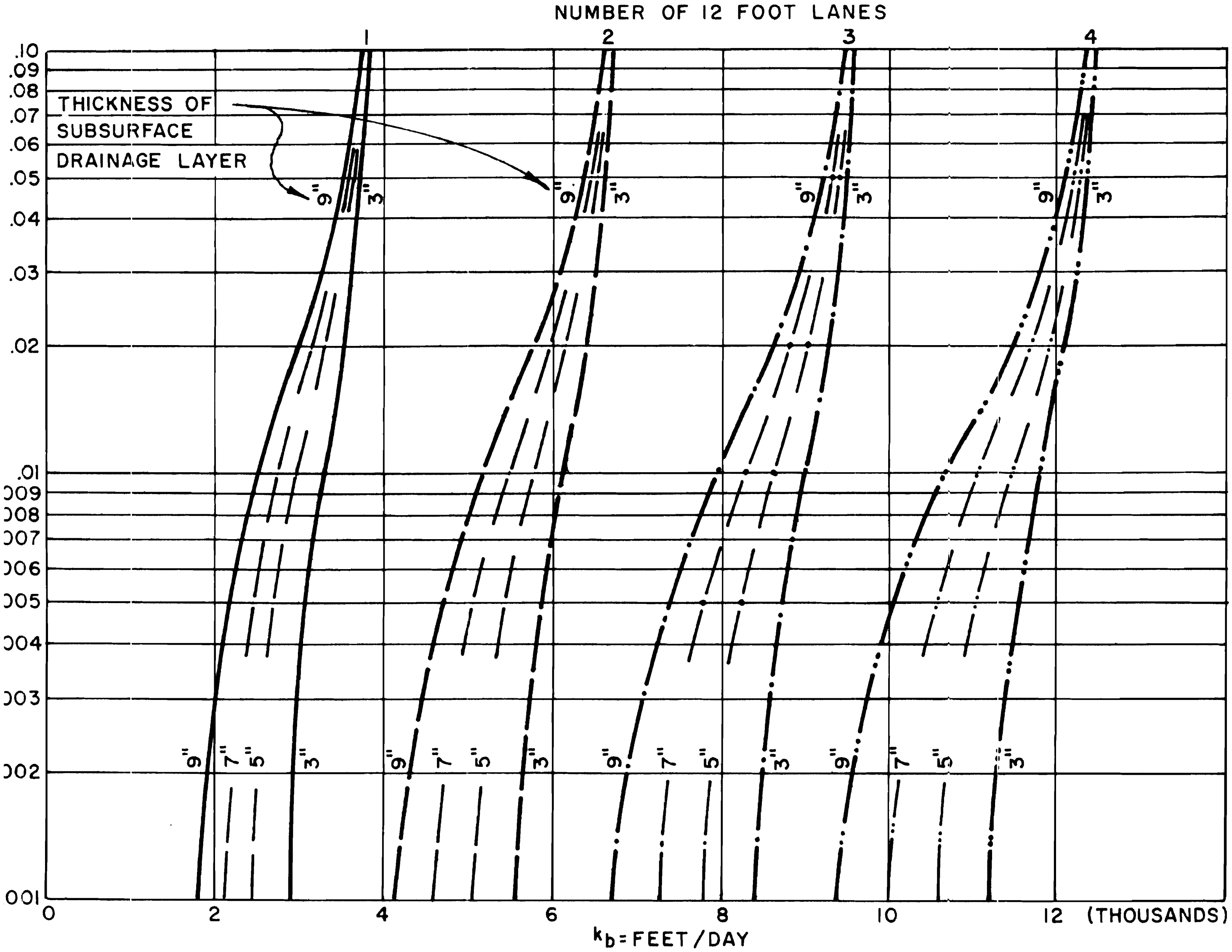
s = CROSS SLOPE OF PAVEMENT

I = DESIGN INFILTRATION RATE - INCHES/HOUR

FIGURE NO. 9 - Coefficient of Transmissibility Versus W/s

Figure No. 9 chart can be utilized as follows: Assume that a 6-inch base course is required for the pavement structural section for strength and that it has been determined that a subsurface drainage system is required (Refer to Section 2). Substitute "inch-for-inch" of open graded base for currently accepted base material. Assume two lanes of pavement 24 feet wide with a cross slope of 0.02; W/s = 1,200; design infiltration rate I = 1.0 inch/hour. From the chart, the coefficient transmissibility C = 29,000 inch-feet/day. The required permeability of the open graded base will be approximately 5,000 feet/day ($k_b = C/t_b$).

Figure No. 10 is a chart that will enable a designer to verify the time it will take a drainage layer to drain for various longitudinal grades and pavement widths. This chart is based on a pavement section cross slope of 2 percent (s = 0.02), porosity (n_b) = 0.20 and for a 1 hour maximum drainage time of the drainage layer.



$k'_b = \frac{k_b}{T}$

$n_b = 0.20$

$s = 0.02$

k_b = PERMEABILITY OF DRAINAGE LAYER WITH T (TIME TO DRAIN) = 1 HOUR

k'_b = REQUIRED PERMEABILITY OF DRAINAGE LAYER WHEN T IS LESS THAN 1 HOUR

FIGURE NO. 10 - Permeability Required In Order To Drain Subsurface Drainage Layer in 1 Hour or Less

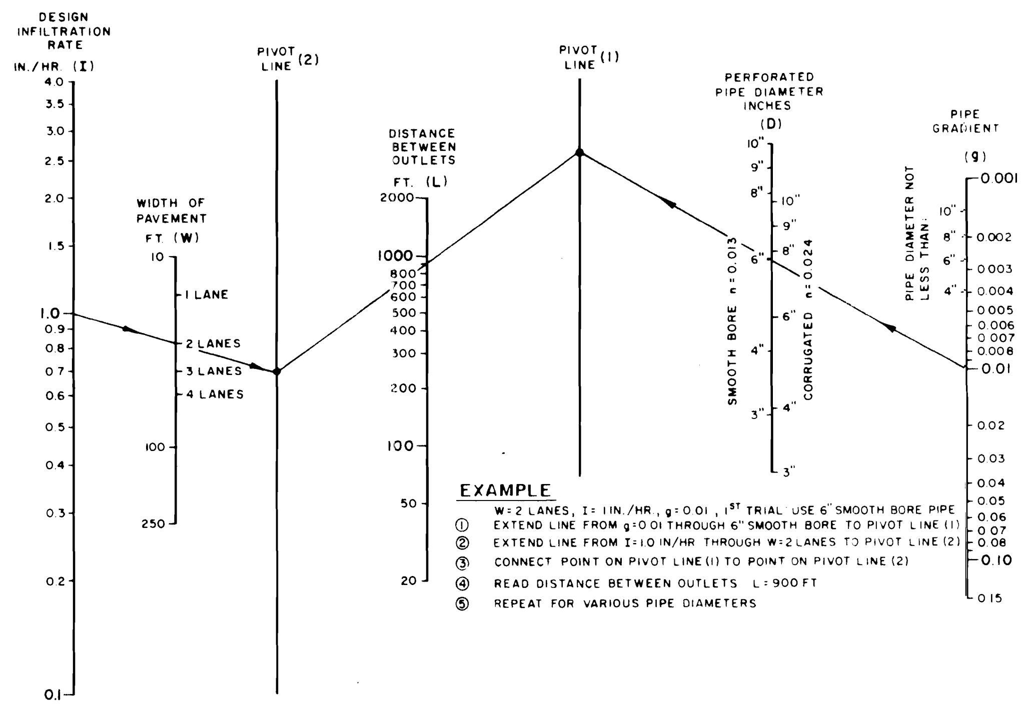
Figure No. 10 chart can be utilized as follows: Assume that a 6-inch base course is required for the pavement structural section for strength and that it has been determined that a subsurface drainage system is required (Refer to Section 2). Substitute "inch-for-inch" of open graded base for currently accepted base material. For a longitudinal grade of 1 percent, the required permeability of the subsurface drainage layer (open graded base) for a two-lane highway (12-foot lanes) is 5,700 feet/day; three-lane, 8,500 feet/day; and four-lane, 11,300 feet/day. This is based on a 1-hour drainage time of the drainage layer. If less drainage time is required, the conversion to the required drainage layer permeability can be made by utilizing the following formula:

$$k'_b = \frac{kb}{T} \text{ (from chart)}$$

where T is the required drainage time in hours.

In areas of severe climatic conditions (freezing and thawing), it is necessary to reduce the drainage time of the drainage layer to 1/2 hour. In no case should the drainage time exceed 1 hour.

Nomograph A was developed to determine subsurface drainage system collector pipe diameters and outlet spacing. The example explains how the designer can utilize the nomograph. Generally, the pipe gradient will approximately follow longitudinal centerline grade of the highway pavement.



NOMOGRAPH A - Selection of Perforated Pipe Diameters and Outlet Spacings

Figure No. 11 is a chart that a designer can utilize to determine the required permeability of the backfill for collector trenches or if the backfill permeability is known, the required width of the collector trench can be determined. This chart can be used in lieu of Formula No. 3 on FORM A.

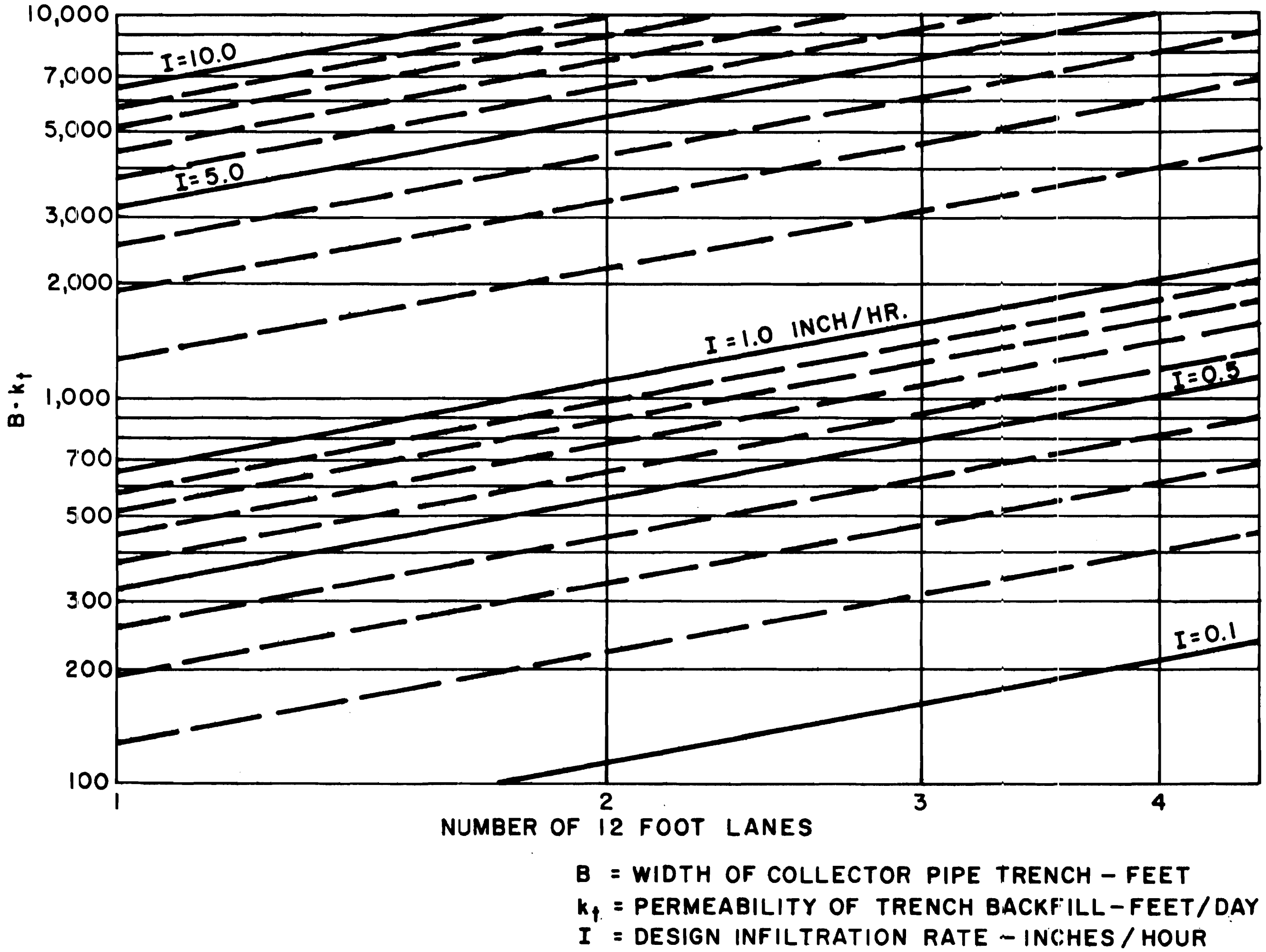


FIGURE NO. 11 - Chart To Determine Either Required Collector Pipe Trench Backfill Permeability or Collector Pipe Trench Width

Figure No. 11 chart can be utilized as follows: Enter chart along abscissa for the number of highway lanes for which subsurface drainage is to be provided, intersect vertically the design infiltration rate, and extend horizontally to the ordinate which is B x k_t, where B is the collector trench width and k_t is the permeability of the trench backfill. Generally, the width of the trench is dictated by the feasibility of installing a collector pipe in a trench. A minimum envelope of 6 inches of permeable backfill should surround the collector pipe.

5 EXAMPLES OF DESIGN OF SUBSURFACE DRAINAGE SYSTEMS

Highway geometrics, design inflow rates, and the availability and cost of materials for subsurface drainage systems will vary throughout the country. The examples of subsurface drainage system designs that follow may not be fully representative but illustrate the application of the method for designing open graded bases as subsurface drainage layers.

5.1 Example No. 1 - Embankment Section

5.1.1 Data

Design subsurface drainage system for straight section of portland cement concrete highway situated on an embankment. Three lanes in each direction separated by a depressed median; paved shoulders. No ground water. Subgrade soil or subbase can be stabilized. Cross slope is 0.02. Maximum grade is 0.03.

The 1 hour/1 year precipitation rate is 0.6 inch/hour. Use design infiltration rate, $I = 0.5 \times 0.6 = 0.3$ inch/hour. The area is subject to frost action. Use T (time to drain drainage layer) = 0.5 hour.

5.1.2 Solution

Enter Figure No. 10 with maximum grade, $g = 0.03$ to intercept family of curves for three lanes ($W = 40$ feet).

Select a thickness of open graded base, t_b and determine k_b. If $t_b = 3$ inches, then $k_b = 9{,}400$ feet/day ($T = 1$ hour).

Calculate k'_b ($T = 1/2$ hour).

$$k'_b = \frac{k_b}{T} = \frac{9{,}400}{0.5} = 18{,}800 \text{ feet/day}$$

Verify the capacity of the subsurface drainage layer. Enter Figure No. 9 with $W/s = 40/0.02 = 2{,}000$ and with $C = k'_b \times (t_b\text{-}1) = 18{,}800 \times (3\text{-}1) = 37{,}600$ inch-feet/day. Read maximum infiltration capacity $I_e = 0.75$ inch/hour which is $> I = 0.3$ inch/hour.

Determine perforated pipe diameter and establish outlet spacing. Enter Nomograph A with $W = 40$ feet, $I = 0.3$ inch/hour, pipe gradient, $g = 0.03$. Select distance between outlets as 700 feet. Required corrugated metal pipe diameter, CMP - 6 inches. Required asbestos cement pipe diameter, ACP - 4 inches.

Determine minimum permeability of collector trench backfill: Enter Figure No. 11 for three-lane pavement (40 feet wide), extend vertically to design I (0.3 inch/hour), and project horizontally to $B \times k_t$ ordinate; $B \times k_t = 470$. Minimum collector trench width $B = 1.5$ feet due to construction feasibility; required permeability of trench backfill ($B \times k_t = 470$) is approximately 310 feet/day.

5.1.3 Summary

Minimum thickness of open graded base: $t_b = 3$ inches.

Minimum permeability of open graded base: $k'_b = 18{,}800$ feet/day.

Minimum trench width: $B = 1.5$ feet.

Minimum permeability of trench backfill: $k_t = 310$ feet/day.

Minimum perforated pipe diameter: CMP - 6 inches; ACP - 4 inches.

Maximum distance between outlets: $L = 700$ feet.

5.2 Example No. 2 - Cut Section

5.2.1 Data

Design a subsurface drainage system for a highway with the same physical characteristics as Example No. 1 except the highway is in a cut section. Assume the ground water flow has a hydraulic gradient (i) of 0.5.

Permeability of subgrade soil k_s = 8 feet/day (4.00 inches/hour). The 1 hour/1 year precipitation rate is 0.8 inch/hour and the design infiltration rate I = 0.5 x 0.8 = 0.40 inch/hour. No frost; the time to drain subsurface drainage layer, T = 1 hour.

5.2.2 Solution

Calculate ground water inflow per square foot of subgrade surface: k_s x i = 4.00 inches/hour x 0.5 = 2.00 inches/hour.

Add ground water inflow to surface infiltration: I' = I + k_s x i; I' = 0.40 + 2.00 = 2.40 inches/hour.

Determine thickness of open graded base required. Enter Figure No. 9 with W = 40 feet, s = 0.02, W/s = 2,000 to intercept with I = 2.40 inches/hour, C = 120,000 inch-feet/day. If k_b = 20,000 feet/day, t_b = (C/k_b) + 1 = 120,000/20,000 + 1 = 7 inches. Enter Figure No. 10 with grade g = 0.03 and intercept family of curves for three 12-foot lanes with 7 inches thickness of subsurface drainage layer to determine permeability required (k_b) to drain subsurface drainage layer in 1 hour or less; k_b = 9,100 feet/day with is < 20,000 feet/day. Calculate time to drain the 7-inch thick subsurface drainage layer with k_b = 20,000 feet/day using Formula No. 2 - FORM A; T = 0.43 hours. If k_b = 10,000 feet/day then the required t_b = 13 inches and T = 0.80 hour. If k_b = 15,000 feet/day then the required t_b = 9 inches, and T = 0.55 hour.

Determine perforated pipe diameter and establish outlet spacing. Enter Nomograph A with W = 40 feet, I = 2.4 inches/hour, pipe gradient g = 0.03. Select distance between outlets as 400 feet. Required corrugated metal pipe diameter; CMP - 8 inches. Required asbestos cement pipe diameter; ACP - 6 inches.

Determine minimum permeability of collector trench backfill. Enter Figure No. 11 for three-lane pavement, W = 40 feet, extend vertically to intersect with design I (2.40 inches/hour), and project horizontally to read B x k_t ordinate; B x k_t = 3,900. Minimum required permeability of trench backfill (B x k_t = 3,900) is approximately 2,600 feet/day.

5.2.3 Summary

Minimum thickness of open graded base: t_b = 7 inches.
Minimum permeability of open graded base: k_b = 20,000 feet/day.
Minimum trench width: B = 1.5 feet.
Minimum permeability of trench backfill: k_t = 2,600 feet/day.
Minimum perforated pipe diameter: CMP - 8 inches; ACP - 6 inches.
Maximum distance between outlet: L = 400 feet.

5.3 Example No. 3 - Curve Section

5.3.1 Data

Design subsurface drainage system for divided urban highway on left curve section. The highway consists of two 12-foot lanes in each direction with paved median. Assume radius of curve is 900 feet and superelevation is 0.04. The total length of the curve section is 800 feet but the superelevation transition extends 200 feet beyond the beginning and end of curve. The grade of the highway is 0.01 and the normal cross slope is 0.02. The 1 hour/1 year precipitation rate is 2.00 inches/hour. Design I = 0.5 x 2.0 = 1.0 inch/hour. The specified permeability (k_b) of the open graded base is 10,000 feet/day; the effective porosity n_b = 0.20.

5.3.2 Solution

The highway section will require transverse and longitudinal collector drains as illustrated on Figure No. 7. The location of the first transverse drain should be at the section where there is no cross slope, s = 0.0.

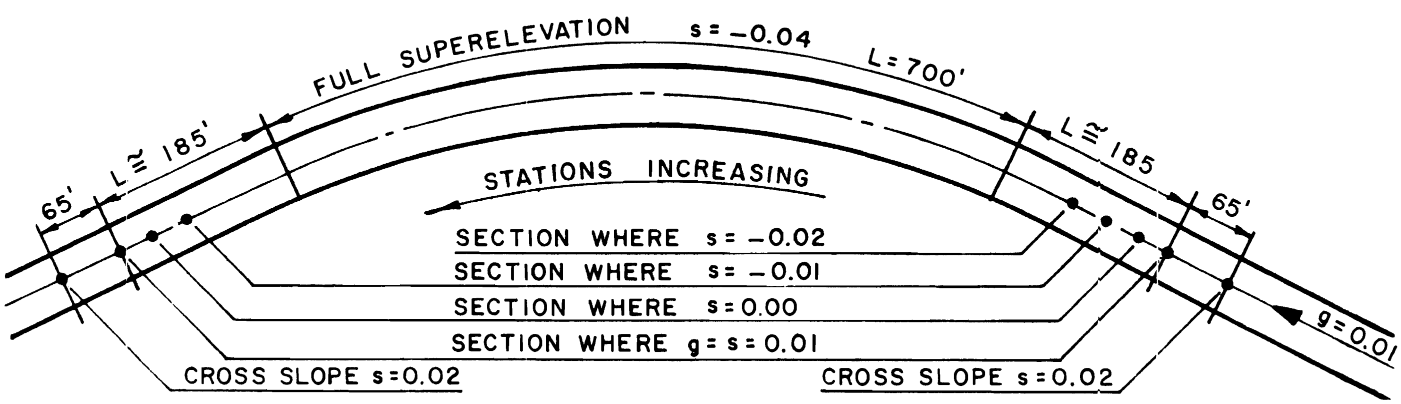


FIGURE NO. 12 - Highway Geometrics for Example No. 3

Length of section (L) that will be drained by the first transverse collector drain will extend back to where g = s (0.01), or approximately 35 feet.

Determine required thickness of open graded base using Figure No. 9. W/s in this instance will be the value of L/g = 35 feet/0.01 = 3,500; I = 1.0 inch/hour. From Figure No. 9, C = 85,000 inch-feet/day. Thickness of open graded base required: $t_b = (C/k_b)+1$ = 9.5 inches where k_b = 10,000 feet/day. USE 10 inches.

Determine perforated pipe diameter. Distance to outlet is width of pavement plus shoulder, 28 feet. Pipe gradient g = 0.02; W = 35 feet, I = 1 inch/hour. Nomograph A indicates that only the minimum pipe size will be required, 3-inch corrugated metal pipe. Using Figure No. 11, determine minimum permeability of backfill for transverse collector pipe system. Width of pavement to be drained, 35 feet. Enter Figure No. 11 midway between two and three lanes and extend to I = 1.0 inch/hour, project horizontally to $B \times k_t$ ordinate. $B \times k_t$ = 1,500. Minimum collector trench width B = 1.5 feet. Required permeability of trench backfill is 1,000 feet/day (1,500/1.5 = 1,000).

Find the locations at the beginning of the curve where the cross slope is -0.01 and -0.02. Determine the required thickness of open graded base at these locations using Figure No. 9. W/s in these instances will be the value of L/g. At the location for cross slope -0.01: L = 37.5 feet, g = 0.01, L/g = 3,750, I = 1.0 inch/hour, C = 90,000 inch-feet/day. Thickness of open graded base required: $t_b = (C/k_b)+1$ = 10 inches when k_b = 10,000 feet/day. At the location for cross slope -0.02: L = 37.5 feet, g = 0.02, L/g = 1,875, I = 1.0 inch/hour, C = 45,000 inch-feet/day. Thickness of open graded base required: $t_b = (C/k_b)+1$ = 5.5 inches when k_b = 10,000 feet/day.

Find the locations at the end of the curve where the cross slope is -0.01, 0.0 and +0.01. Determine the required thickness of open graded base at these locations using Figure No. 9. W/s in these instances will be the value of L/g. At the locations for cross slope -0.01, 0.0 and +0.01, required thickness of open graded base is 10 inches as previously determined above.

Determine the required thickness of open graded base for the full superelevated section (s = -0.04) using Figure No. 9. W = 28 feet, s = 0.04, W/s = 700, design I = 1.0 inch/hour, C = 17,000 inch-feet/day. Thickness of open graded base required: $t_b = (C/k_b)+1$ = 2.7 inches, where k_b = 10,000 feet/day. USE 3 inches.

Determine permeability of open graded base required (k_b). Use Formula No. 1 - FORM A when t_b = 3, W = 28 feet, I = 1.0 inch/hour, s = 0.04; k_b = 8,400 feet/day. Specified permeability k_b = 10,000 feet/day > 8,400 feet/day. Verify time to drain open graded base per Formula No. 2 - FORM A. T = 0.30 hour.

Determine longitudinal perforated collector pipe diameter. An outlet is required at the midpoint of the full superelevation. Therefore, outlet spacing is $\sim$ 400 feet. Using Nomograph A: W = 28 feet, I = 1.0 inch/hour. Required corrugated metal pipe diameter: CMP - 6 inches. Required asbestos cement pipe diameter: ACP - 6 inches.

Determine minimum permeability of longitudinal collector trench backfill. Using Figure No. 11, enter chart for two-lane pavement (28 feet wide), extend vertically to intersect with I = 1.0 inch/hour and project across to $B \times k_t$ ordinate, $B \times k_t$ = 1,200. Minimum collector trench width B = 1.5 feet. Required permeability of trench backfill is 800 feet/day (1,200/1.5 = 800).

5.3.3 Summary

Construct six transverse collector drains as follows:

Beginning of Curve: 0.00 cross slope
Beginning of Curve: -0.01 cross slope
Beginning of Curve: -0.02 cross slope

End of Curve: -0.01 cross slope
End of Curve: 0.00 cross slope
End of Curve: +0.01 cross slope

Required thickness of open graded base:

Beginning of Curve from 0.00 cross slope to -0.02: t_b = 10 inches
Full Superelevation: t_b = 3 inches
End of Curve from -0.01 cross slope to +0.01: t_b = 10 inches

Longitudinal collector pipe data:

Minimum trench width: B = 1.5 feet
Outlet spacing: 400 feet
Required pipe diameters: CMP - 6 inches; ACP - 6 inches
Minimum permeability of backfill: 800 feet/day

Transverse collector pipe data:

Minimum trench width: B = 1.5 feet
Outlet spacing: 37.5 feet
Required pipe diameters: CMP - 3 inches; ACP - 3 inches
Minimum permeability of backfill: 1,000 feet/day

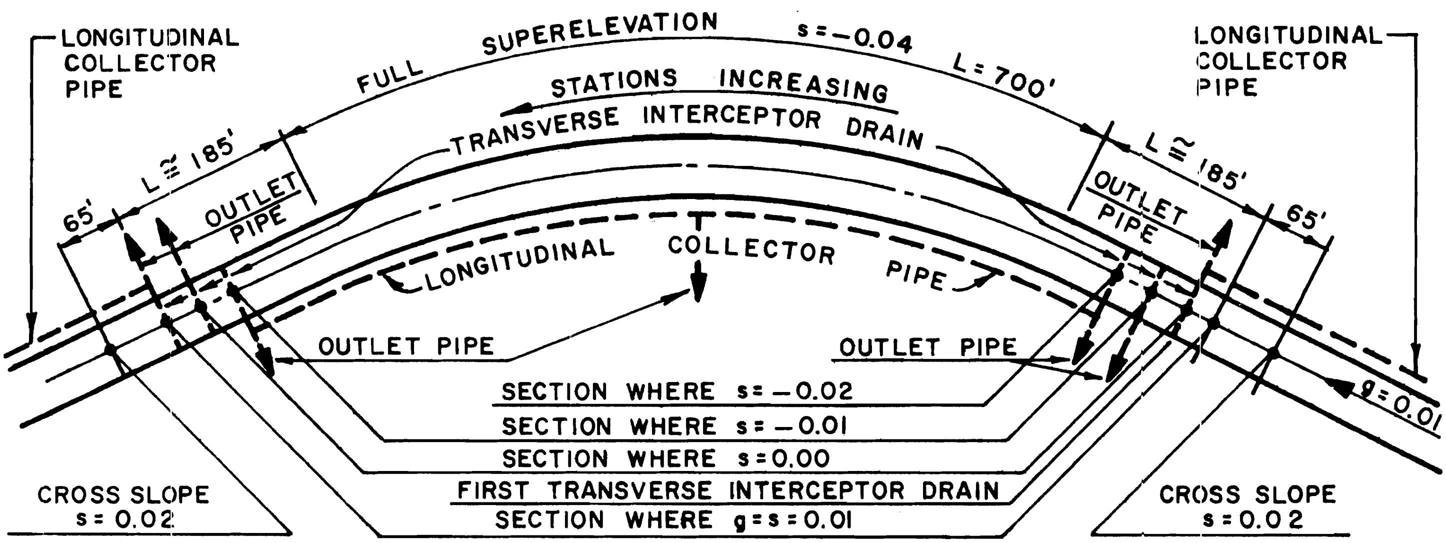


FIGURE NO. 13 - Subsurface Drainage Design for Example No. 3

6 GENERAL GUIDANCE FOR SUBSURFACE DRAINAGE SYSTEMS

6.1 In Design

6.1.1 It is virtually impossible to prevent surface water from entering highway pavement structural sections. It is not uncommon to make assumptions of possible degrees of permeability of pavement surfaces that are unfortunately underestimated by a factor of 1,000 to 10,000. As pavements age, joints and cracks open up and surfaces become less resistant to inflows, effective permeabilities increase, and more water enters into the structural sections.

6.1.2 Highway geometrics unfavorable to drainage should be avoided as far as possible (i.e. consecutive reverse curves connected by short tangents; insufficient cross slope less than 1-1/2 percent; and poorly drained depressed medians).

6.1.3 Avoid the use of any type of material that will restrict the free flow of water into open graded drainage layers.

6.1.4 Positive drainage is needed for continuous, free flow of water from open graded drainage layers into collector pipes. Collector pipe drains should be properly located so that optimum utilization of the discharge capacities of open graded drainage layers can be achieved and the entrapment of water in the drainage layer avoided.

6.1.5 Outlets for the collector pipe drains should be provided as needed to prevent the accumulation of water within the subsurface drainage system.

6.2 In Construction

6.2.1 The components of subsurface drainage systems must be carefully constructed in accordance with plans and specifications to ensure that the system will perform and function as intended by the design. Contamination of filter or drainage layers by tracking of mud or foreign matter on these layers by construction equipment must be prevented.

6.2.2 All collector and outlet pipes must be continuous and free of blockages of the waterway. Pipe outlets must not be blocked or covered by materials placed on slopes for landscaping or other purposes.

6.3 In Operation

6.3.1 Normal sealing practices for pavement surfaces, joints, etc. should be continued on regular basis to minimize the quantities of water that can enter into the pavement structural sections.

6.3.2 Prohibit the injection of significant amounts of joint sealing or other pavement maintenance materials into any part of the subsurface drainage system that could possibly inhibit drainage.

6.3.3 Prohibit any maintenance operation that will damage or plug outlets or obliterate or damage protective posts or markers.

SUBSURFACE DRAINAGE SYSTEM COMPUTATIONS

PROJECT: Sheet __ of __
LOCATION: Computed by: Date:
SECTION: Sta. to Sta. Checked by: Date:

DATA
Total Width of Pavement: $W =$ feet
Cross Slope: $s =$ Grade: $g =$ $y=g/s=$
Permeability of Open Graded Base: $k_b =$ feet/day
Permeability of Trench Backfill: $k_t =$ feet/day
Effective Porosity of Open Graded Base: $n_b =$
1 Hr Duration/1 Hr Frequency Precipitation: $P =$ in/hour
Design Infiltration Rate: $I =$ in/hour

COMPUTATIONS

1. Calculate Required Minimum Thickness of Drainage Layer:

$$t_b = \frac{24 \times I \times W}{k_b \times s} + 1 \quad \text{inches}$$

2. Calculate Time to Drain Open Graded Base:

$$T = \frac{24 \times W \times n_b}{k_b\left[s + \dfrac{t_b}{24 \times W(1+y^2)}\right]} \quad \text{hours}$$

3. Calculate Minimum Collector Trench Width:

$$B = \frac{40 \times I \times W}{k_t} \quad \text{feet}$$

4. Determine Collector Pipe Diameter and Outlet Spacing: (Nomograph A)

Pipe Diameter (inches)	Outlet Separation (feet)

FORM A

50304