user's guide

U.S. Department of Transportation
Federal Highway Administration

Program Developed by ERES Consultants, a Division of Applied Research Associates, Inc.

CONVERSION FACTORS

Approximate conversions to SI units

Multiply	By	To Obtain
in	25.4	mm
ft	0.3048	m
ft^2	0.0929	m^2
ft^3	0.0283	m^3
m^3	1000	liters
ft^3/day	3.277×10^{-7}	m^3/s
ft^3/day/ft	1.075×10^{-6}	m^3/s/m
ft^3/day/ft^2	3.528×10^{-6}	m^3/s/m^2
ft^3/day	3.277×10^{-4}	liters/s
ft/day	3.528×10^{-4}	cm/sec
cm/sec	864	m/day
lbs/ft^3	0.1571	kN/m^3
lbs/ft^2	0.0479	kN/m^2
lbs/in^2	6.895	kN/m^2

Approximate conversions from SI units

Multiply	By	To Obtain
mm	0.0394	in
m	3.2808	ft
m^2	10.7639	ft^2
m^3	35.3147	ft^3
liters	0.001	m^3
m^3/s	3.05×10^{6}	ft^3/day
m^3/s/m	9.30×10^{6}	ft^3/day/ft
m^3/s/m^2	2.8345×10^{5}	ft^3/day/ft^2
liters/s	3051.572	ft^3/day
cm/sec	2834.467	ft/day
m/day	0.0012	cm/sec
kN/m^3	6.3654	lbs/ft^3
kN/m^2	20.8856	lbs/ft^2
kN/m^2	0.1450	lbs/in^2

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16. Abstract

USER'S GUIDE: This User's Guide provides instructions for operating the updated version of DRIP 2.0, a Windows-based microcomputer program for drainage analysis. These instructions guide the user on the operation, use, and application of the software. An overview of the program, including a summary of the new program features, is presented in chapter 1. Chapter 2 contains instructions on program installation and uninstallation. In chapter 3, the program operation is discussed, including topic areas such as general DRIP features, graphing and plotting in DRIP, accessing DRIP outputs and file handling, and DRIP property pages. The technical basis for DRIP is discussed in chapter 4, followed by step-by-step practical example problems in chapter 5 that take the user through all aspects of the program.

DRIP 2.0: This program was developed for subsurface design for highway pavements. The most significant changes in DRIP 2.0 are related to program usability—interface improvements, improved help, refined analysis, and easy program output access. Most of the analysis routines developed in the original version of DRIP were retained. The program performs the following key functions:

- Performs drainage designs for flexible and rigid pavements and retrofit edgedrains.
- Calculates the time-to-drain and depth-of-flow in the drainage layer.
- Performs separator layer and geotextile designs.
- Performs edgedrain and geocomposite fin-drain designs.
- Converts input and output from SI to English units, or vice versa.

SYSTEM REQUIREMENTS: DRIP 2.0 requires an IBM-compatible PC with at least a Pentium processor, 32 MB of RAM, and 15 MB of available hard disk space. Due to the graphical nature of the program, a monitor capable of 800x600 resolution is recommended.

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CHAPTER 1 - INTRODUCTION

Brief History of DRIP Development

Moisture-related pavement distresses have long been recognized as a primary contributor to premature failures and accelerated pavement deterioration. The Federal Highway Administration (FHWA) provides design guidance for drainage in its manual numbered FHWA-TS-80-224, "Highway Subdrainage Design." Under a study known as Demonstration Project No. 87, or simply "Demo 87," the FHWA Pavement Division developed a comprehensive effort to provide design guidance for handling water that infiltrated into the pavement structure from the surface. That study resulted in the production of the Participant Notebook for Demonstration Project No. 87. Engineers needed a concise and user-friendly microcomputer program that replicates the subsurface drainage design procedures in the Participant's Workbook for Demonstration Project No. 87. Also, because of the increasing use of the SI unit system, there was a need for the program to incorporate both SI and pound-inch (U.S. Customary) units.

In response to these needs, Applied Research Associates, Inc., developed a microcomputer program titled "Drainage Requirements in Pavements (DRIP) Version 1.0" under a contract from the FHWA (contract No. DTFH61-95-C-00008). Mr. Robert Baumgardner of the FHWA supplied technical control for the project. The ARA principal investigator was Dr. Walter Barker, and development of the computer program was led by Mr. Tim Wyatt. Dr. Jim Hall served as program manager. The program was delivered to the FHWA in September 1997.

In 1998, a new National Highway Institute course (NHI Course No. 131026) titled "Pavement Subsurface Drainage Design" was developed to further improve the guidance on pavement subsurface drainage design, construction, and maintenance. DRIP Version 1.0 was completely integrated into this course to perform hydraulic design computations. The program has since been used in the industry and has received excellent reviews. However, several valuable suggestions were made by DRIP users to further improve the program. The suggestions mainly pertained to improving design input screen graphics, variable plot displays and outputs, and the user's manual. Certain key drainage calculations and plotting options were also suggested to enhance DRIP's technical capabilities. In addition, there was a need to upgrade the program to be compatible with the computing environments prevalent today.

To make these program modifications, the FHWA entered into a contract (FHWA Contract No. DTFH61-00-F-00199) with the ERES Division of ARA. Mr. Robert Baumgardner and Mr. Bing Wong of the FHWA supplied the technical control for the project. The ERES principal investigator was Dr. Jim Hall, and Mr. Gregg Larson implemented the program modifications. Mr. Jagannath Mallela of ERES served as the project manager. Under this contract, the microcomputer program "Drainage Requirements In Pavements (DRIP) Version 2.0" and a revised user's guide were developed.

New Features in DRIP Version 2.0

DRIP 2.0 incorporates several significant advancements in user interface and capabilities:

- *Win32 support*. Fully compatible with Windows 95/98/NT.
- *Normal and Expert modes*. Normal mode warns users of potential errors during input and offers suggestions on proper program use. Expert mode suppresses these warnings, allowing experienced users of program the ability to edit data more quickly, without continually acknowledging warning screens.
- *Tabbed property pages*. The individual data input and analysis screens employed in DRIP Version 1.0 have been updated/improved and are now displayed using a property page format. This new format allows a more intuitive navigation through the various program screens. Each property page can be accessed by means of the tabs displayed continually along the top of the DRIP client area.
- *Analysis type selection*. The DRIP program allows the user to select the type of roadway geometry, inflow calculation method, permeable base analysis type, separator layer analysis type, and edgedrain type. The selections available under each of these categories are usually located in the upper left corner of the respective property page in the form of radio buttons. By making the appropriate selection, the user can customize the analysis performed on each property page. For example, to perform time-to-drain design of permeable bases, the user should select the "Time to Drain" radio button on the ***Permeable Base*** property page. The program then configures the page to display appropriate inputs and outputs for this analysis.
- *Hyper-linked input data fields*. In the DRIP program, certain variables appear on multiple property pages. The hyper-linking feature is aimed at preventing the novice user from inadvertently entering different values for the same DRIP variable on different property pages. By clicking the left mouse button on a hyper-linked variable (identified by an underline beneath it), the program transports the user to a property page where this variable should most logically be configured.
- *Improved graphics*. The graphics that illustrate drainage input variables have been improved.
- *Summary screen*. A linked summary list is now present on the left side of the DRIP client window. This list allows the user to get an update on the status of the current DRIP session.
- *Context sensitive help*. Right clicking on any variable in the DRIP program displays a short description of that variable.
- *Improved online help*. The complete DRIP user's manual is now available and searchable online and from within the program.
- *HTML analysis summary*. A formatted report on the inputs used and outputs calculated in the current DRIP session is available using the File | Export Summary command. This information contained in this file is in standard HTML format and can be read and edited using standard browser applications, word processing programs, or spreadsheet software.

- *Print analysis summary*. A well-formatted printed report displaying the inputs used and outputs calculated in the current DRIP session is available using the File | Print Summary command.
- *Improved gradation library*. The importing and saving of sieve gradation analysis has been improved. The program allows descriptive file naming to save input gradations for future use.
- *Additional sieve sizes*. Particle sizes determined from hydrometer tests can now by used by the DRIP model.
- *Improved graphing*. Graphing of grain size distributions and sensitivity analysis plots has been simplified. Graphs generated by DRIP can now be imported directly into other Windows® applications or saved as JPEG files.
- *Power 0.45 and semi-log plots*. Sieve analyses can be viewed on either power 0.45 or semi-log plots.

DRIP Capabilities

DRIP 2.0 retains the capabilities of the earlier version of the program but makes the execution more efficient and incorporates all the new features explained in the previous section. The salient features of DRIP are described below. Each of these features can be executed independently from within the program. More details regarding the various features, including a discussion on the corresponding input and output variables, will be presented in chapter 3.

Roadway Geometry Calculations

Using this program feature, the user can compute the length and slope of the true drainage path based on the longitudinal and transverse grade of the roadway, as well as the width of the underlying base material. The user can perform these calculations for the two common roadway cross-sections commonly encountered—crowned and superelevated (uniform slope) sections.

Sieve Analysis Calculations

The effective grain sizes (D_x), total and effective porosities, coefficient of uniformity and gradation, and coefficient of permeability can be computed for any user-entered gradation using this program feature. Plots of the gradations on semi-log and FHWA power 45 templates can also be obtained from this program screen.

Inflow Calculations

The amount of moisture infiltrating the pavement structure from rainfall and meltwater can be computed using this program option. The surface infiltration calculations can be performed using two different approaches—the Infiltration Ratio approach and the Crack Infiltration approach. Meltwater computations can be performed for a variety of soil types and pavement cross-section depths.

Permeable Base Design

The program offers two permeable base design options—depth-of-flow and time-to-drain. These methods allow the user to design an open-graded base that can handle the inflow entering the pavement structure.

Separator Layer Design

Using this program option, the user can design two types of separator layers—geotextile and aggregate separator layers. Based on the gradations of the proposed permeable base and the subgrade under consideration, the program also verifies whether a separation layer is required at all.

Edgedrain Design

Two types of edgedrains can be designed using this program option—geocomposite of fin drains and pipe edgedrains. The program calculates the edgedrain capacity and the outlet spacing required.

Organization of the User's Manual

This manual is organized so that both the novice and experienced DRIP users can easily navigate through the program's many different features. The content of this manual is also available with the program as online help. In an effort to minimize repetition, topics that are identical in different parts of the program are usually only covered once in detail; when repeated, the reader is referred to previous explanations.

Each section of this manual, discussed briefly below, serves as a comprehensive guide to a set of DRIP features or modules.

Getting Started

In Getting Started, the user will learn about the minimum system requirements for running DRIP 2.0 on a personal computer or network, DRIP 2.0 installation, and the usage of DRIP 2.0 to perform pavement drainage analysis and design.

General DRIP Operation

This section provides an in-depth guide on how to use DRIP 2.0, including file handling, data input, data analysis, and report generation. Operation of the DRIP plotting package—DripPlot—is also fully described.

Technical Background

This section contains a detailed explanation of the theory and practice behind DRIP 2.0, including water inflow into pavements, edgedrain and geocomposite material, base course and separator layer materials, and pavement geometry.

Examples Problems

This section provides example problems to assist the user in developing a proficiency in the use of the program.

Sensitivity Analysis

This chapter discusses the design sensitivity to changes in various parameters, which can be used both as a design reference and as an example of the type of detailed analyses that can be performed using the DRIP program.

CHAPTER 2 - GETTING STARTED

Introduction

Getting started with DRIP 2.0 is easy, especially if you already have installed a Win32 operating system (Windows 95/98 or NT) and are familiar with that environment. This chapter describes the procedures for installing and operating DRIP 2.0 on your computer.

System Requirements

To run DRIP 2.0 on your computer, the following minimum hardware and software requirements must be met:

- IBM-compatible PC with at least a Pentium processor.
- 32 MB of RAM.
- 15 MB of available hard disk space.
- One CD-ROM drive (for installation only).
- Monitor capable of 800x600 resolution.
- Mouse or compatible pointing device.
- Printer (optional).

Also, the computer on which DRIP 2.0 is installed must be running Microsoft Windows 95/98 or Windows NT 4.0 operating system (or compatible later version).

Installing DRIP

The DRIP 2.0 installation CD uses the Windows auto-run feature. To install the software:

1. Start Windows.
2. Close any applications that are already running.
3. Insert the DRIP 2.0 CD into the CD-ROM drive.

If the *Choose Destination Location* screen shown in Figure 2-1 does not start within a few seconds, follow the instructions below to start the installation procedure:

1. Double-click on My Computer icon on the Desktop.
2. Double-click on the DRIP CD-ROM icon.
3. Run setup.exe.

Destination Location

The *Choose Destination Location* screen identifies where on your hard drive DRIP 2.0 is installed. The default installation subdirectory is C:\Program Files\FHWA\DRIP as shown in Figure 2-1. This will be referred to the DRIP directory in this manual.

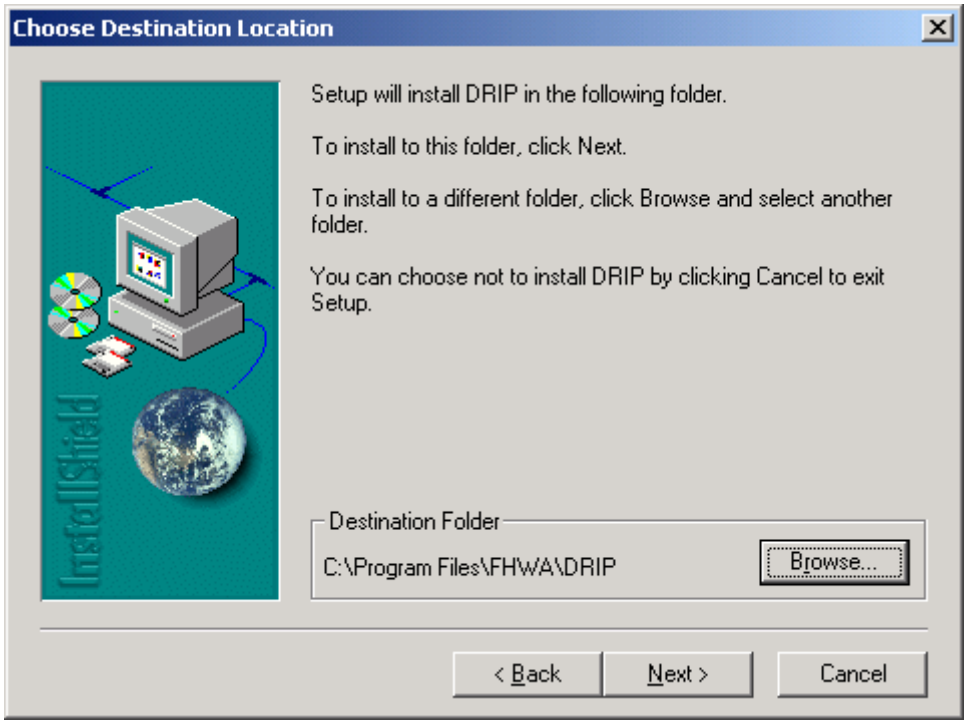


Figure 2-1. Destination location.

Clicking "Browse" allows you to select any other path. When satisfied with the choice of the installation directory, select "Next >." Note that the "<Back" on this screen is redundant.

It is recommended that the destination directory selected for DRIP 2.0 installation be different from the one that may contain an earlier version of DRIP. This is recommended to avoid accidentally overwriting any files that were created using previous versions of DRIP. The default DRIP 2.0 destination directory meets this criterion.

The installation procedure provides a continuous update on its status. When the installation is complete it is recommended that the user check the README.txt file. This file contains information on any changes or corrections to DRIP that are not addressed in this user's guide.

Running DRIP

During installation, a DRIP 2.0 program group will be added to the Windows Start menu and a DRIP program shortcut icon is added to the desktop. To run DRIP from the Windows Start menu, click the "Start" button (usually located in the bottom left corner of your screen), go up to the "Programs" option to see a list of folders, choose the Drip 2.0 program folder, and select the DRIP icon (the first icon shown in Figure 2-2).

Alternatively, the program can also be run by double-clicking the DRIP icon on the desktop.

Figure 2-2. Start menu.

If the DRIP Plot icon shown in Figure 2-2 is selected, a DripPlot window opens up and the last graph/plot generated by DRIP is displayed in it. The Drip Help icon opens the online version of this user's guide.

Uninstalling DRIP

To uninstall the DRIP software, follow these steps:

1. Select the Windows *Start* button.
2. Select or move the mouse to *Settings*.
3. Select *Control Panel*.
4. Select *Add/Remove Programs*.
5. Uninstall the DRIP software.

CHAPTER 3 – GENERAL DRIP OPERATION

Introduction

When the user starts the DRIP program, a splash screen appears briefly, followed by the DRIP client window shown in Figure 3-1. The DRIP client window has the following features:

- A menu bar across the top, which includes the File menu, the Options menu, and the Help menu.
- A program summary column on the left side of the screen that displays all the important DRIP outputs. The summary information is continually updated as the analysis progresses.
- A series of six tabs arranged from the left to right titled ***Roadway Geometry***, ***Sieve Analysis***, ***Inflow***, ***Permeable Base***, ***Separator***, and ***Edgedrain***. When selected, these tabs display the respective property pages. Each property page has the following common elements: edit boxes for data input, on-screen graphics describing the problem, and calculator and/or graph icons for output computation. In addition, some property pages have module-specific analysis options, e.g., the ***Edgedrain*** property page allows the user to choose between pipe edgedrain or geocomposite edgedrain analysis types. All the hydraulic design and analysis in DRIP takes place within these property pages.

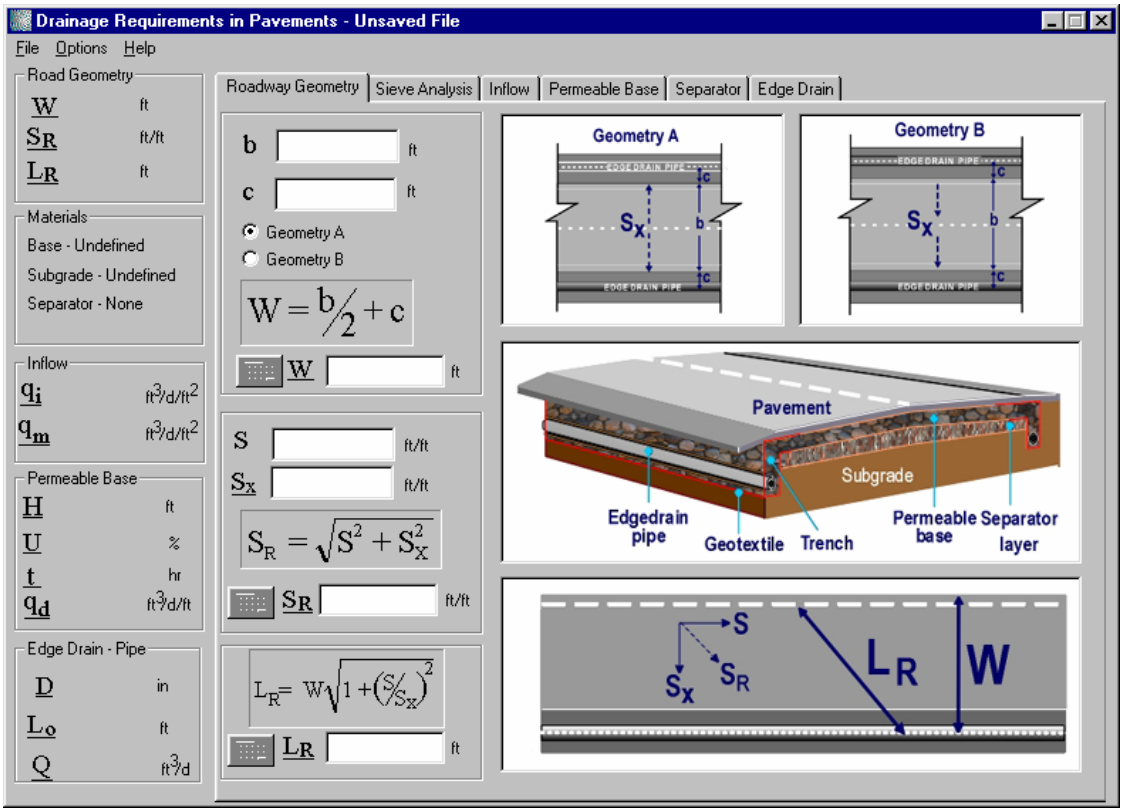


Figure 3-1. The DRIP client window.

DRIP has many features that can be used from anywhere within the program. These include file or project actions such as saving and printing, as well as the functions of certain function keys, and on-screen buttons. This chapter describes many such features that are available throughout the program. In addition, a detailed description of the functionality of each tabbed property page is also provided. The description of the DRIP program features and operation is broken down and presented under the following section headings:

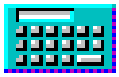
- General DRIP features – DRIP icons, context sensitive help, hyper-linking, error checking.
- DripPlot – Graphing and plotting package for DRIP.
- DRIP Menus – File handling, Help, and Options.
- DRIP Property Pages – Tabbed property pages each containing one of the six sub-processes required for a complete drainage analysis.
- Project Summary – Summary of important input and output data for the program.

General Features

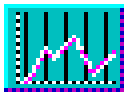
DRIP has many features to assist the user in operating the program, including special icons, context sensitive help, hyper-linking of variables, and input data error checking.

DRIP Icons

There are three of types of icon buttons in DRIP – Calculator, Graph, and Balance. The icons are illustrated and explained below.



Calculator icon: Allows the user to perform a calculation based on the inputs provided by the user. This icon is activated (turns colorful) only when all the necessary inputs for a given calculation are configured. For example, in Figure 3-1, the parameter *W* can be calculated by pressing the calculator icon only after the inputs *b* and *c* have been configured. In certain instances, pressing the calculator icon opens a dialog box (e.g., heave rate determination in the ***Inflow*** property page), or transports the user to an appropriate property page where inputs to calculate the parameter under question should be configured (e.g., the D_x calculation in the ***Separator*** property page). Calculator icons appear on every property page.



Graph icon: Generates appropriate graphs for the property page in which it is located and opens DripPlot to display them. The graph icons appear on ***Sieve Analysis***, ***Permeable Base***, and ***Separator*** property pages.

Balance icon: Checks whether the design criteria for the aggregate and geotextile separator layers are satisfied on the ***Separator*** property page.

DRIP Help

Context-sensitive help can be accessed for any program variable by right-clicking the mouse button while the cursor is on top of that variable. A small help box will appear superimposed above the DRIP dialog box, giving a short description of the variable in question.

Hyper-Linking in DRIP

Most of the property pages in DRIP are interconnected. As a consequence an input on a certain page may be an output on another page. Therefore, a given variable can appear on multiple property pages. For example the parameter, *W*, appears on both the ***Roadway Geometry*** and ***Inflow*** property pages. However, it is actually an output on the ***Roadway Geometry*** property page and an input in the ***Inflow*** property page. This could lead to some confusion in the mind of the novice user on where to enter the value for parameter *W*. In order to address such situations, a hyper-link was provided for all variables that appear on multiple screens. All hyper-linked variables are identified by an underline beneath them. If a hyper-linked variable is selected with a left-click of the mouse, the program will jump to where that variable should most logically be entered. By editing the variable on the analysis page suggested by DRIP, the user can avoid inadvertently entering different values for the same variable on different screens. Although the user is not required to use this feature, it is highly recommended, especially for novice users and also when an analysis utilizing only a few of the property pages offered by the program is attempted.

Error Checking

DRIP displays a warning when a dependent variable is about to be changed. DRIP also warns the user when data input is inappropriate, such as entering a negative unit weight for a material. While this feature is helpful for a novice DRIP user, these warnings can become an annoyance for the experienced user. To aid the experienced DRIP user, an *Expert Mode* is available. When DRIP is running in the *Expert Mode* all warning and informational dialog boxes are suppressed, allowing the user to enter potentially incorrect data, or to edit a dependent variable. Only experienced users should attempt to use DRIP in the *Expert Mode*. The *Expert* or *Normal* mode selection is made under the *Options* | *Mode* menu item. When first run, DRIP defaults to the *Normal* mode, with all the warning and informational dialog boxes activated.

DRIP Menus

Menus in DRIP are used to control file handling, help, and program options. All menu items can be accessed from any of the tabbed property pages.

File Menu Options (Including Print Summary)

The *File* menu controls file handling, printing, and summary output. When DRIP is first started, the program opens into a new DRIP project or session file. This new DRIP file is empty except for a few default input parameters. At this time the user should either open a previously generated DRIP project file by using the *File* | *Open* menu command or name the newly created DRIP project file by using the *File* | *Save* menu command.

File | *New* – Creates a new DRIP project file, clearing all user input data from the currently active project file. There can only be one active project file for each DRIP client window. Creating a new DRIP project file with the *File* | *New* command within an active DRIP client will close the currently active DRIP file. A newly created DRIP project file is unnamed. It is suggested that the newly created DRIP project file be named using the *File*| *Save* menu command. While each DRIP client window allows only a single DRIP project file to be active, it is possible to have several DRIP client windows running on one computer.

File | *Open* – Opens a previously saved DRIP project file (identified by a *.drp extension). The current active DRIP project file is closed without saving. The *File* | *Open* dialog box is of the MS Windows Explorer® style, allowing the user to rename, copy, and paste files within it. Figure 3-2 illustrates the *File* | *Open* dialog box.

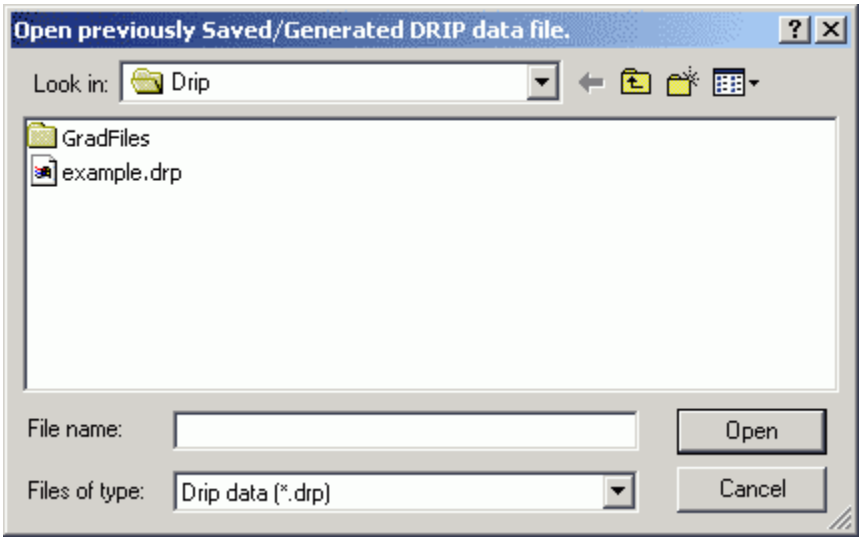


Figure 3-2. The file open dialog box.

File | *Save* – Saves the current active DRIP project. When this option is selected, a dialog box, such as the one shown in Figure 3-3 opens prompting the user to save the current DRIP project. The user may choose to save a DRIP project with a file

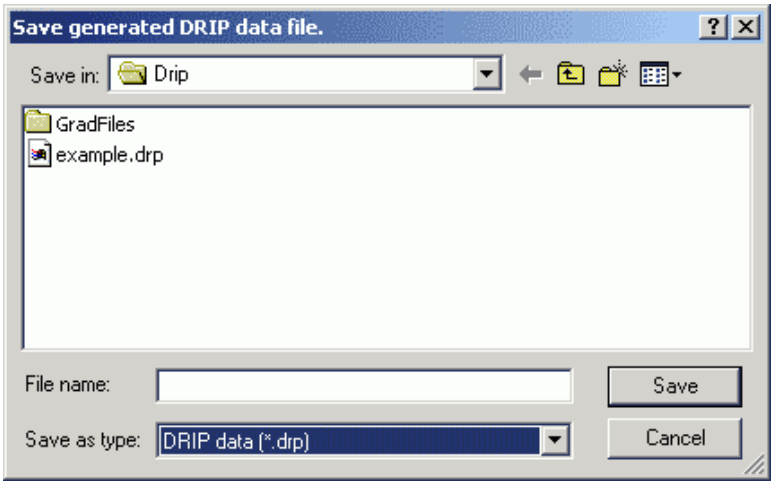


Figure 3-3. File save dialog box.

extension other than the default *.drp extension. However, this is not recommended since files saved with an alternative extension will not appear automatically in the dialog box when the *File* | *Open* menu command is executed. If the current active DRIP project has been previously saved, the *File* | *Save* menu command will not open the "Save generated DRIP data file" dialog box, but instead will overwrite the previously saved DRIP project file.

File | *Save As* – Same as *File* | *Save* menu command except that this command will always open the "Save generated DRIP data file" dialog box shown in Figure 3-3.

File | *Export Summary* – Creates a summary of the active DRIP project file. The format of this file is Hypertext Markup Language (HTML) and it can be viewed using any Web browser, spreadsheet, or word processing program. Since DRIP analyses are modular in nature, the summaries provided are also divided into subsections—Roadway Geometry, Sieve Analysis, Inflow, Permeable Base, Separator Layer, and Edge Drain. A summary for a particular subsection is output only if data has been entered for that analysis or that analysis has been completed. If no data has been entered, only the primary header of that analysis module is provided.

To export the project summary to an HTML file the following steps need to be followed:

1. Select the *File* | *Export Summary* command from the *File* menu. A "Create DRIP summary file" dialog box similar to the one shown in Figure 3-4 pops up prompting the user to enter to enter a file name under which the DRIP project file summary will be saved.
2. Save the summary file to an appropriate directory on the computer by specifying a file name. Note that the summary files are automatically saved with an extension of *.htm.

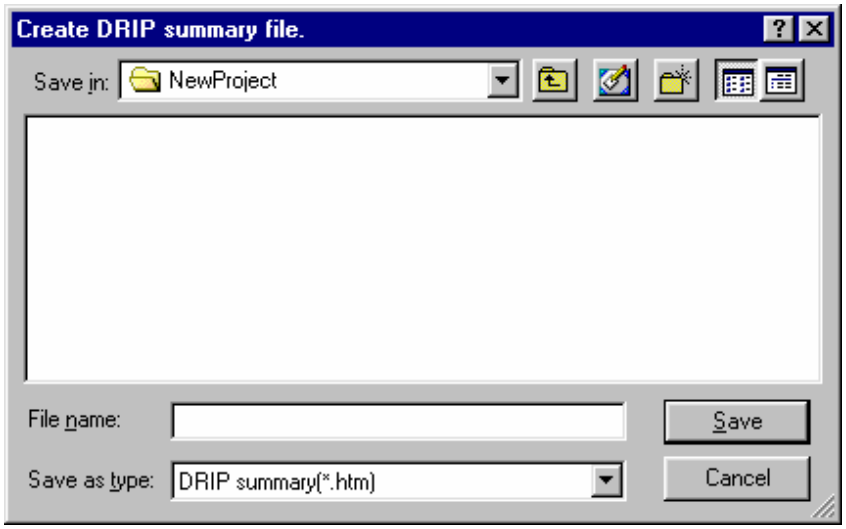


Figure 3-4. Dialog box to save project summary information.

Once the summary information is saved to a file, it is automatically displayed on the computer screen using the default HTML browser application. The information can be printed directly from this application using standard print commands. Alternatively, the summary information file can also be opened with any standard word processing or spreadsheet programs that reads HTML documents e.g., Microsoft Word® or Microsoft Excel®. The advantage of using a word processing or spreadsheet application is that they enable the user to custom format the information contained in the file. Further, tabular data is stored using HTML tables, and therefore can be utilized directly by a spreadsheet applications such as Microsoft Excel® to create custom plots of DRIP data. This capability is in addition to the intrinsic plotting package (DripPlot) provided with DRIP.

File | *Print Summary* – Prints the output summary information. The following steps need to be followed to print the summary information.

1. Select the *File* | *Print Summary* command from the file menu. A "Create DRIP summary file" dialog box similar to the one shown in Figure 3-4 pops up prompting the user to enter a file name under which the DRIP project file summary will be saved.
2. The user can choose to either save the summary information to be printed to a file by clicking the *Save* button (recommended) or can opt not to save it by pressing *Cancel* button. Note the summary files are automatically saved with an extension of *.htm.
3. After the file *Save* or *Cancel* operations are performed, the program automatically opens the "Print" dialog box shown in Figure 3-5 from where the user can select the printer to send the output to (the printer choices displayed will obviously be a function of the user's local environment).

Note that the output will be printed using default format settings. If the formatting of the default output layout needs to be changed, the user will need to open the saved summary file using standard word processing or spreadsheet programs to edit the file.

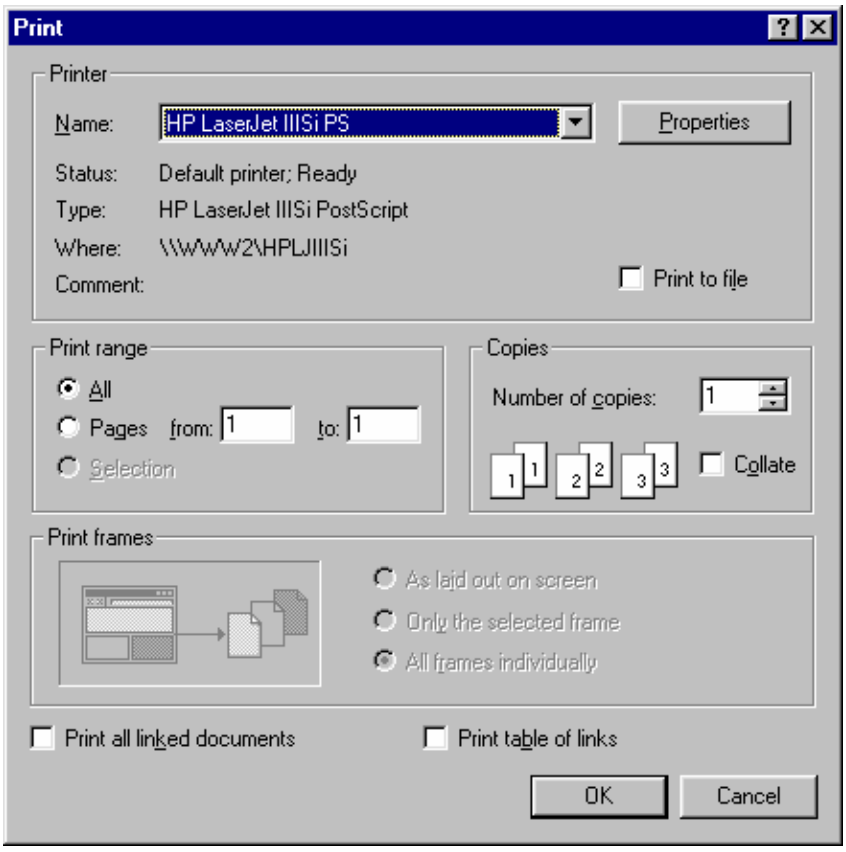


Figure 3-5. The Print dialog box.

File | *Exit* – Ends the current DRIP session. If the user selects this option or clicks on the Close icon on the client window, DRIP will generate a dialog box prompting the user to save the current project file. From here the user can choose to save the file, exit the program, or cancel the dialog box and return to the program. If the user chooses to save the file, the dialog box shown in Figure 3-3 will appear to facilitate data storage.

Options Menu

The *Options* menu sets the program options available in DRIP—Units, Mode, Sensitivity, and Plot Scale.

Options | *Units* – This menu command allows the user to toggle between metric and English standard units. All input and output variables in DRIP are converted when using the *Units* menu command. A checkmark appears next to the unit type in use. English units are used as default in DRIP.

Options | *Mode* – Determines the level of information and warning dialog boxes employed by DRIP. These dialog boxes inform the user when a program action or function deviates from those recommended by this manual. While this feature prevents the novice user of the program from making mistakes, it can become cumbersome for the

experienced user. When the *Normal* menu item is checked, all warnings and information dialog boxes are displayed. The *Expert* mode suppresses all but the most important warning boxes, allowing the experienced user to make informed changes of input data, both dependent and independent. DRIP defaults to the *Normal* mode when started.

Options | *Sensitivity* – This option is specific to the Time to Drain and Depth of Flow analyses performed within the ***Permeable Base*** property page. It allows the user to determine which sensitivity analyses are to be performed during permeable base design. The choices are length, slope, permeability, inflow, drain (degree of drainage), thickness, and porosity. If any of these menu items is checked, a corresponding sensitivity analysis is performed during the permeable base design. DRIP defaults to performing sensitivity analysis for all appropriate input variables.

Options | *Scale* – Determines whether the horizontal scale of the sieve analysis plot is logarithmic or Power 0.45. If the former is chosen, logarithms of the sieve sizes are plotted against the percent passing to produce a semi-log plot. If the latter is chosen, the sieve sizes are raised to the 0.45 power and plotted against the percent passing to yield an FHWA power 0.45 chart. DRIP defaults to a power 0.45 scale for all gradation plots.

The semi-log plot is best used when plotting materials with large amounts passing the #200 (0.075-mm) sieve for which hydrometer analysis data is available. When these gradations are plotted on an FHWA power 0.45 chart, the plot is not as visually appealing. Semi-log plots are also useful when multiple gradations with widely differing sieve sizes are being plotted on the same chart, such as in aggregate separator layer design. An example comparison of a fine-grained material plotted using the Power 0.45 and semi-log scales is presented in Figure 3-6 and Figure 3-7. Note that the gradations used in both figures are identical. The advantage of using a semi-log plot scale for this gradation is obvious from these figures.

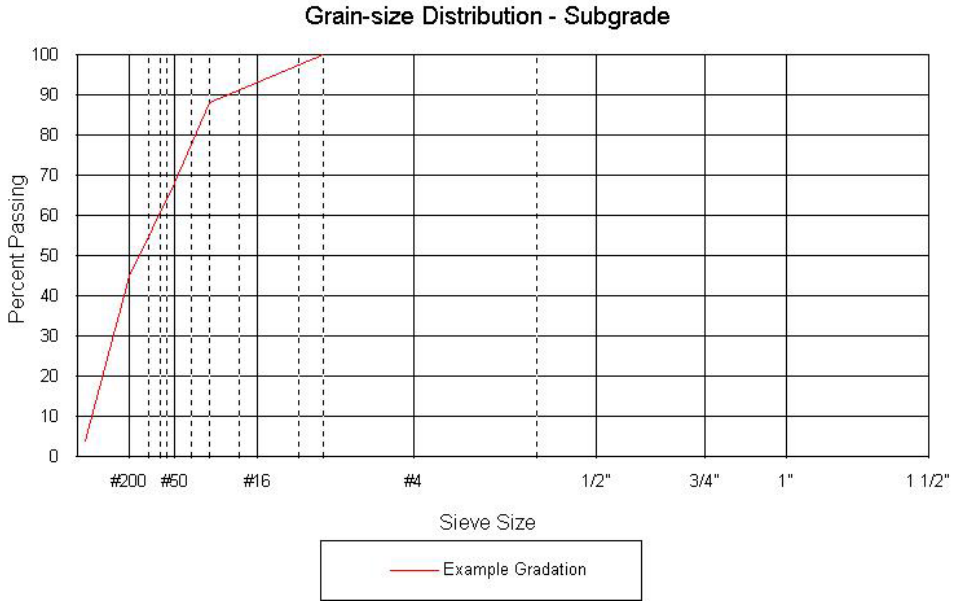


Figure 3-6. Sample subgrade gradation plot on FHWA power 0.45 chart.

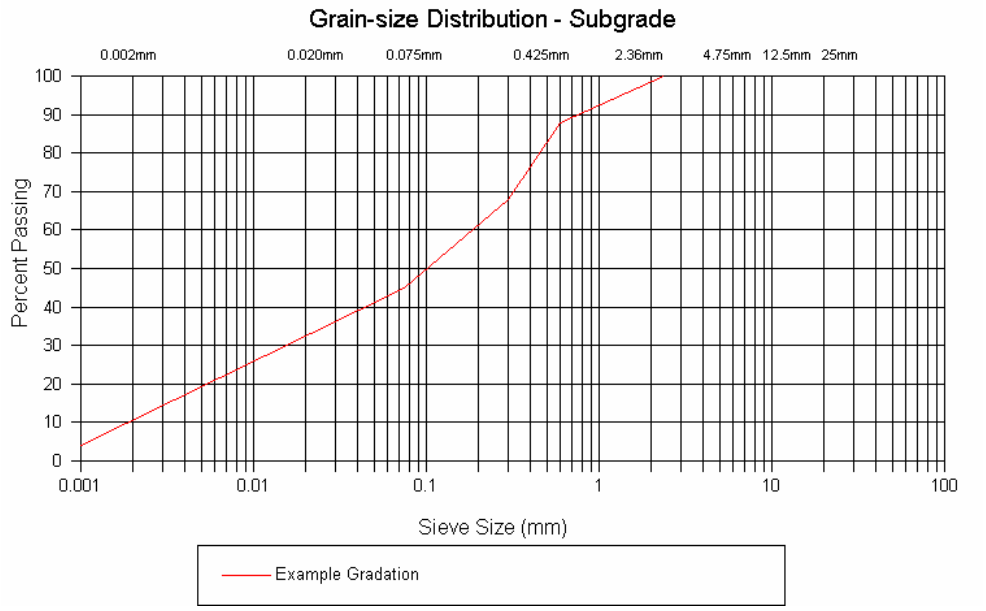


Figure 3-7. Sample subgrade gradation plot on a semi-log chart.

On the other hand, when plotting coarse-grained materials on a semi-log chart, the gradations have a tendency to fall within one or two logarithmic cycles, making the plot more difficult to read. The Power 0.45 scale is better for plotting coarse-grained materials.

Help Menu

DRIP employs Windows HTML Help. The contents of this manual are available online and can be accessed by selecting the *Help* | *Contents* command from the menu. Context-sensitive help can be accessed from anywhere within the program by pressing the F1 function key. The DRIP HTML help is fully searchable by contents, index, or keyword. The contents of the help file can be printed directly using the standard print options provided.

DripPlot

DripPlot is a companion program to DRIP that creates plots of gradations, aggregate separator design, and sensitivity analysis for permeable bases. The information on the operation of DripPlot is provided below.

DripPlot does not contain file handling or data editing capabilities. Changes to the plotted data should be made using DRIP, and the results re-plotted with DripPlot. Once a plot is generated, the user may alter the plot's appearance. DripPlot allows the editing of titles, legends, font sizes, scales of the vertical and horizontal axes, line types, line colors, and line thicknesses.

Plots generated by DripPlot can be saved either as device independent bitmaps (*.dib) or as JPEG files (*.jpg). This allows the user to import data into other Windows programs for report preparation. The user may also copy a DripPlot graph using the *Copy* menu command or shortcut key (*control-C*) and paste the graph directly into any Windows program that allows cutting and pasting.

DripPlot Menus

The DripPlot menu contains several commands that are common to almost all Windows® applications. A short summary of these commands is included for completeness. Menu commands that are unique to DripPlot are discussed in detail.

File Menu

File | *New* – Opens another window with the currently plotted screens. This allows the user to have multiple windows of the same plot open. This feature is used primarily to view plots with differing scales, legends, titles, and so on.

File | *Save as Dib File* – Saves the current plot as a device independent bitmap. Saving a file as a *Dib* allows the user to import this plot into another Windows® application. The file is saved as it appears on the user's screen, including size, line color, and titles.

File | *Save as Jpeg File* – Save the current plot as a JPEG graphic file. Saving a file as a *Jpeg* allows the user to import this plot into another Windows® application. The file is saved as it appears on the user's screen, including size, line color, and titles.

File | *Print* – This menu command prints the current plot. By default, the plot is printed in portrait mode, with the margins set in *File* | *Print Page Setup*.

File | *Print Preview* – This command displays how each plot will look when printed.

File | *Print Setup* – Allows the user to select which printer to user, as well as edit that printer's properties such as paper source, paper size, and orientation.

File | *Print Page Setup* – Calls the Print Page Setup dialog box, which is shown in Figure 3-8. The dialog box sets the margins used when printing a DripPlot graph. Valid inputs in these boxes range from 0 to 100, and represent the distance from the top and left margins. For example, a value of 10% for the *Top Margin* means that the top margin will end 10% from the top of the page. A *Bottom Margin* of 60% means the bottom margin begins 60% from the top of the page. The net effect in this case is that the plot will take up 50% of the page.

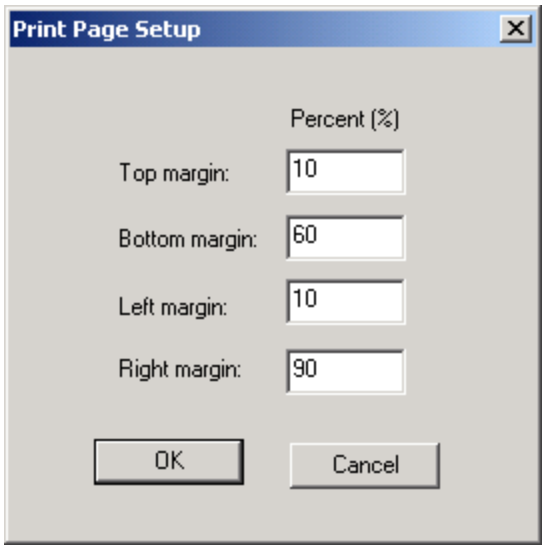


Figure 3-8. Print page setup.

Edit Menu

The *Edit* menu currently has a single menu command, which is *Copy*. The *Copy* command allows the user to copy the current plot onto the Windows® clipboard and to directly paste that plot into any applications that accept Windows® bitmaps.

View Menu

The *View* menu commands allow the user to change the basic look of the DripPlot application. *View* | *Toolbar* toggles whether the shortcut toolbar is displayed beneath the DripPlot menu. The *View* | *Status Bar* toggles whether the status bar is displayed along the bottom of the DripPlot Window. The status bar gives a short description of each menu item and displays whether the Num-lock, Cap-lock, and Scroll-lock keys are set.

Window Menu

The *Window* menu is designed to arrange and navigate among the plots generated by DRIP. At the bottom of this menu is a list of plot files currently open. Any plot can be brought to the foreground by selecting that plot name from among the menu options.

Window | *New Window* – Creates a new plot with current DRIP data. Used to recreate a modified plot.

Window | *Cascade* – Arranges plots one on top of the other, in a manner similar to that of a deck of playing cards. Each plot is slightly offset from the one directly above and below.

Window | *Tile* – Arranges plots side by side in the DripPlot window.

Window | *Arrange Icon* – Arranges minimized plots along the bottom of the DripPlot window.

Chart Menu

The *Chart* menu is used to modify the appearance of DRIP plots. DripPlot is designed to be a simple, straightforward plotting package. It is not completely customizable. If a user wishes to make highly customized plots, it is suggested that the information from DRIP be output using *File* | *Export Summary* to create an HTML summary file. This summary file can be imported directly into most standard graphing packages.

Chart | *Titles and Labels* – This command allows the user to edit the axis label and plot title text. The user can also change the font size of the all labels and titles. The "Titles and Labels" dialog box with sample graph and axes titles is shown in Figure 3-9. The default font sizes for the titles are also shown in the figure. Once the user is finished with entering the desired option values on this screen, the changes can be accepted by pressing the OK button.

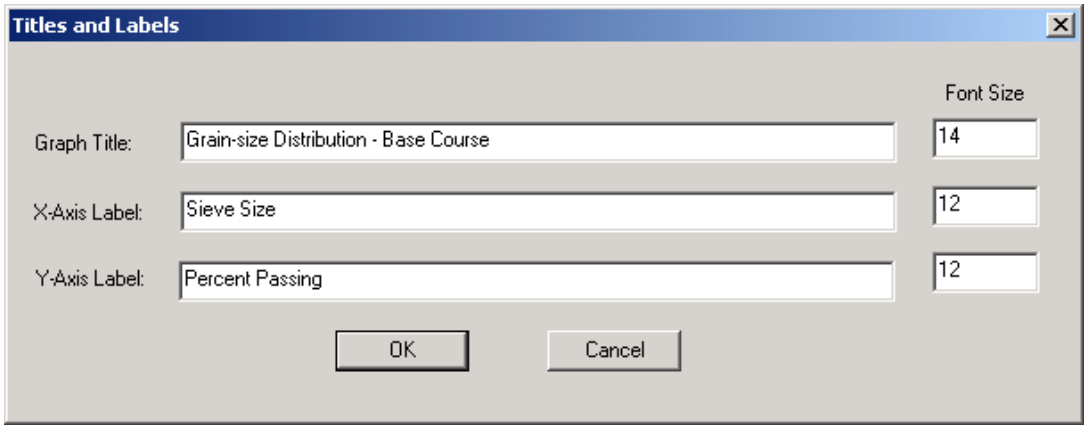


Figure 3-9. Title and Labels dialog box.

Chart | *Lines/Legends and Scale* – This command allows the user to edit the legend labels and their font size, line color, line type, and line thickness. For graphs that do not involve gradation plotting, it also allows the user to adjust the minimum and maximum values displayed on the X- and Y-axes. The tick marks can also be adjusted for scaling the axes. The "Lines/Legends and Scale" dialog box is shown in Figure 3-10.

The following points should be borne in mind when using the above referenced dialog box:

- Five separate legend entries appear in the box, which is the maximum number of individual series that can appear on a single DRIP plot. For plots with fewer than five series, the additional edit boxes are disabled.
- The Line Color edit boxes control the color of the plots generated by DRIP. The standard line thickness used by a plot generated by DRIP is 2. However, different line thicknesses (from 0 to 10), types (solid, dotted, dashed, and dashed-dot), and colors can be used to identify different series.

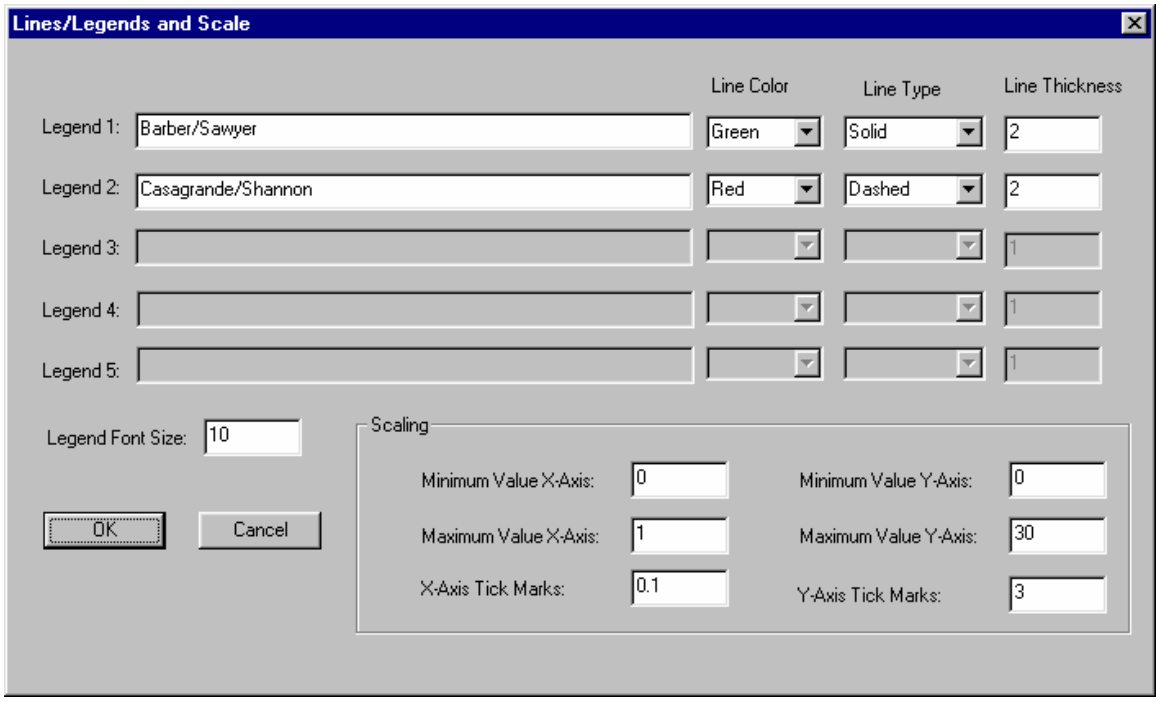


Figure 3-10. Lines/Legends and Scale dialog box.

- For the sensitivity plots, although the program allows the maximum value for the X-axis to be changed to any number, the plotted data might not be extend over the entire range. This is because the data plotted in the sensitivity charts is precomputed for realistic ranges of the independent value. These ranges are hardcoded into the program and cannot be changed. However, the minimum X-value can be changed to any level to increase the resolution of the plotted graphs.

DRIP Property Pages

DRIP has been arranged to flow smoothly from beginning to end of the design process. This has been accomplished by breaking the entire drainage design process into six sub-processes and developing a tabbed property page for each: ***Roadway Geometry***, ***Sieve Analysis***, ***Inflow*** (with the ***Meltwater*** sub-screen), ***Permeable Base*** design, ***Separator*** layer design, and ***Edgedrain*** design. The user can access any of these property pages by selecting the appropriate tab along the top of the DRIP client window. The layout of the property pages on the DRIP client window (see Figure 3-1) suggests a logical left-to-right flow of drainage design, which is recommended. However, the program has the flexibility to allow the user to start at any point within the program and to use only a few of the program components including the use of only a single property page. While the property pages can be utilized in a stand-alone manner, they are somewhat interdependent in that the inputs on one page can be taken from the calculations on another. The interdependencies of the DRIP property pages are shown in Figure 3-11.

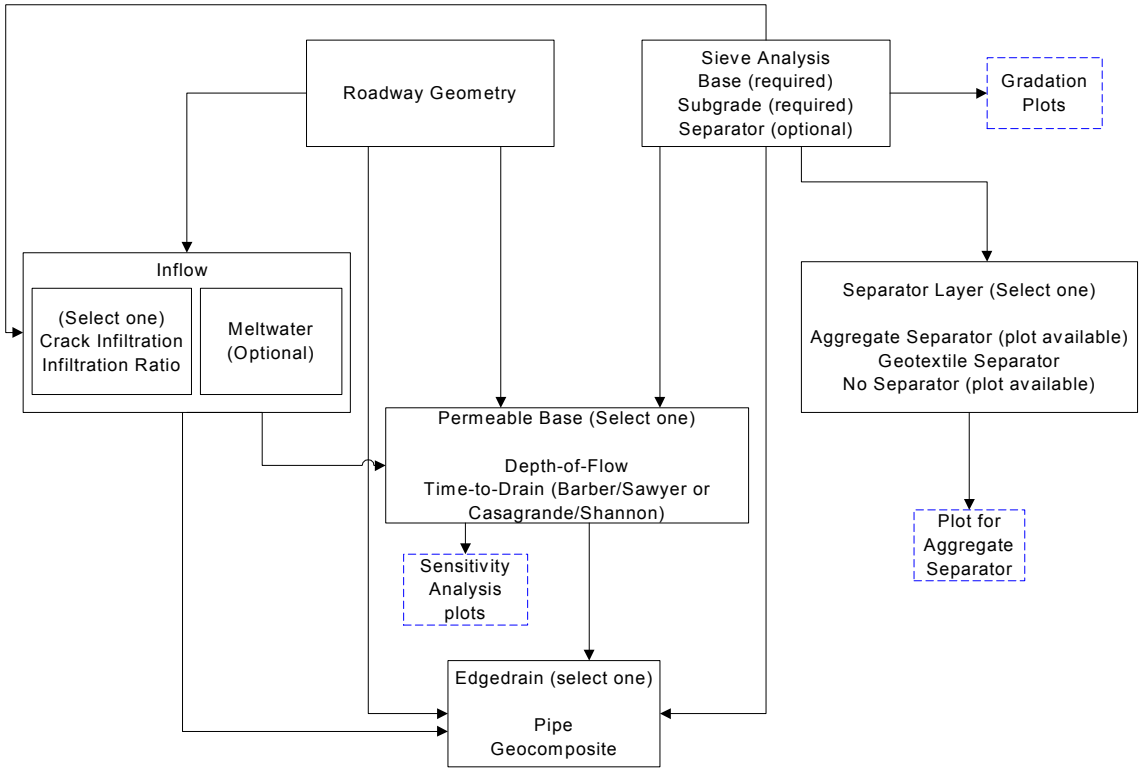


Figure 3-11. Interdependencies of DRIP property pages.

The ***Sieve Analysis***, ***Inflow***, ***Permeable Base***, ***Separator***, and ***Edgedrain*** screens are actually multiple property pages in one. By selecting a specific analysis type using the radio buttons located in the upper left-hand corner of the property page, the analysis performed by that page can be changed. For example, on the ***Inflow*** property page the user can choose either the *Crack Infiltration* method or the *Infiltration Ratio* method by selecting the appropriate radio button. On the ***Permeable Base*** property page, the analysis can be set either to the *Depth-of-Flow* or the *Time-to-Drain* method, the ***Separator*** property page can design either pavements without or with a separator layer (aggregate or geotextile), and the ***Edgedrain*** property page can be used to design either pipe or geocomposite pavement edgedrains. In addition, a number of other dialog boxes are accessible from within certain property pages. For example, a dialog box for the estimation of the quantity of meltwater using Moulton's chart is available from the ***Meltwater*** property page.

A number of plots are available from the DRIP property pages including 1) depth-of-flow and time-to-drain sensitivity plotting, accessible from the ***Permeable Base*** property page; 2) meltwater inflow plotting, accessible from the ***Inflow*** property page; and 3) aggregate gradation plotting, accessible from the ***Separator*** layer property page or the ***Sieve Analysis*** property page.

Input and Output

DRIP uses standard Windows edit boxes within each property page to display input and output values, which allows the user to input a value for any parameter after positioning the screen cursor over the appropriate edit box and clicking the left mouse button. The user can then type the input value from the keyboard. In many cases, however, it is desirable to let DRIP calculate the parameter value based on user-provided input values for other parameters.

Calculator icons beside the parameter labels identify cases where the variable should be calculated by the program. Calculator icons often are accompanied by an equation that indicates which parameter values must be input. When the required input values have been provided, the calculator icon will become enabled, or "activated"; an active calculator icon is blue in color. By positioning the screen cursor over an active calculator icon and clicking the left mouse button, the value is calculated and displayed in the edit box. Thus, edit boxes are used as the primary means of both input and output.

An alternative method for navigating to the calculator icon is to press the Tab key until the desired button has the focus (i.e., until a faint dotted line appears around the button text). Once the button has the focus, hitting the space bar selects the button.

Even when it is desirable to let the system calculate a value for a specific parameter, the user always has the option to type a value into the edit box. To permit this feature, the program diligently checks for data conflicts to maintain consistency within a design and integrity of the program. Thus, typing a value for a parameter that should be calculated may cause conflicting values for other parameters to be erased.

A list of parameters used in this program is included in appendix A, "Standardized Nomenclature."

Roadway Geometry

Although DRIP operates in a modular manner and the design process can be performed in any order, it is suggested that the user access the ***Roadway Geometry*** property page first. The ***Roadway Geometry*** property page screen is shown in Figure 3-12. On the upper right side of the screen are two graphics representing the available options—a roadway with crown in the centerline and a roadway that slopes in the same direction on both sides of the centerline. Indicate which geometry best fits the design situation by clicking the appropriate radio button. The equation for width of drainage path W reflects the geometry selection, as will the profile graphic in the middle right side of the screen.

To calculate W, the user must first provide values for the parameters b, the width of pavement surface, and c, the distance from the pavement shoulder to the edge of the permeable base, by entering this data in the appropriate edit box. When values have been supplied for both parameters, the calculator icon beside the parameter W will become

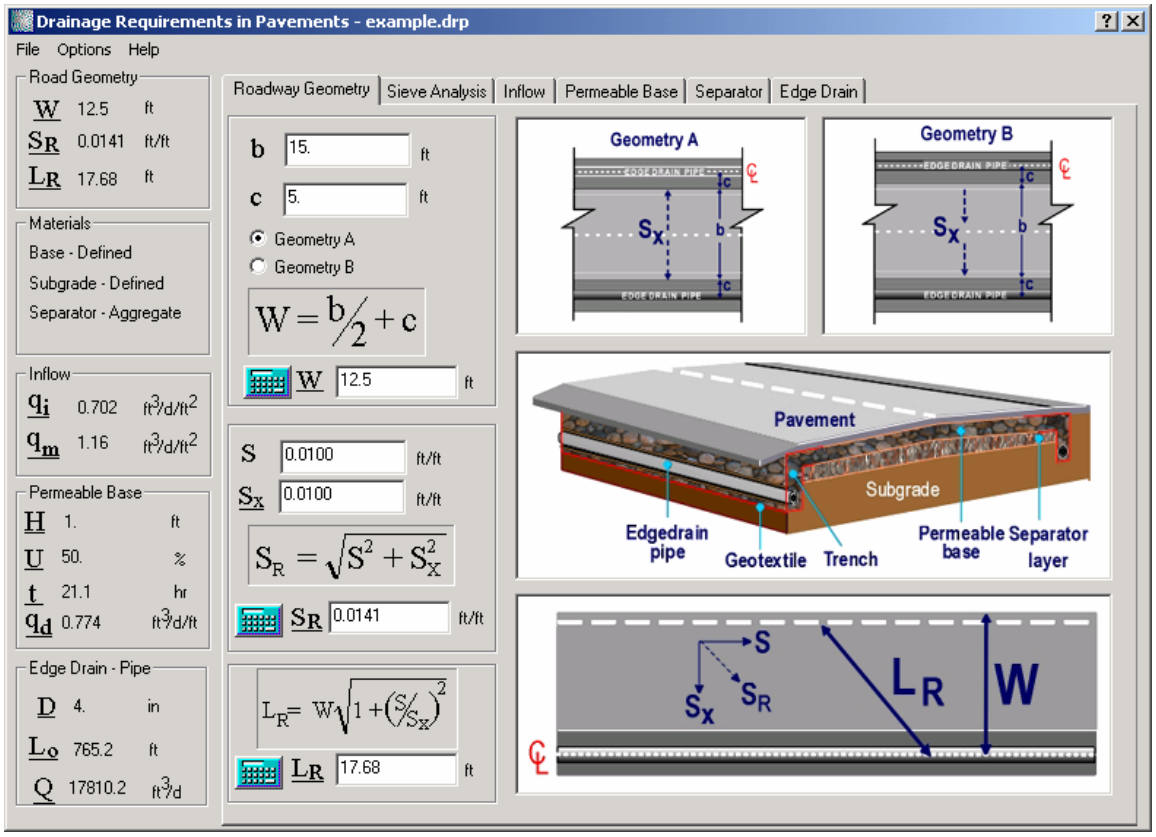


Figure 3-12. Roadway Geometry property page.

activated. Clicking on this icon will cause the value for *W* to be calculated using the equation shown. In the same manner, when values are provided for longitudinal slope *S* and cross slope S_X, the calculator icons for resultant slope S_R and resultant length of drainage path L_R are activated.

The calculator icons become activated whenever all data values that are required to evaluate the respective equations are available. The user always has the option to type in a value for the parameter rather than use the equation to calculate it. However, doing so may cause the program to erase values of other parameters (to avoid inconsistencies).

For example, assume that the user has provided values of 9.3 m and 1.2 m for parameters *b* and *c*, respectively. Selecting the calculator icon yields a *W* value of 5.85 m. Now proceed to provide values of 0.05 and 0.03 for *S* and S_X, respectively, and calculate values of 0.0583 for S_R and 11.37 m for L_R. Now manually edit the value of *W*, rounding it up to 6 m. Doing so erases the value of *c*, because the combination of *b* and *c* that are provided cannot result in a *W* value of 6 m. The program also erases the value of L_R, because the value of 11.37 m does not reflect the new design parameter that was provided. This process of erasing data requires the user to recalculate values that reflect new inputs, thereby adding to the integrity of the final design. It also prevents the user from mistakenly assuming that values of dependent parameters are still valid.

A flowchart showing the data flow in the ***Roadway Geometry*** property page is presented in Figure 3-13.

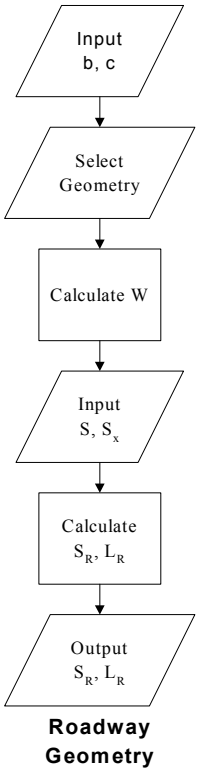


Figure 3-13. Flowchart for the Roadway Geometry property page.

Sieve Analysis

The ***Sieve Analysis*** property page, shown in Figure 3-14, is used for gradation analysis and to input other material properties for the base course, separator, and subgrade layers. The spreadsheet-style grid on the left side of the property page is used for entering and editing sieve analysis data. Sieve data may be entered in this grid in any order, and cells may be left blank if data is not available for a particular sieve size. Two types of sieve analysis data entry forms, *Range* and *Value*, are available to the user. The *Range* analysis, selected by the corresponding radio button near the top left side of the property page, allows the user to input a range of sieve data that a particular material is bracketed by. The *Value* analysis requires the user to input a single value at sieve sizes for which data is available. The numbers entered are the percent passing a particular sieve, by weight, and therefore should range from 0 to 100. For example, 100% passing should be input as 100 and 55.3% passing should be input as 55.3.

When all of the sieve data has been entered, the user can select the calculator button located in the Gradation Analysis box to perform a grain size distribution analysis. If the entered gradation data is not consistent, DRIP warns the user by changing the font color of the value in question to red. For example if the user entered 50% passing the #4 Sieve,

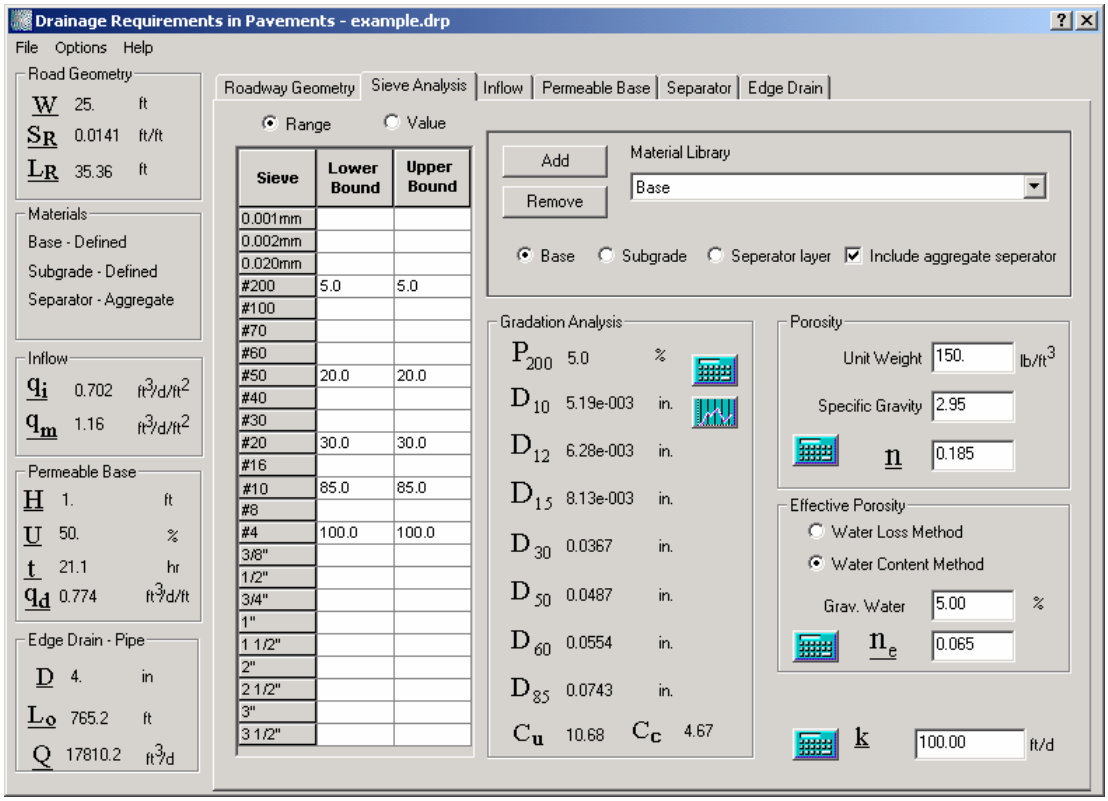


Figure 3-14. Sieve Analysis property page.

and 100% passing the #8, the number 50.0 would be highlighted in red since it is physically impossible to have such a gradation.

DRIP allows the user to enter both the sieve and hydrometer analysis data when determining grain size distribution. It is important to include the sieve size where less than 10% passes so that the program can properly determine D_{10}. It is also important to include the sieve where at least 85% of the material is passing so D_{85} can be properly determined. When the user selects the calculator button in the Gradation Analysis box, a grain size distribution analysis is performed to calculate effective sizes at different percentages (D_{10}, D_{12}, D_{15}, D_{30}, D_{50}, D_{60}, D_{85}), percent passing the #200 sieve, C_U (coefficient off uniformity), and C_c (coefficient of curvature or gradation).

After the calculator button is selected in the Gradation Analysis category box, the Gradation plot button becomes active. Selecting this button calls DripPlot and displays a grain size distribution plot. The program defaults to a Power 0.45 horizontal scale, but the user may change this to a semi-log scale using the *Options | Plot Scale* menu command. On the main DRIP window, the gradation of the AASHTO #57 material is plotted in Figure 3-15 on a Power 0.45 chart as an example.

In addition to entering sieve data, DRIP allows the user to select materials from the resident *Material Library*. When a material is selected from the *Material Library,* all of the sieve and property data saved for that material will be entered in the appropriate edit boxes, overwriting the data already present.

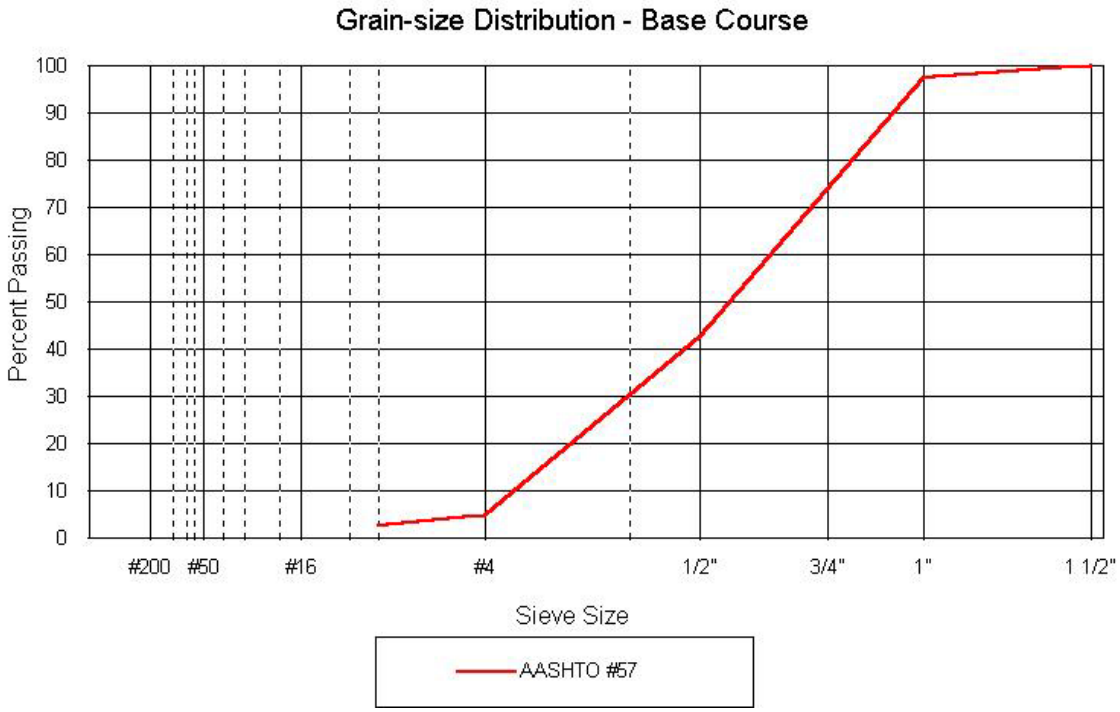


Figure 3-15. Example output of a value input sieve analysis.

The user can also save custom gradation data to the *Material Library* along with other material property information such as unit weight, porosity, and effective porosity by following these simple steps:

1. Select the type of layer—base, subgrade, or separator—for which data will be entered. This can be done by selecting the appropriate radio button on the ***Sieve Analysis*** property page.
2. Select either the *Range* or *Value* data entry form and enter the desired gradation data.
3. Click on the Add button in the Material Library box. Assuming that the input data does not contain inconsistencies, an "Add Gradation to Library" dialog box appears (see Figure 3-16). If there is an error in gradation data entry, the inconsistent data appears in red colored font and will need to be corrected.
4. Enter a text-based file descriptor that will be also used as a file name. This file name will have the extension .sgd attached to it and will be saved in the GradFiles folder in the DRIP directory. Avoid using any DOS file control characters (*,/,\,:,?) when describing the material.

After the material is saved to the *Material Library,* that description will appear in the library pull down list box. If the user edits this file by entering new numbers in the *Sieve Analysis* spreadsheet, the material type will return to <*user defined*>. The <*user defined*> material type is a temporary name and will not be saved if a specific material is selected from the *Material Library.*

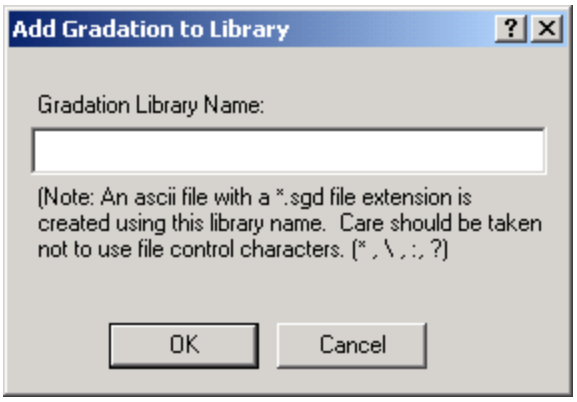


Figure 3-16. Add gradation to Material Library.

Materials that are added to the *Material Library* remain in the library until the file is removed using the Remove button or deleting the appropriate *.sgd file from the GradFiles subdirectory. When a user starts entering data in the sieve analysis spreadsheet, the name of the material changes to <*user defined*>. It is possible to have separate <*user defined*> entries for the base, subgrade, and separator layers.

Besides gradation analysis, the ***Sieve Analysis*** property page requests several other user inputs. These values can be entered directly or calculated using empirical formulae. Permeability, k, of a layer can be calculated using Moulton's empirical formulation, which requires particle size and porosity information. DRIP allows the user to compute porosity after the unit weight and the specific gravity of the material is entered. A more accurate estimation of porosity can be gained through laboratory testing. If such data are available, they should be used in place of the empirical formulae.

Two analysis methods are supplied for computation of the effective porosity, n_e—the water loss method and the water content method. As the user clicks the appropriate radio button for each method, the equation changes accordingly. For fine materials such as subgrades, the water content method is recommended. In order to use this method to estimate n_e, the approximate value of the water content should be entered.

For coarse materials such as permeable bases, the water loss method is recommended. To use this method, the user should first select the *Water Loss Method* radio button. The "Water Loss" dialog box similar to the one shown in Figure 3-17 opens automatically. This dialog box contains a table that shows values for water loss for P_{200} of 0%, 2.5%, 5%, and 10%, for either gravel or sand materials. The user should indicate the type of fines (filler, sand, or clay) contained in the material by clicking the appropriate radio button. If the user has already calculated P_{200} for the given material, that value will appear as a column in the grid shown in Figure 3-17. Two water loss values, one for sand and other for gravel, are automatically computed and displayed in the dialog box in the P_{200} column. The user should then select one of the water loss values corresponding to the material being analyzed with the screen cursor. Once the selection is made and the

Figure 3-17. Water Loss dialog box.

"Water Loss" dialog box is closed by pressing the "OK" button, the selected value appears in the Water Loss edit box on the ***Sieve Analysis*** property page.

Inflow

The next recommended step in a drainage analysis is to calculate the pavement infiltration due to rainfall and meltwater (where applicable). This calculation is handled in the ***Inflow*** property page. The user can perform this calculation using the Infiltration Ratio method or the Crack Infiltration method by selecting the appropriate radio buttons. By default the program uses the latter method. Adding meltwater to the inflow calculation can be enabled or disabled by means of the *Include Meltwater* check box.

The ***Inflow*** property page configured for the Infiltration Ratio method is shown in Figure 3-18. In the Infiltration Method category box, the user can indicate whether the surface is asphalt or concrete by clicking the appropriate radio button. The range of acceptable values for infiltration coefficient C is noted below the edit box. The user may type an estimate of the value in the edit box or click the $\bar{x}$ icon to automatically fill the edit box with the midpoint value. Changing the surface type will erase any displayed value of C and will require the user to provide a new value.

The lower portion of the screen allows the user to type in a value for the rainfall rate R, which can be approximated from the rainfall map displayed in online help when the calculator icon is pressed. By default, the program displays the map for a 2-year, 1-hour storm, which is recommended in FHWA report number FHWA-SA-92-008 (1992). The user can opt to display instead the map for a 1-year, 1-hour storm, which is recommended in FHWA-TS-80-224 (Moulton, 1980). Both maps show R values in units of in/hr, so if the analysis is employing metric units, the user needs to manually convert these values to their metric equivalent.

When values have been provided for both R and C, the calculator icon for inflow, q_i, is activated. Clicking the icon will calculate q_i using the equation shown.

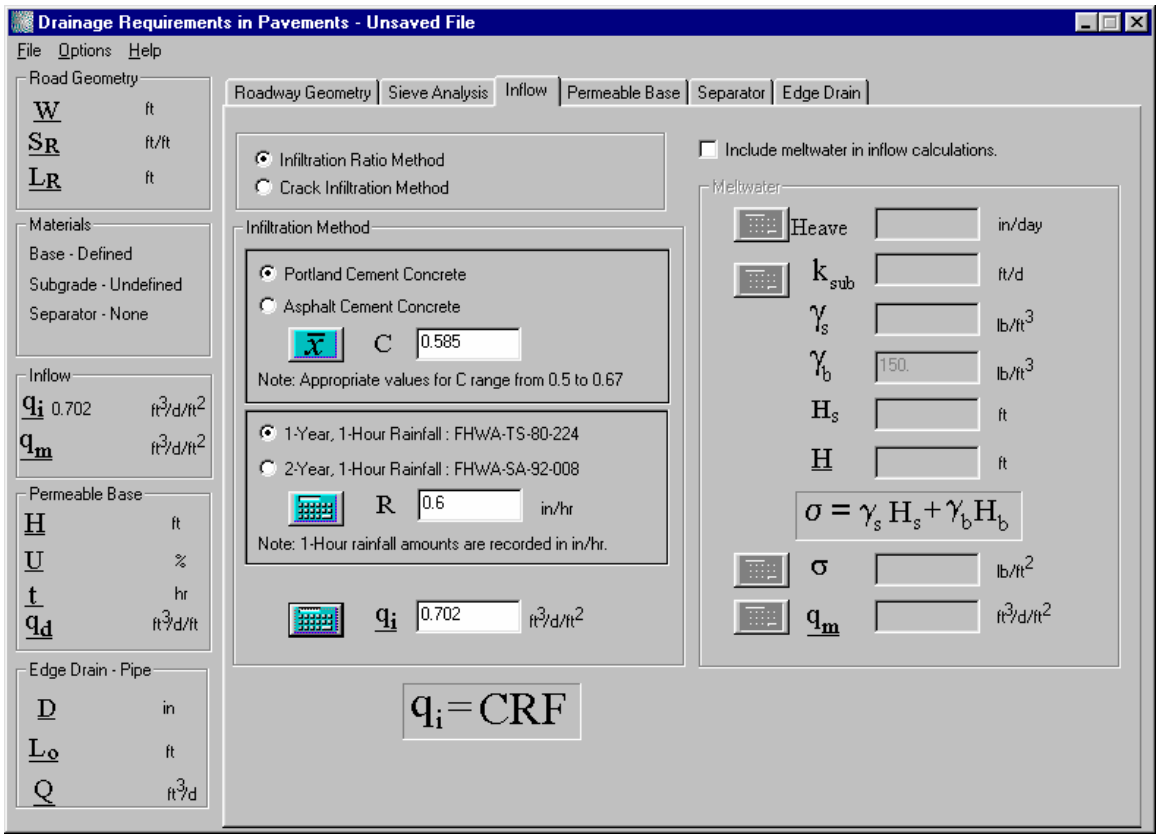


Figure 3-18. Inflow (Infiltration Ratio) property page.

The ***Inflow*** screen for the Crack Infiltration method is shown in Figure 3-19. When the program begins, the crack infiltration rate I_C has a default value of 2.4 ft^3/day/ft (0.22 m^3/day/m). Some other input parameter values may already be filled in when the property page is first selected if they have been generated by previous inputs and calculations. For example, if the user calculated W = 5.85 m on the ***Roadway Geometry*** screen using Geometry A and values of 9.3 m and 1.2 m for b and c, respectively, then the W edit box will contain the number 5.85 and the edit box for width of pavement W_C will contain the number 4.65 (or b/2). Other parameters to be supplied are permeability k_p of the pavement surface, transverse crack spacing C_S, and number of contributing longitudinal cracks N_C. N_C is generally equal to one plus the number of contributing traffic lanes. When values are provided for all these parameters, the calculator icon for q_i will be activated, allowing the calculation to be performed. The user should compare the value calculated here to the value calculated using the Infiltration Ratio method, and choose the larger number for the sake of conservatism.

Along the same conservative vein, the user may wish to include meltwater in the total inflow calculation. The ***Inflow*** property page with the *Include Meltwater* box checked is shown in Figure 3-20. The heave rates for different types of subgrade soils can be determined by selecting the calculator icon to the left of the *Heave* edit box label. A "Heave Determination" dialog box such as the one shown in Figure 3-21 will open. This dialog box presents minimum and maximum heave rates for a variety of soil types with

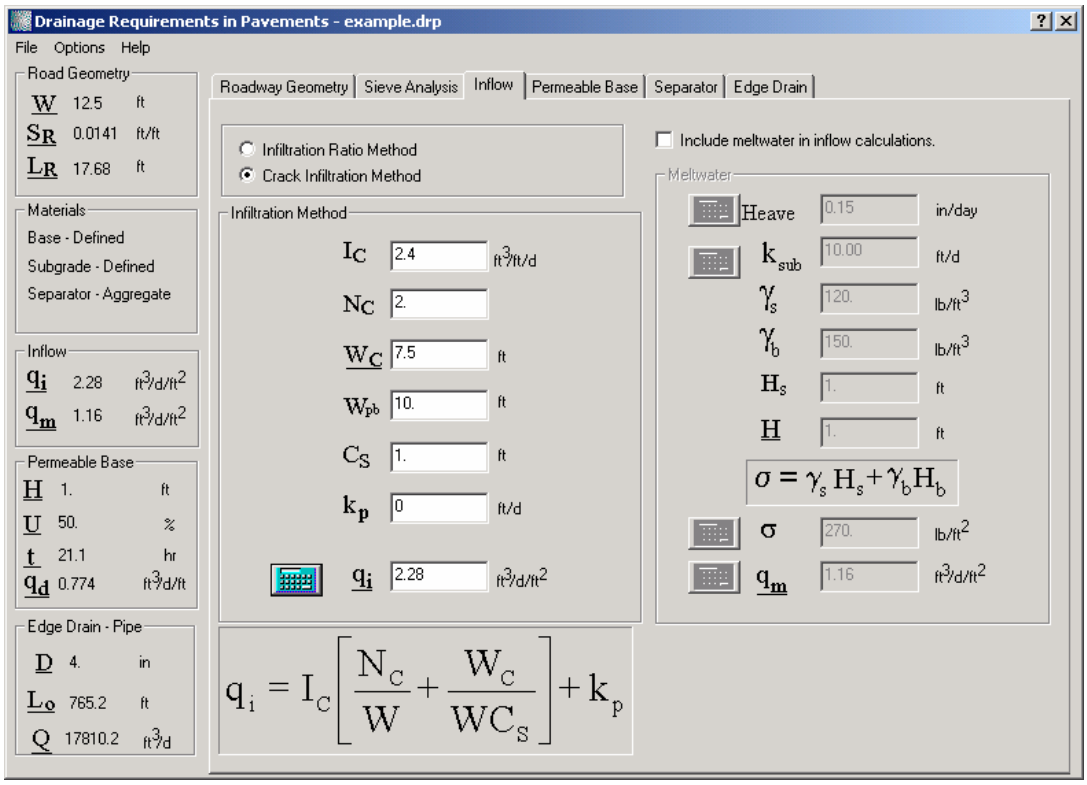


Figure 3-19. Inflow (Crack Infiltration) property page.

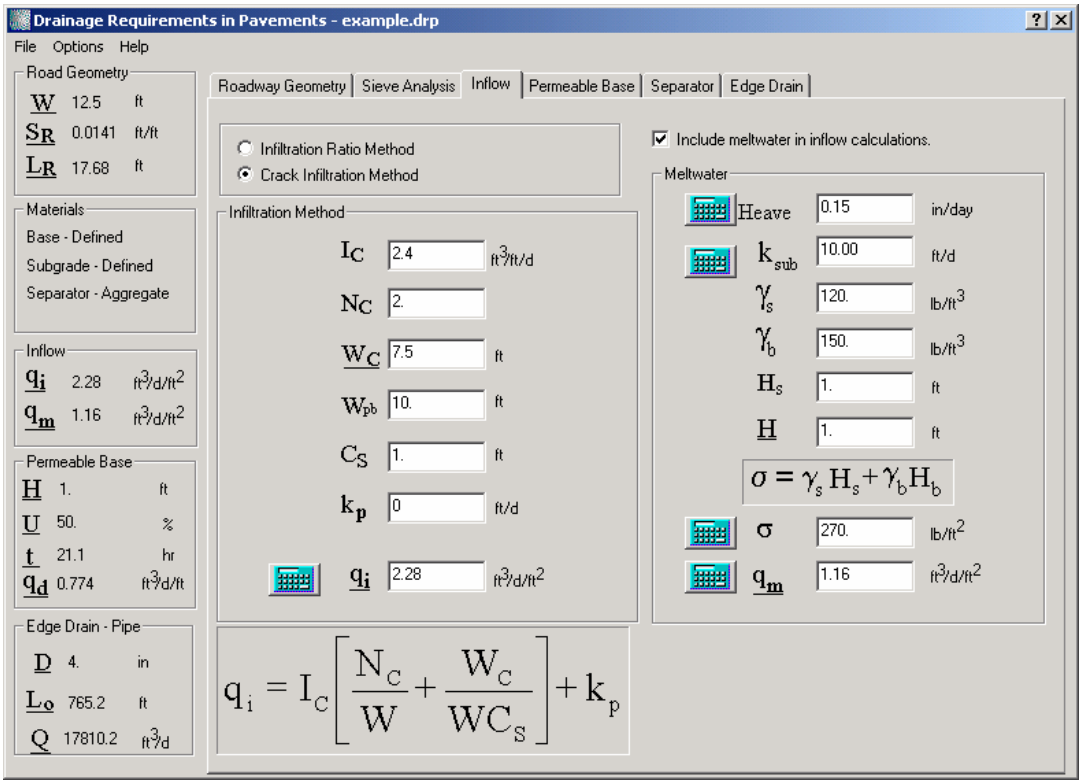
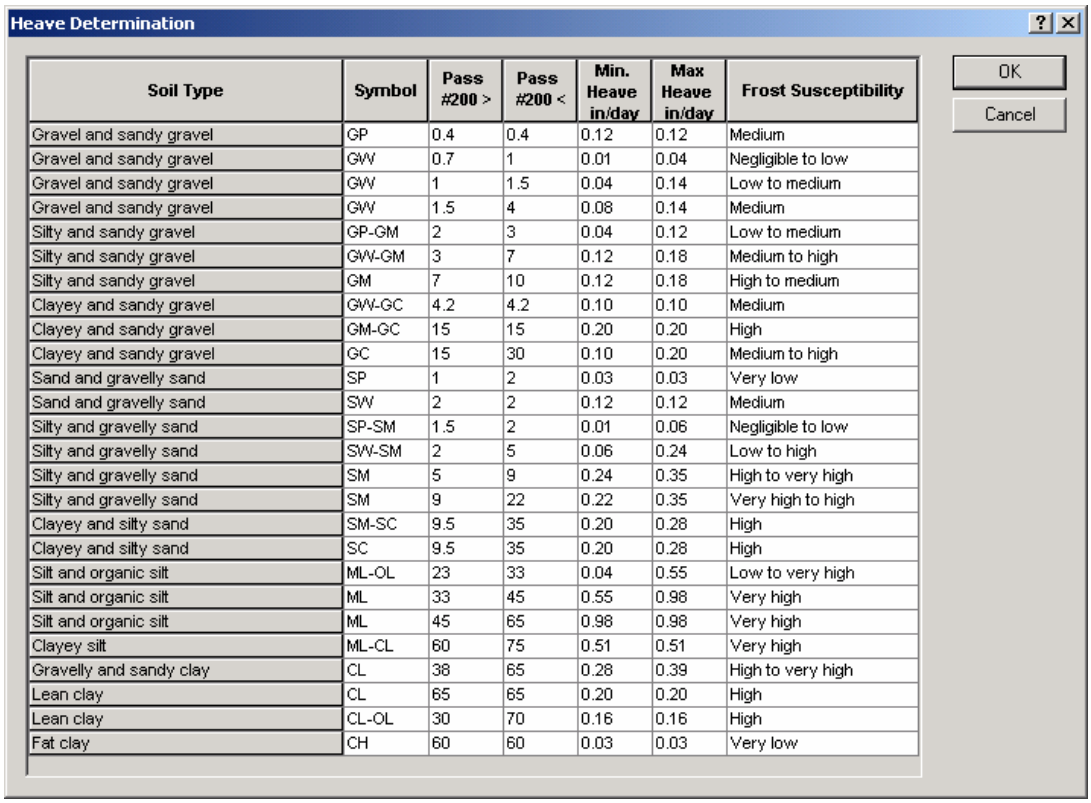


Figure 3-20. Inflow calculation with Meltwater included.



Soil Type	Symbol	Pass #200 >	Pass #200 <	Min. Heave in/day	Max Heave in/day	Frost Susceptibility
Gravel and sandy gravel	GP	0.4	0.4	0.12	0.12	Medium
Gravel and sandy gravel	GW	0.7	1	0.01	0.04	Negligible to low
Gravel and sandy gravel	GW	1	1.5	0.04	0.14	Low to medium
Gravel and sandy gravel	GW	1.5	4	0.08	0.14	Medium
Silty and sandy gravel	GP-GM	2	3	0.04	0.12	Low to medium
Silty and sandy gravel	GW-GM	3	7	0.12	0.18	Medium to high
Silty and sandy gravel	GM	7	10	0.12	0.18	High to medium
Clayey and sandy gravel	GW-GC	4.2	4.2	0.10	0.10	Medium
Clayey and sandy gravel	GM-GC	15	15	0.20	0.20	High
Clayey and sandy gravel	GC	15	30	0.10	0.20	Medium to high
Sand and gravelly sand	SP	1	2	0.03	0.03	Very low
Sand and gravelly sand	SW	2	2	0.12	0.12	Medium
Silty and gravelly sand	SP-SM	1.5	2	0.01	0.06	Negligible to low
Silty and gravelly sand	SW-SM	2	5	0.06	0.24	Low to high
Silty and gravelly sand	SM	5	9	0.24	0.35	High to very high
Silty and gravelly sand	SM	9	22	0.22	0.35	Very high to high
Clayey and silty sand	SM-SC	9.5	35	0.20	0.28	High
Clayey and silty sand	SC	9.5	35	0.20	0.28	High
Silt and organic silt	ML-OL	23	33	0.04	0.55	Low to very high
Silt and organic silt	ML	33	45	0.55	0.98	Very high
Silt and organic silt	ML	45	65	0.98	0.98	Very high
Clayey silt	ML-CL	60	75	0.51	0.51	Very high
Gravelly and sandy clay	CL	38	65	0.28	0.39	High to very high
Lean clay	CL	65	65	0.20	0.20	High
Lean clay	CL-OL	30	70	0.16	0.16	High
Fat clay	CH	60	60	0.03	0.03	Very low

Figure 3-21. Heave determination dialog box.

different ranges of minus 200 material. In some cases, the lower bound heave rates are the same as upper bound heave rates, indicating that there is very little variability in the data. The user may use this table to estimate a heave rate for a given soil type and manually enter it into the *Heave* edit box, or alternatively obtain the value by clicking on the desired row in the table. If the latter method is used, the midpoint of the selected range of heave values will automatically appear in the edit box. In addition to heave rate determination, the user should also provide a value of subgrade permeability k_{sub}. An estimate of the subgrade permeability can be directly entered based on laboratory test data or can be determined based on sieve data. Selecting the calculator icon next to the k_{sub} edit box returns the user to the ***Sieve Analysis*** property page from where this parameter can be estimated. The other parameter required to estimate inflow due to meltwater is load of the pavement structure, σ, which includes loads from both the pavement surface and the base. The user can either directly enter a value for σ, if it is known *a priori*, or can compute it by first entering values for unit weights γ_p and γ_b and the thickness H_S and H of the pavement surface and base, respectively, and then clicking on the calculator icon to the left of the σ label.

When values have been provided for σ, k_{sub}, and the *Heave* rate, the graph icon for meltwater, q_m, is activated. The user can click this icon to display Moulton's chart for estimation of meltwater shown below in Figure 3-22. The vertical axis represents heave rate, in mm/day, and a red line is drawn to indicate the heave rate value. The user can

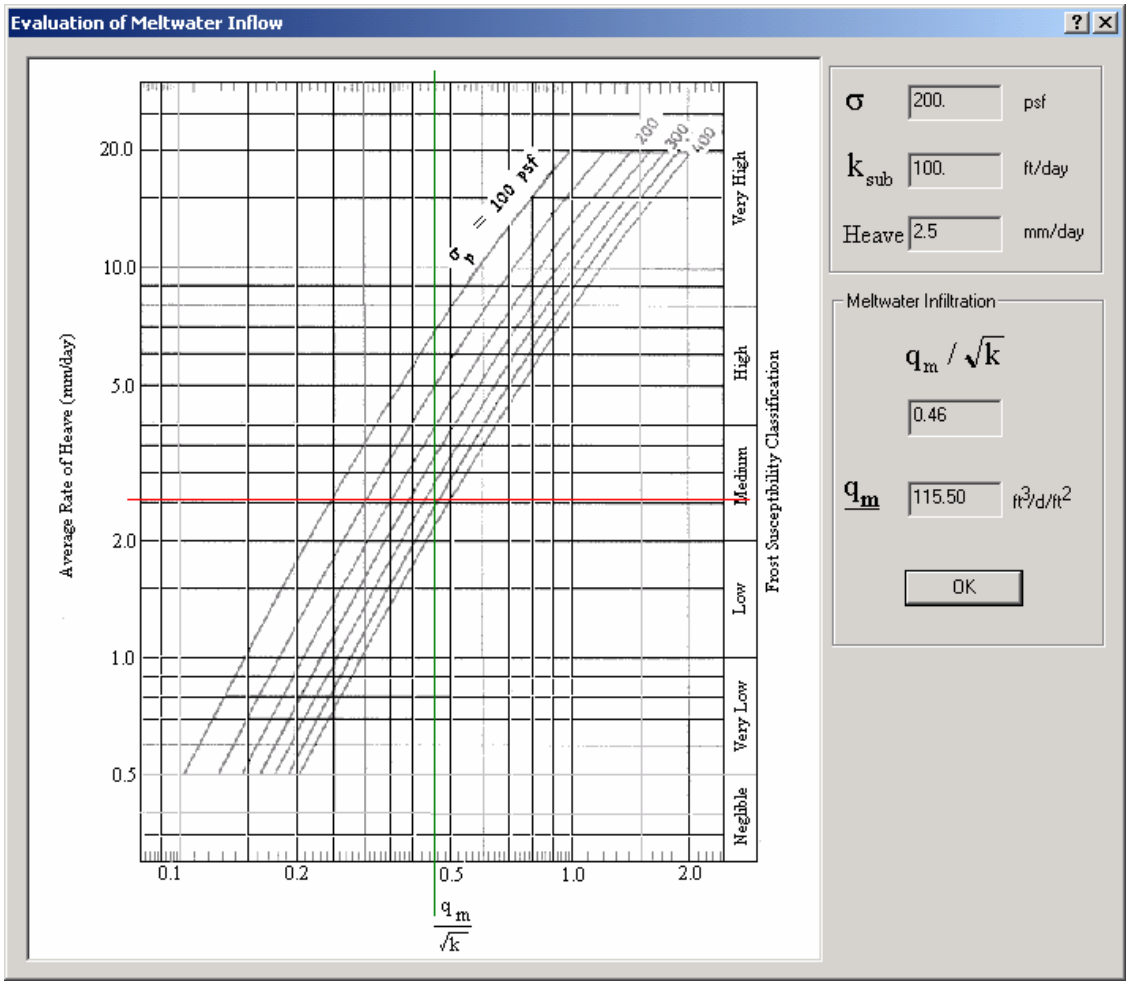


Figure 3-22. Meltwater inflow computation dialog box.

move the mouse to drag a crosshair along the red line. The horizontal axis represents $q_m/\sqrt{k_{sub}}$. The curves on the graph represent multiple values of σ, in units of lb/ft^2. The values of k_{sub}, σ, and heave rate are displayed at the top of the screen in the required units, as is the current position of the cursor with respect to the horizontal axis. Position the crosshair at a graph location indicative of the value of σ, and click the mouse button. The value of q_m will be calculated and displayed at the top of the screen. When this dialog box is exited, the calculated value will appear in the q_m edit box on the ***Meltwater*** screen.

Example – Meltwater Computation

Assume for this example that the subgrade permeability (k_{sub}) is 100 ft/day, the heave rate (*Heave*) is 0.1 in/day, and the vertical stress on the top of the subgrade (σ) is 200 lb/ft^2. Enter these values in the appropriate edit boxes and click on the graph icon to determine q_m. Moulton's meltwater chart appears on the screen. On this chart a horizontal red line marking the entered heave rate of the subgrade (0.1 in./day) appears. In order to compute the meltwater, the computer mouse can be used to slide the vertical tick line along the

horizontal red line to the location where σ is approximately 200 lb/ft^2. When the mouse is at the right position the value for $q_m/\sqrt{k_{sub}}$ should read 0.36. A left click of the mouse button will then produce a value for q_m of 3.61 ft^3/day/ft^2. This value is transported to the q_m edit box on the ***Inflow*** property page when the "Evaluation of the Meltwater Inflow" dialog box is closed.

While including meltwater is a conservative approach, engineering judgment may need to be exercized in adding this value the pavement infiltration from rainfall – q_i. The combined inflow of q_i and q_m could be unreasonably high in some situations.

A flowchart illustrating the data flow on the ***Inflow*** property page is presented in Figure 3-23.

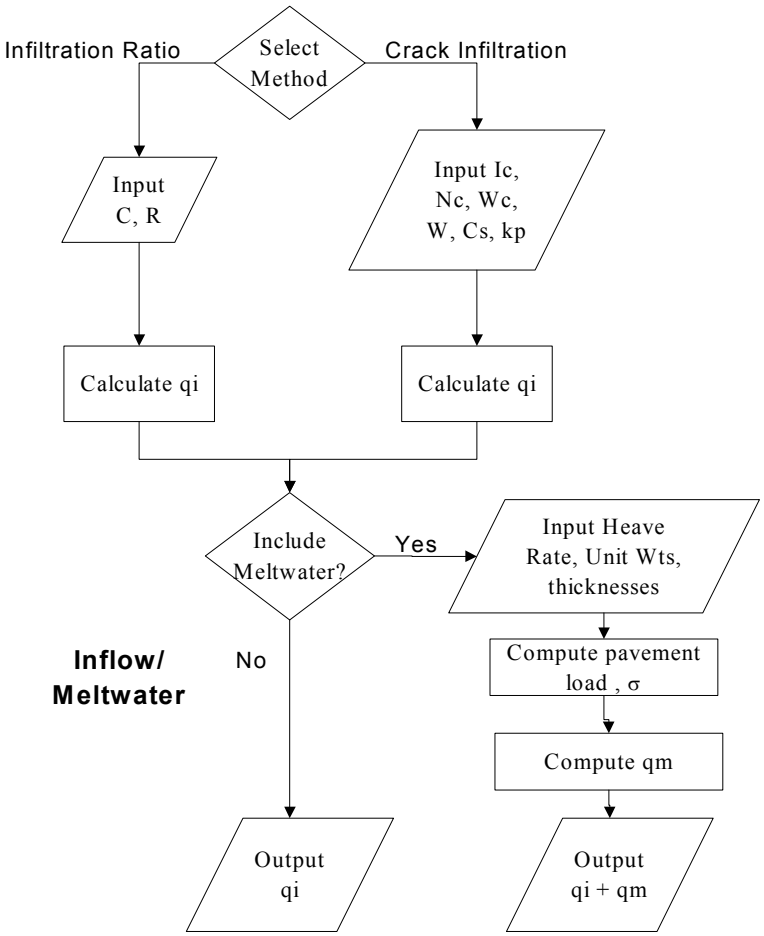


Figure 3-23. Flowchart for the Inflow property page.

Permeable Base

On the top left corner of the ***Permeable Base*** property page, the user may choose whether to design the permeable base based on depth-of-flow or time-to-drain criteria by clicking the appropriate radio buttons. It is suggested that total inflow be calculated before attempting to perform the base design using the depth-of-flow method. The ***Permeable Base*** property page configured for the depth-of-flow method is shown in Figure 3-24.

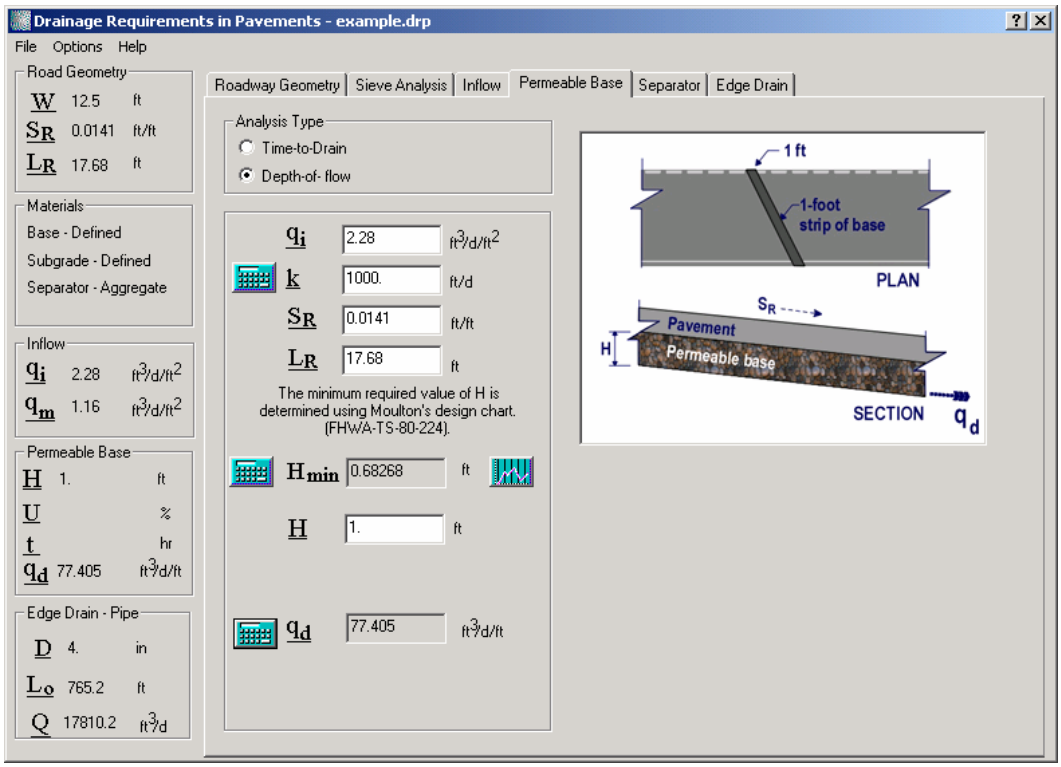


Figure 3-24. Permeable Base (depth-of-flow) property page.

If the left-to-right hydraulic design flow recommended in this manual is followed, values for several parameters will already be present on this screen. For example, S_R and L_R will have been calculated on the ***Roadway Geometry*** property page, q_i will have been calculated on the ***Inflow*** property page, and a value for H may have also been provided on the ***Inflow*** property page. If these values are not present, they may be manually entered in the appropriate edit boxes on this screen. However, for hyperlinked variables (all variables identified with an underline), a more correct procedure would be to first identify the appropriate property pages where these inputs should be logically entered, and then entering them there. In addition to these variables, the user will also need to provide a value for permeability, k, of the permeable base. It is recommended in hydraulic design practice that this value be obtained directly from laboratory testing. The laboratory k value, if available, can be directly entered on this screen. Alternatively, the user may click the calculator icon located to the left of this parameter to estimate permeability based on the gradation of the permeable base aggregate. This action will

take the user to the ***Sieve Analysis*** property page where the computation can be made. However, it must be noted here that the underlying statistical relationship that estimates permeability from the gradation data was derived for materials with a significant quantity of material passing the #200 sieve. Therefore, it may not be very suitable for estimating the permeability of open-graded materials, which typically have very low percent passing the #200 sieve.

When values have been provided for q_i, k, S_R, and L_R, the calculator and graph icons beside the H_{min} parameter are activated. If the calculator icon is clicked at this point, the program will use the equations underlying Moulton's permeable base design chart to calculate the minimum required thickness H_{min} of the permeable base. The user should check to make sure that the input value of H is greater than the minimum thickness required, H_{min}. Clicking the graph icon to the right of the H_{min} edit box will plot the calculated value of H_{min} over a given range of values for the independent parameters selected in the *Options* | *Sensitivity* menu command. This allows the user to analyze the sensitivity of the design to variations in inputs. A few typical sensitivity plots for the depth-of-flow method are shown in Figure 3-25 and Figure 3-26.

Once the user is satisfied that the value provided for base thickness H is sufficient to handle any possible variations in the design parameters, the capacity of the permeable base, q_d, can be computed by clicking the calculator icon located to the left of the corresponding label.

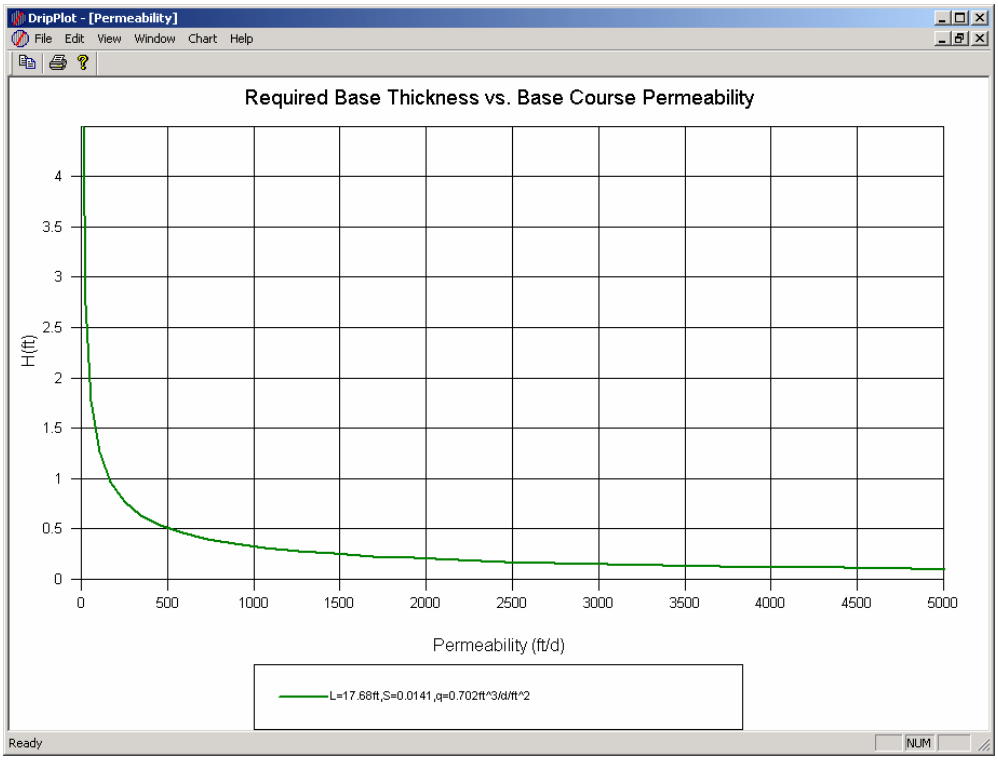


Figure 3-25. Sensitivity analysis for the depth-of-flow method – base permeability versus base thickness.

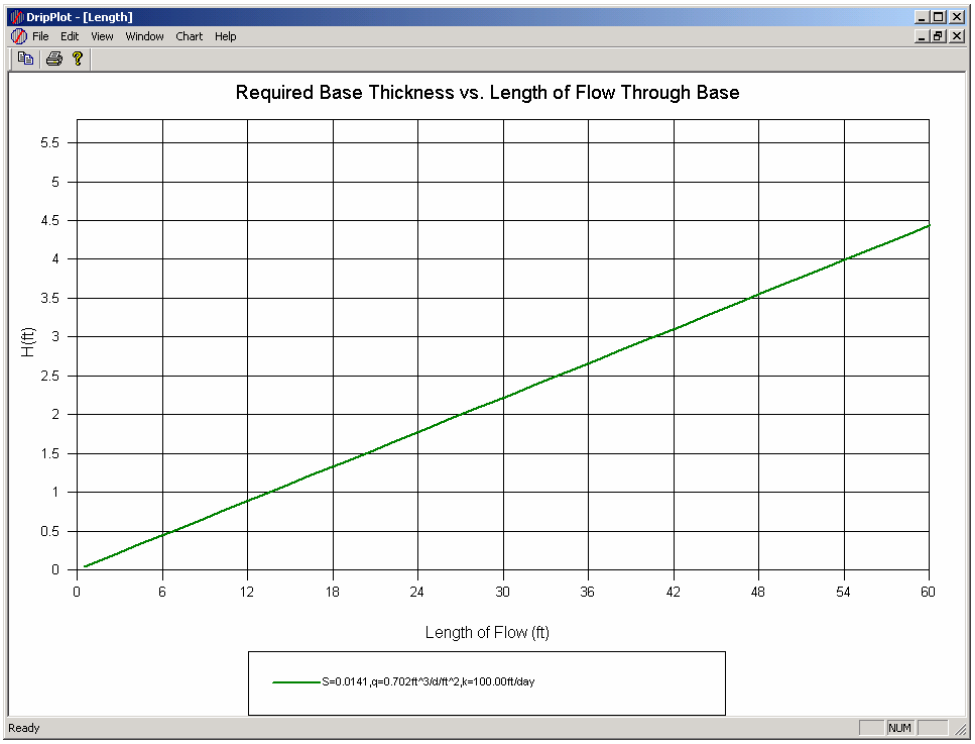


Figure 3-26. Sensitivity analysis for the depth-of-flow method – length of flow versus base thickness.

The ***Permeable Base*** property page configured for the time-to-drain method is shown in Figure 3-27. As with the depth-of-flow method, values would already have been supplied for many of the parameters from previous screens. There are calculator icon buttons beside the labels for permeability k and effective porosity n_e that the user can click to call the ***Sieve Analysis*** property page. Estimated values for these parameters can be determined based on aggregate gradation input in that page. However, it is recommended that these values be obtained instead through laboratory testing. Once the values for k, n_e, S_R, L_R, H, and percent drainage U, are supplied, the user can click the calculator icon to determine the time required to drain, t. By default, the parameter t is estimated using the Barber and Sawyer equation. Alternatively, if the Casagrande and Shannon Method is the preferred method, the corresponding radio button must be first selected and the calculator button next the t parameter clicked to compute the appropriate value.

The resulting value for time t required for drainage from either methods can be compared to the table on the right-hand side of the screen to estimate the permeable base quality of drainage. By default, the table displays the quality of drainage based on the AASHTO 50 percent drained criteria. Alternatively, the user can choose to display base drainage quality based on the pavement rehabilitation manual 85% saturation criteria by clicking the appropriate radio button. To translate these criteria to the current design parameters, the user should select the given equation to calculate percent saturation from the values of n, n_e, and U. The user may have to modify the value of U until it results in a value of $S \cong 85\%$.

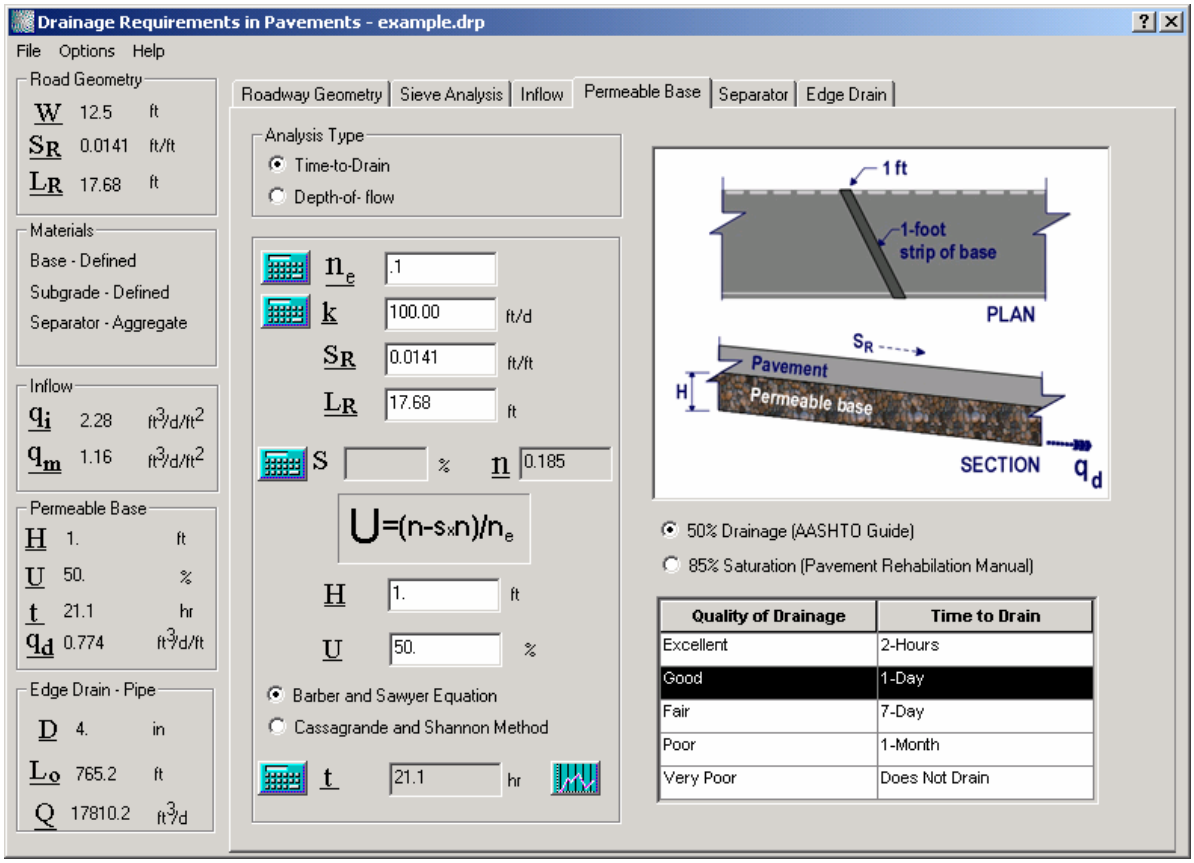


Figure 3-27. Permeable Base (time-to-drain) property page.

As with the depth-of-flow screen, the time-to-drain screen also provides sensitivity plotting. These plots can be accessed by clicking on the graph icon located to the right of the time-to-drain parameter *t* on the ***Permeable Base*** property page. Prior to clicking this icon, the independent parameters to be plotted on the horizontal axis against the dependent variable *t* need to be selected using the *Options* | *Sensitivity* menu command. The sensitivity plots always include the results computed using both Barber and Sawyer as well as the Cassagrande and Shannon equations. A typical sensitivity analysis plot from the time-to-drain analysis is presented in Figure 3-28. In this figure, the time-to-drain parameter *t* is plotted against the degree of drainage, *U*. It can be observed from the figure that as the degree of drainage approaches 100 percent, the time to drain increases exponentially. Note that *U* is expressed as a fraction in the Figure 3-28.

A flowchart depicting the data flow in the ***Permeable Base*** property page is shown in Figure 3-29.

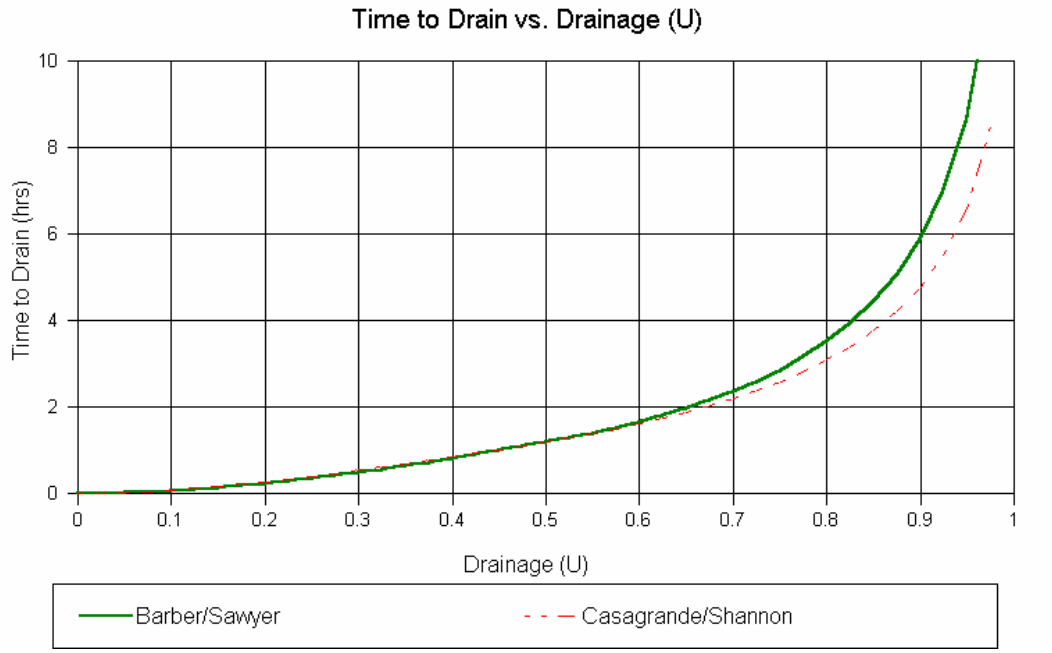


Figure 3-28. Sensitivity plot for the time-to-drain analysis – time to drain versus degree of drainage.

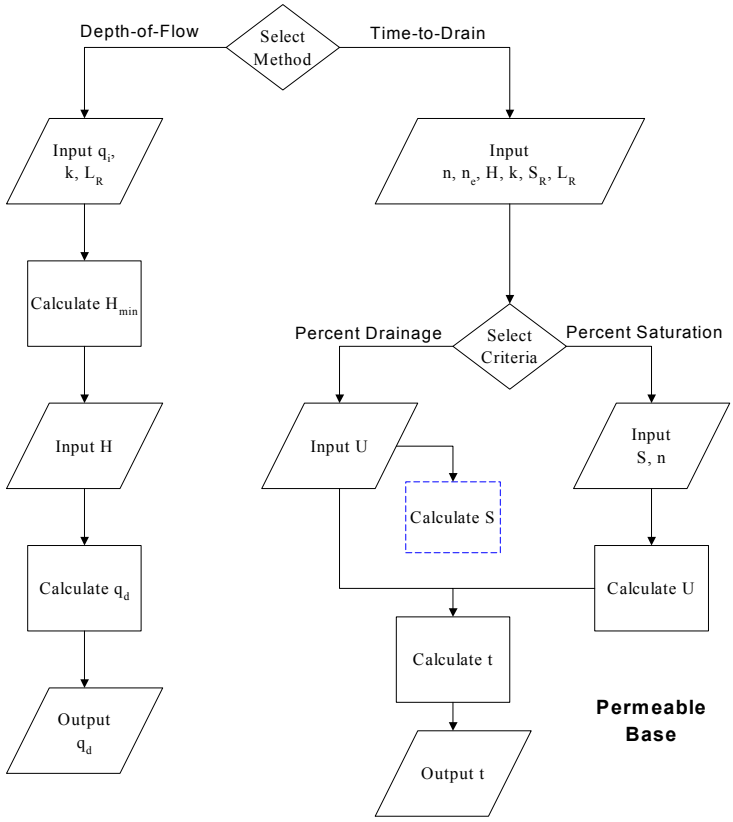


Figure 3-29. Flowchart for the Permeable Base property page.

Separator Layer

The default screen that appears when the ***Separator*** property page is first selected during a DRIP session is the configured for the *No Separator* option. If a design is performed using this option, DRIP will determine whether a separator layer is required. If instead the user wishes to perform an aggregate separator layer design, the appropriate radio button located on the left top of the property page should be clicked. The design screen configuration after this selection is made is shown in Figure 3-30. The right side of the design screen displays particle size criteria to prevent intermixing of layers. The left side of the screen allows the user to input particle size values (e.g., D_{10}, D_{15}, D_{50}, and D_{85}) for the permeable base, subgrade, and separator layers. These values should already be present if a complete gradation analysis has been completed for all the materials on the ***Sieve Analysis*** property page. If the particle size values are missing for any given layer, the user should go to the ***Sieve Analysis*** property page to compute these values. This can be done either by clicking the calculator button adjacent to the layer in question or by clicking the Sieve Analysis tab on the DRIP client window. When all the required D_x values are configured, the balance and graph icons on the right side of the screen turn blue in color. By clicking on the balance icon, the aggregate separator layer design criteria can be checked.

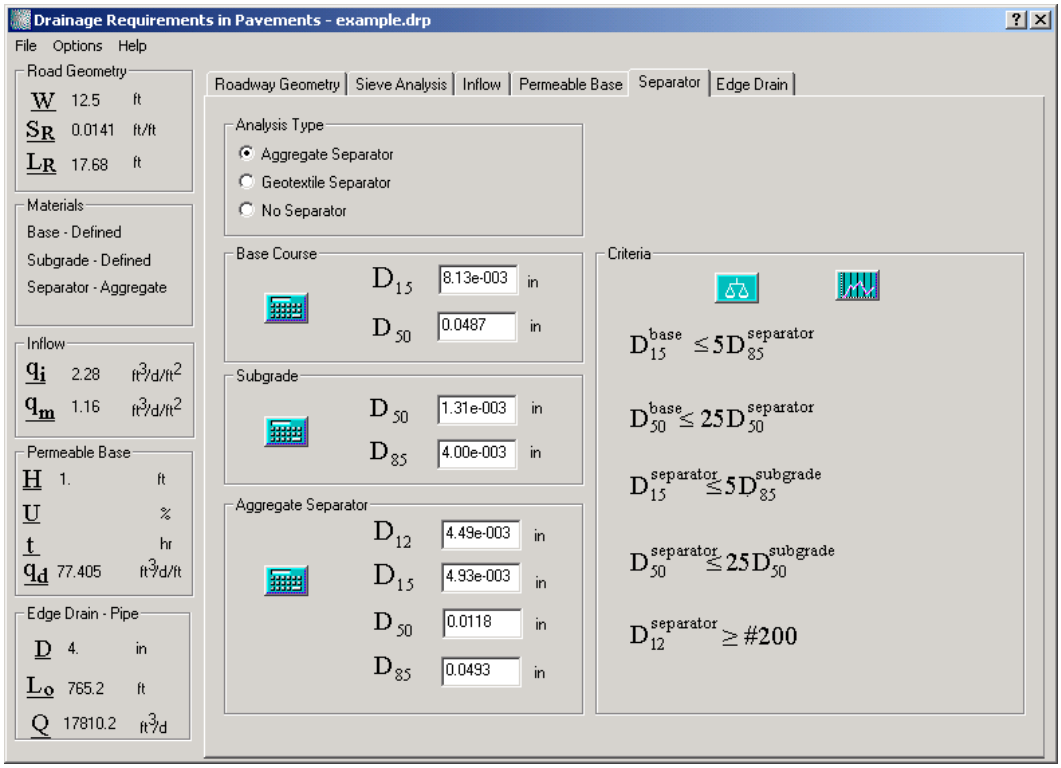


Figure 3-30. Separator (aggregate separator layer) property page.

After DRIP determines whether the design passes the necessary separator layer criteria, left-clicking the graph icon located in the Criteria category box will generate a plot which graphically summarizes the design performed. For an aggregate separator layer design,

this plot contains the gradation plots of the subgrade, the base course, and the separator layer. In addition, the numerical values of the design criteria are also plotted and are represented using red triangles. The right-pointing triangles denote the lower limit, while the left-pointing triangles denote the upper limit of the desired gradation band for the separator layer.

A sample plot generated from the ***Separator*** property page is shown in Figure 3-31. If a chosen separator layer passes all the required design criteria, its gradation should fall within this desired band as illustrated in Figure 3-31. As with the plots generated on the ***Sieve Analysis*** property page, either a Power 0.45 or a logarithmic scale can be employed for the horizontal axis for this plot.

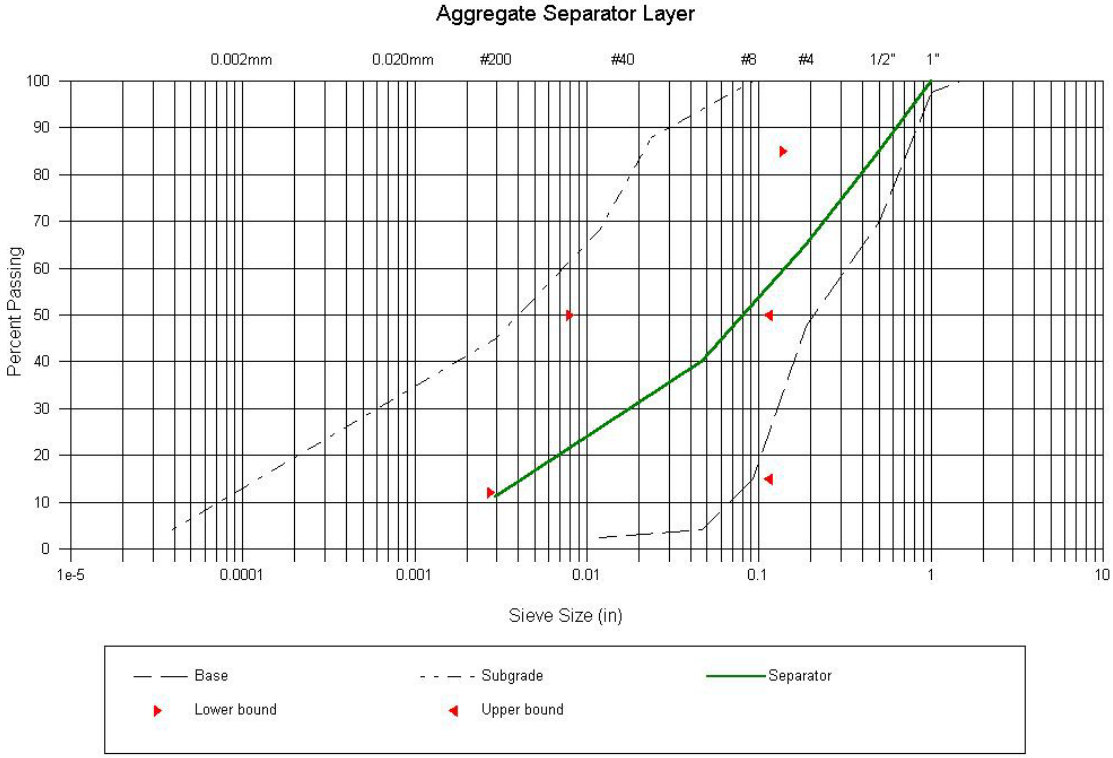


Figure 3-31. Separator (aggregate separator) Power 45 plot.

Figure 3-32 presents the ***Separator*** property page configured for performing a geotextile separator layer design. Selecting the *Geotextile Separator* radio button enables this analysis screen. As with the aggregate separator layer analysis, the design criteria for the geotextile separator layer are also displayed on the right-hand side of the screen. The criteria displayed are dependent on the user's selections for soil retention criteria (steady-state or dynamic flow), permeability/permittivity criteria (normal or critical), clogging criteria (normal or critical), and the amount of fines in the subgrade material (P_{200}).

Material properties for the subgrade should already be in the edit boxes, carried over from the ***Sieve Analysis*** property page. After the necessary values have been provided for all the subgrade parameters, the calculator icon in the Separator Layer category box becomes enabled. Clicking this button determines the maximum allowable apparent

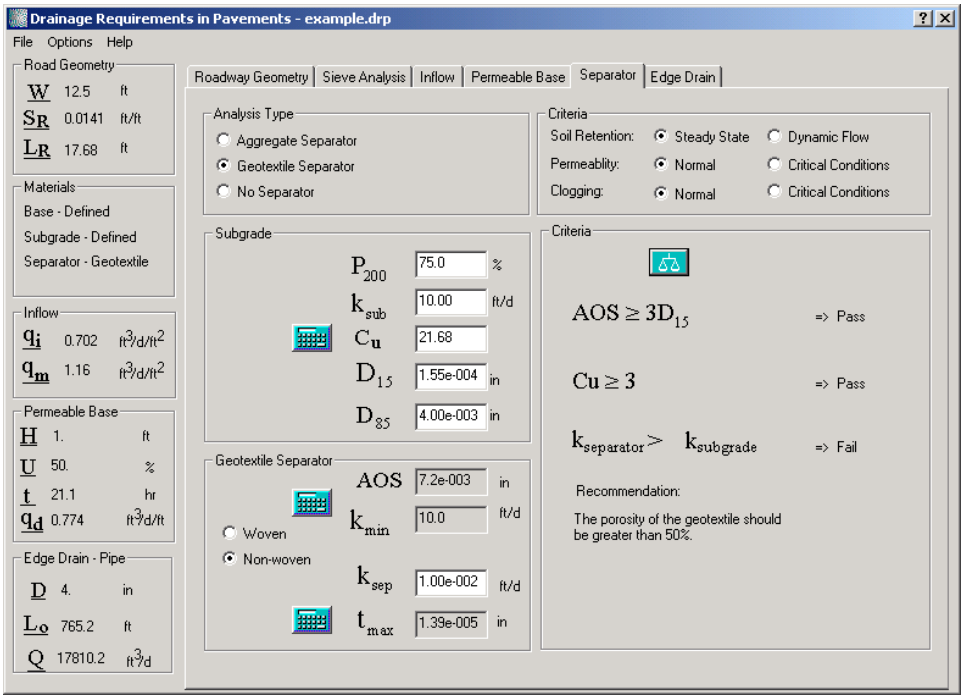


Figure 3-32. Separator (geotextile separator) property page.

opening size *AOS* of the geotextile and the minimum allowable permeability k_{min} of the geotextile. Typically, at this stage, in design, a geotextile that satisfies the *AOS* and k_{min} requirements is selected and its actual permeability is entered in the k_{sep} edit box. The calculator icon for t_{max} will then become enabled and the maximum allowable thickness of the geotextile for permittivity requirements can be computed. Note that the recommendation at the bottom of the screen changes based on the geotextile type.

A flowchart illustrating the data flow of the ***Separator*** property page is shown in Figure 3-33.

Edgedrain

In the upper left-hand corner of the ***Edgedrain*** property page select either the *Pipe* or *Geocomposite* radio button to identify the type of edgedrain. The *Pipe Edgedrain* analysis screen is shown in Figure 3-34. Typical values for Manning's roughness coefficient, $n_{manning}$, for smooth and corrugated pipes are provided on the right-hand side of the screen. If $n_{manning}$ for the pipe being analyzed is unknown, one of these typical values can be adopted by selecting the appropriate check box. Once the user has supplied values for $n_{manning}$, slope S of the edgedrain (by default the longitudinal slope), and pipe diameter D, the calculator icon for pipe capacity Q becomes activated and can be clicked to calculate the quantity.

After calculating Q, there are three options for determining the required outlet spacing. The *Pavement Infiltration* approach is based on the estimated inflow into the permeable base; this is the default selection in DRIP. The *Permeable Base* approach is based on the *Depth of Flow* capacity of the permeable base. Finally, the *Time to Drain* approach is

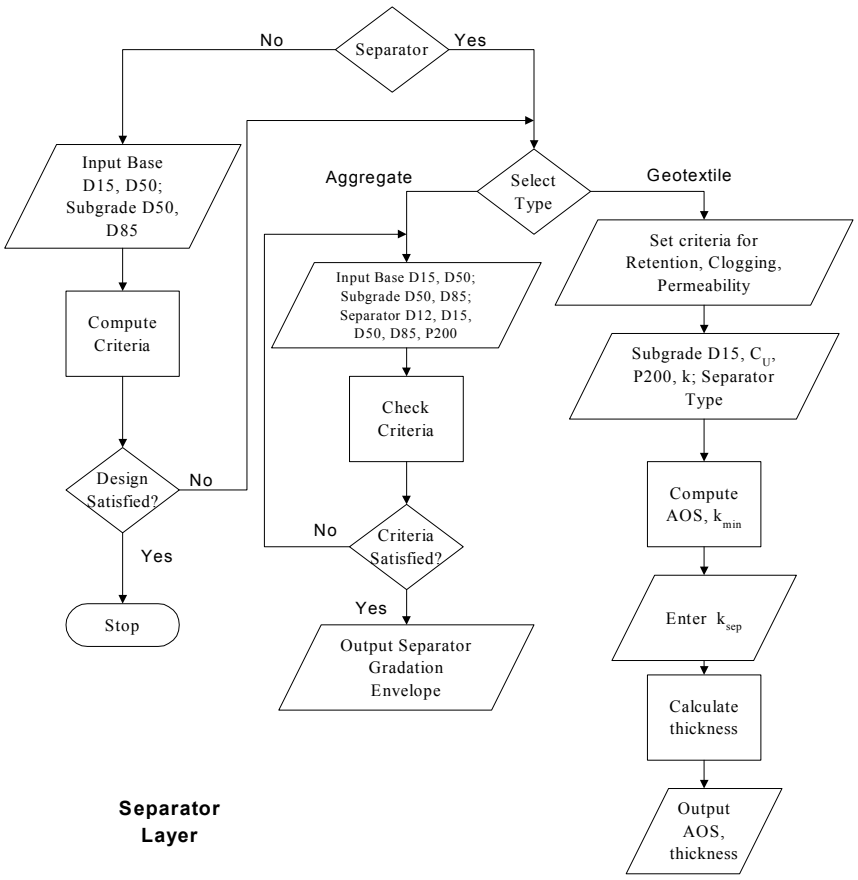


Figure 3-33. Flowchart for the Separator property page.

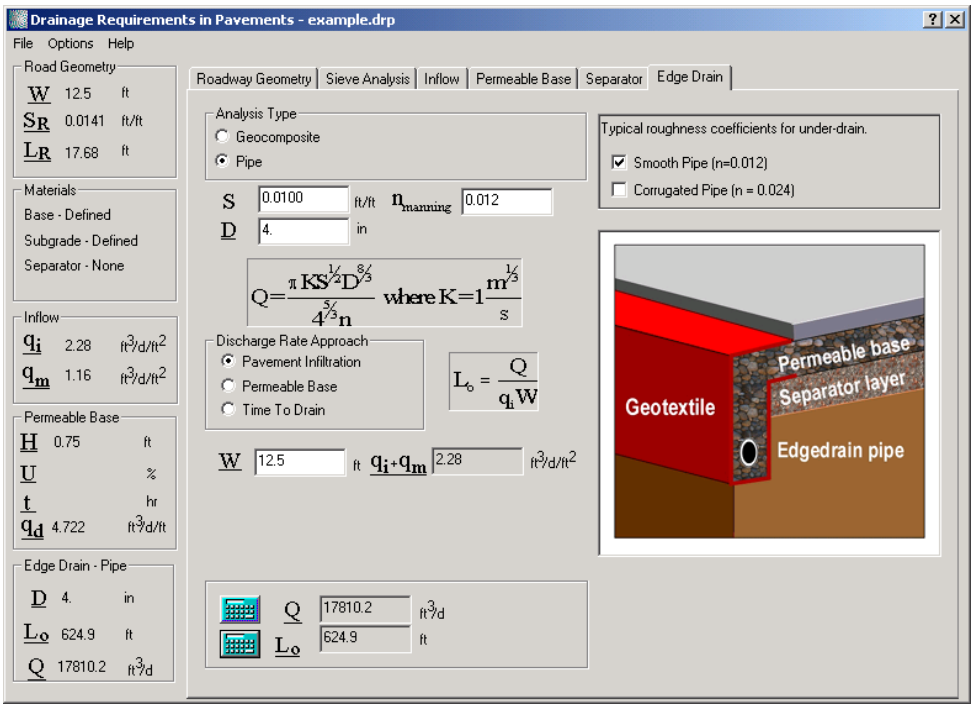


Figure 3-34. Edgedrain (pipe edgedrain) property page.

approach is based on the time required for a specific percentage of the water to drain from a saturated permeable base. Any of these approaches can be selected by clicking the appropriate radio button. When a discharge rate approach is selected in this manner, the equation that will be used to compute the outlet spacing is displayed on the screen. Edit boxes to enter values required to compute these parameters also appear on the screen. If the user has followed the suggested design flow, values will have already been provided for each parameter used. Therefore, the user can quickly calculate the required outlet spacing for each approach and compare the results.

The *Geocomposite Edgedrain* analysis screen, shown in Figure 3-35, differs mainly in the calculation of edgedrain capacity Q. For a geocomposite edgedrain, outlet pipe spacing L_o is actually a parameter used in the calculation of Q, along with slope S of the edgedrain, initial height of flow D_1, final height of flow D_2, and flow coefficient C_g. Thus, the calculation of the outlet spacing L_o is an iterative process. The program begins with an initial value of L_o of 100 m, calculates Q, then iteratively recalculates L_o. The process is repeated until a result is converged upon.

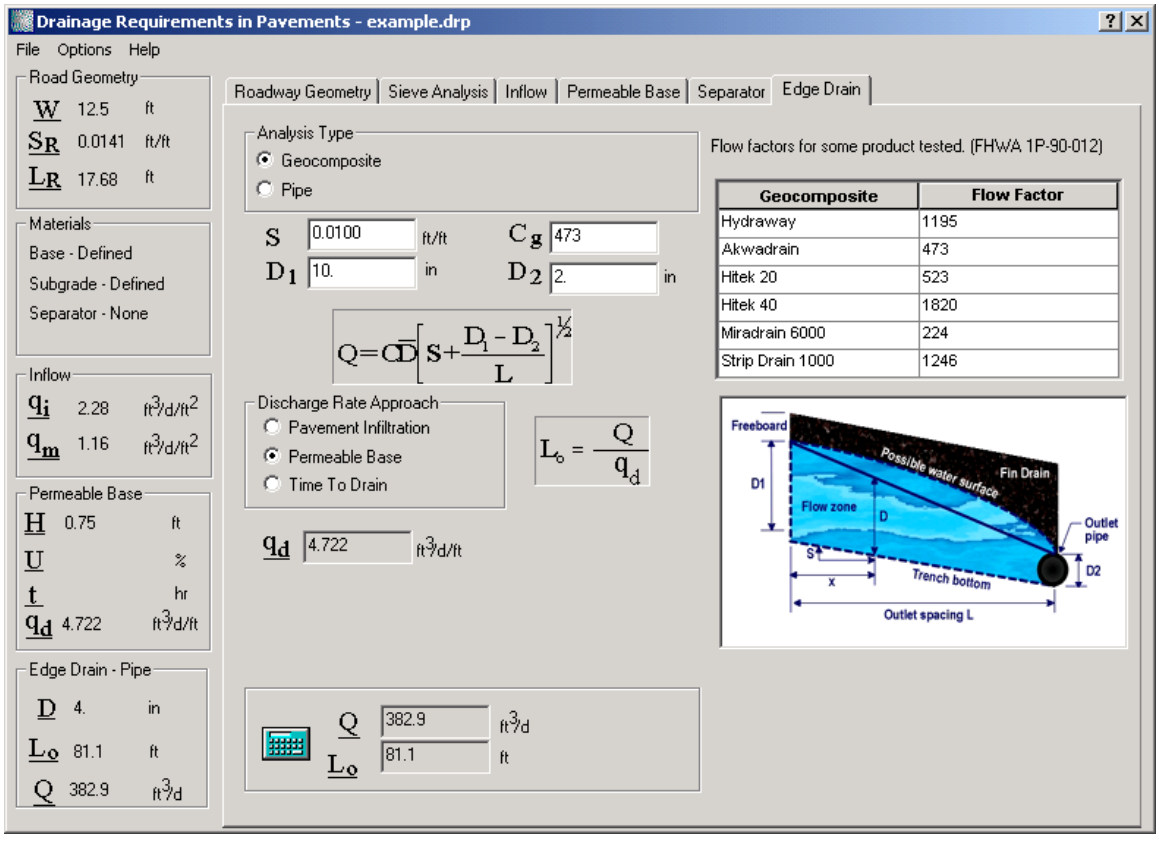


Figure 3-35. Edgedrain (geocomposite) property page.

A flowchart of the ***Edgedrain*** property page depicting the data flow in this screen is shown in Figure 3-36.

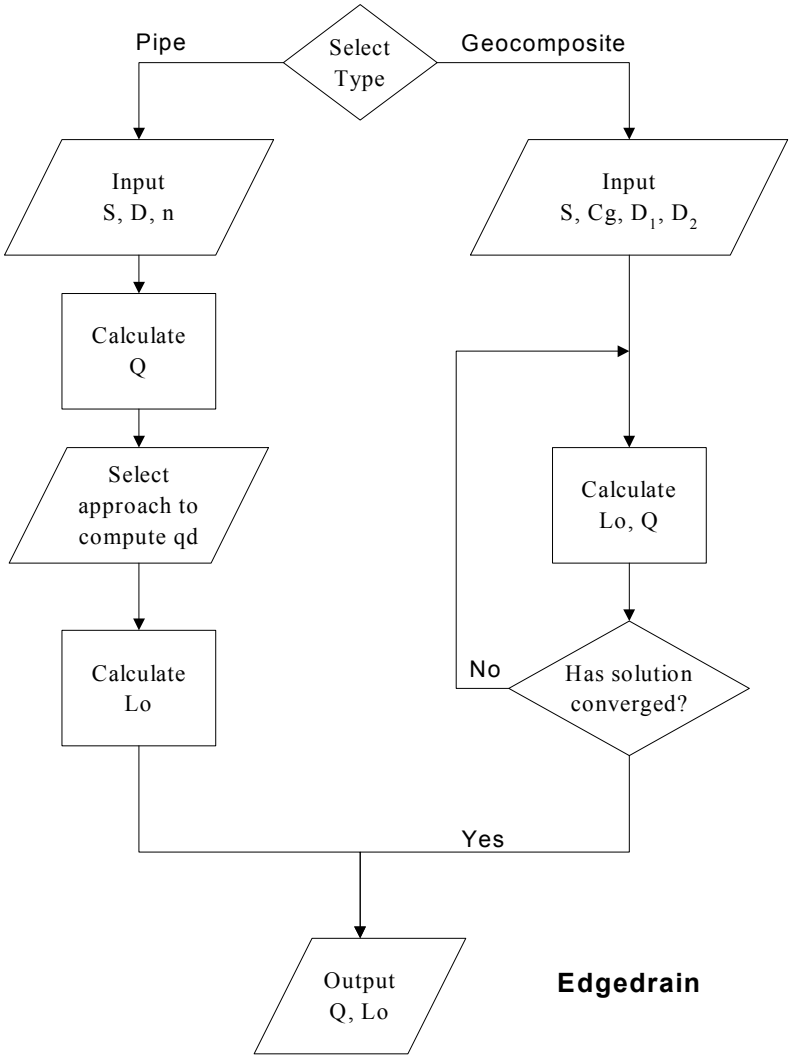


Figure 3-36. Flowchart for Edgedrain property page.

Project Summary

The two methods of obtaining analysis reports from DRIP are either to export the project summary using the *File* | *Export Summary* option or to print it using the *File* | *Print Summary* option. The format of exported summary file is HTML, and it can be viewed using any Web browser, spreadsheet, or word processing program. The steps involved in exporting and printing project summaries have already been outlined in the section dealing with DRIP menus. Since DRIP analyses are modular in nature, the summaries provided are also divided into subsections—Roadway Geometry, Sieve Analysis, Inflow, Permeable Base, Separator, and Edgedrain. A summary for a particular subsection is output only if data has been entered for that analysis or that analysis has been completed. If no data has been entered, only the primary header of that analysis module is provided.

CHAPTER 4 - TECHNICAL BACKGROUND

Design Concepts

Design concepts have been developed and put into practice for subsurface drainage systems for highway pavements. Most of the design procedures used in DRIP are identical to the procedure advocated by Demonstration Project 87 (FHWA, 1994) and the NHI Course No. 131026 (FHWA, 1999) on pavement subsurface drainage design. The major steps in the procedures are:

1. Quantifying water inflow.
2. Designing the permeable base.
3. Designing the separation layer.
4. Quantifying flow to edgedrains.
5. Computing outlet spacing.
6. Checking outlet flow.

Flowcharts depicting the various components of the program, their respective functions, and the inter-relationships between each component were presented in Chapter 3. In this chapter, the theoretical background for each of the program components is discussed in detail.

Geometric Considerations

Geometric design decisions such as maximum and minimum slopes, pavement and shoulder interface, cross-sections, location of filter fabrics, overlap of fabrics, joints, separation layer location, trench dimensions, and so on are critical to pavement performance. Filter fabrics should be selected only when the subgrade provides adequate support for compaction of the drainage layer. Pipe cover requirements are a function of loading and frost depth. In freeze-thaw areas, trench walls should not be steeper than 10 vertical on 1 horizontal for the depth of frost penetration to minimize differential heave (AASHTO, 1986). Sloping of the trench is not required in non-frost areas unless the pavement over the trench is subject to high-speed traffic. Trench backfill is a critical component, and proper selection of backfill material and construction procedures are necessary.

For rigid pavements, the permeable base is generally placed directly beneath the portland cement concrete (PCC). A separator layer is placed between the permeable base and the subgrade to prevent fines from migrating into the permeable base. For flexible pavements, the permeable base may be directly beneath the asphalt concrete (AC) layers. However, placing the open-graded material directly beneath a thin AC surface could lead to early failures. Adequate surface thickness is essential to protect the relatively weak permeable base layer. The design pavement thickness and location of the permeable base should be in accordance with the AASHTO Guide (AASHTO, 1986), NHI Course 131026 (FHWA, 1999), or other standard design practice.

In designing the drainage of a permeable base, it is important to use the true slope and width of the permeable layer. When the longitudinal slope (S) is combined with the pavement cross slope (S_x), the true or resultant slope (S_R) of the flow path is determined by the equation:

$$S_R = (S^2 + S_x^2)^{1/2} \qquad \text{Eq. 4-1}$$

where,

S_R = Resultant slope, ft/ft
S = Longitudinal slope, ft/ft
S_x = Cross slope, ft/ft

The resultant length of the flow path is:

$$L_R = W\,[1 + (S/S_x)^2]^{1/2} \qquad \text{Eq. 4-2}$$

where,

L_R = Resultant length of flow path through permeable base, ft
W = Width of permeable base, ft

Coefficient of Permeability

The *coefficient of permeability* depends primarily on the characteristics of the permeable base materials. The most significant properties affecting permeability are effective grain size, D_{10}, porosity, n, and percent passing the No. 200 sieve, P_{200}. These parameters accounted for over 91 percent of the variation in the hydraulic conductivity measured. However, proper gradation and density are vital to the stability of granular materials. To obtain the desired permeability, it is obvious that the fine portion of the aggregate must be removed; thus, the stability for the drainage layer may be adversely affected. Stabilizing with a small amount of asphalt or portland cement, particularly for the more open-graded materials, can compensate for this adverse effect. The addition of the stabilizer reduces the permeability only slightly.

Due to the complexity in quantification of the coefficient of permeability, various empirical methods have been used to estimate it. A number of approximate relationships exist between permeability and grain size. The most common relationship is that suggested by Hazen (for filter sands):

$$k = C_k D_{10}^2 \qquad \text{Eq. 4-3}$$

where,

k = Permeability, mm/s
D_{10} = Effective grain size corresponding to size passing 10 percent
C_k = Experimental coefficient

A statistical relationship for permeability, developed by Moulton (1980), has the form:

$$k = [(6.214 \times 10^5) D_{10}^{1.478} n^{6.654}] / P_{200}^{0.597} \quad \text{Eq. 4-4}$$

where,

n = Porosity
P_{200} = Percent passing No. 200 sieve

The above equations show that elimination of fines (passing No. 200 sieve) significantly increases the permeability. The character of the fines (i.e., plastic or non-plastic), compacted density, and hydraulic gradient may significantly alter in-place permeability.

Porosity

The void ratio or *porosity* of soils, though less important than grain size and soil structure, often has a substantial influence on permeability. The void ratio of a soil will also dictate the amount of fluid that can be held within the soil. The denser a soil, the lower its permeability and the less water it can retain. The amount of water that can be contained in a soil will relate directly to the void ratio. Not all water contained in a soil can be drained by gravity flow since water retained as thin films adhering to the soil particles and held by capillary action will not drain. Consequently, to determine the volume of water that can be removed from a soil, the *effective porosity* (n_e) must be known.

The effective porosity is a measure of the volume of water that can be drained by gravity flow from a soil. Whereas porosity is the ratio of volume of total voids to the total volume of a sample, the effective porosity is a ratio of the volume of voids that can be drained by gravity to the total volume of voids. The effective porosity can be seen to represent the yield of water to the drainage system. The difference in the porosity and effective porosity is the volume of water held in a sample by capillary and film forces. For a sample having a total volume of V_T and a volume of voids of V_v, the porosity is:

$$n = V_v/V_T \quad \text{Eq. 4-5}$$

for the case where:

$$V_T = 1$$

then:

$$n = V_v \quad \text{Eq. 4-6}$$

The volume of voids can be estimated if the specific gravity, G_s, and dry unit weight (γ_d) of the material are known by:

$$Vv = V_T - V_S \quad \text{Eq. 4-7}$$

or

$$Vv = V_T - (\gamma_d V_T)/ (\gamma_w G_s) \quad \text{Eq. 4-8}$$

and

$$n = V_v = 1 - \gamma_d / (\gamma_w G_s) \quad \text{Eq. 4-9}$$

when:

$$V_T = 1$$

The effective porosity then can be represented by:

$$n_e = (V_v - V_R)/V_T = n - V_R / V_T \quad \text{Eq. 4-10}$$

where V_R is the volume of the water retained in the soil.

The volume of water retained in a soil is computed by

$$V_R = \gamma_d w_c / \gamma_w \quad \text{Eq. 4-11}$$

where w_c is the water content of the soil after draining.

For the case where:

$$V_T = 1$$

$$n_e = n - \gamma_d w_c / \gamma_w \quad \text{Eq. 4-12}$$

Thus, the effective porosity can be estimated if the material specific gravity, dry density, and drained water content are known.

A simple test can also be devised where the volume of water (V_e) draining under gravity from a known volume of material is measured. The effective porosity is then computed from

$$n_e = V_e / V_T \quad \text{Eq. 4-13}$$

For certain types of materials, the ratio of effective porosity to the porosity expressed as a percentage has been determined and can be used to estimate the effective porosity (FHWA, 1992).

Thus,

$$n_e = n\ W_L / 100 \qquad \text{Eq. 4-14}$$

where W_L is the *water loss,* which is the percentage of water drained from the sample. Reported values of W_L expressed as a percent are (FHWA, 1992):

	< 2.5 Percent Fines			5 Percent Fines			> 5 Percent Fines		
	Filler	Silt	Clay	Filler	Silt	Clay	Filler	Silt	Clay
Gravel	70	60	40	60	40	20	40	30	10
Sand	57	50	35	50	35	15	25	18	8

Water Inflow Into Pavements

The major sources of inflow into the pavement structure are surface infiltration, water flow from high ground, groundwater seepage, and meltwater from ice lenses (Cedergren, 1994; FHWA, 1990; AASHTO, 1986). In the Participant Notebook for Demonstration Project 87 (FHWA, 1992) and the NHI Course No. 131026 (FHWA, 1999), only surface infiltration is considered in estimating the inflow. In the case of a high water table, the amount of groundwater seepage entering the permeable base may be a concern, but subsurface drainage layers are normally not installed as a corrective measure for groundwater seepage. In northern climates with frost heave, the meltwater from ice lenses must also be considered in determining the total amount of inflow. While the total amount of inflow is not required while designing pavements based on the time-to-drain method, it plays an important role in the depth-of-flow based design.

Infiltration

The single largest source of water in pavements is that entering the pavement surface through cracks and joints in the surface, cracks or joints between the pavement and shoulder, through the shoulders, and from side ditches (AASHTO, 1986; FHWA, 1992; Cedergren, 1974). A new pavement may have a virtually impermeable surface, but well before the end of the design life, the pavement will likely contain unsealed cracks and joint openings. The design of the permeable base should be based on the cracked surface condition and should account for the total infiltration that could be expected. Permeability of uncracked specimens of AC after being subjected to traffic and PCC are on the order of 1×10^{-9} cm/s (15×10^{-5} ft/day), indicating that any infiltration is through cracks and joints, and not through the pavement surface itself (Barber and Sawyer, 1952). For pavements in Connecticut, Ridgeway (1976) found that the duration of rainfall is more important than its intensit. Ridgeway also found that the infiltration to be related directly to cracking of the pavement, and recommended a design infiltration rate (I_c) of 2.4 ft^3/day/ft of crack.

Meltwater

In areas of frost, Moulton (1980) suggests that flow caused by frost melt should also be included in the inflow rate and has provided charts for determination of the design rates. Moulton developed a chart for estimating the inflow of meltwater from ice lenses, as shown in Figure 4-1. The rate of seepage is greatest immediately following thawing and increases rapidly. Because the maximum rate of drainage exists for only a short time period, the design inflow rate q_m is the average rate during the first day of thawing. The inflow q_m depends on the average rate of heave and the permeability k of the subgrade, as well as the consolidation pressure σ_p on the subgrade. The average rate of heave can be determined from laboratory tests or estimated using Table 4-1. The value of σ_p can be determined by calculating the density of the pavement overburden.

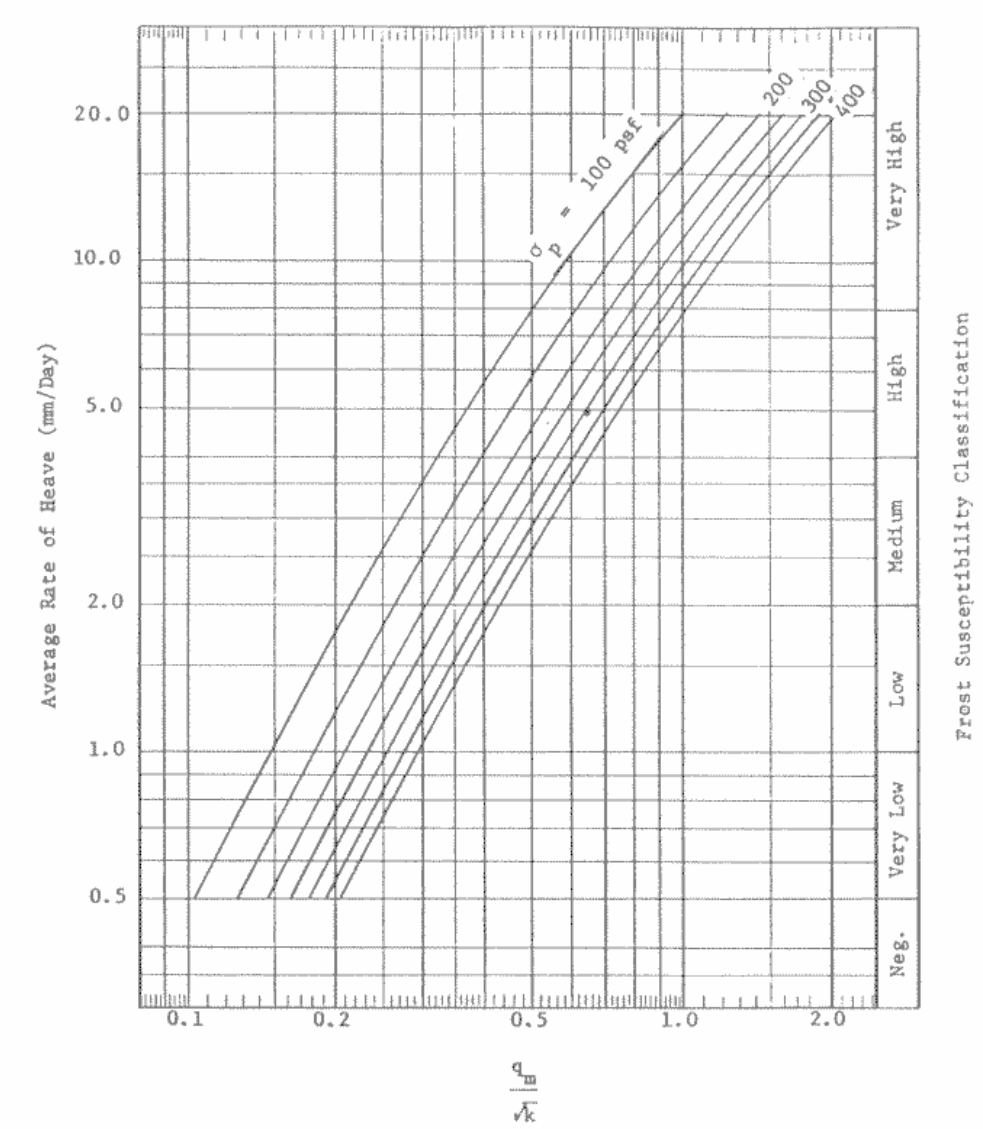


Figure 4-1. Chart for estimating meltwater (Moulton, 1980).

Table 4-1. Heave rates for various soil types (Moulton, 1980).

Unified Classification	Symbol	Percent < 0.02 mm	Heave Rate mm/day	Frost Susceptibility
Gravels and Sand Gravels	GP	0.4	3.0	Medium
Gravels and Sand Gravels	GW	0.7 - 1.0	0.3 - 1.0	Low
Gravels and Sand Gravels	GW	1.0 -1.5	1.0 - 3.5	Low to Medium
Gravels and Sand Gravels	GW	1.5 - 4.0	3.5 - 2.0	Medium
Silty and Sandy Gravels	GP - GM	2.0 - 3.0	1.0 - 3.0	Low to Medium
Silty and Sandy Gravels	GW - GM & GM	3.0 - 7.0	3.0 - 4.5	Medium to High
Clayey and Silty Gravels	GW - GC	4.2	2.5	Medium
Clayey and Silty Gravels	GM - GC	15.0	5.0	High
Clayey and Silty Gravels	GC	15.0 - 30.0	2.5 - 5.0	Medium to High
Sands and Gravelly Sands	SP	1.0 - 2.0	0.8	Very Low
Silty and Gravelly Sands	SW	2.0	3.0	Medium
Silty and Gravelly Sands	SP - SM	1.5 - 2.0	0.2 - 1.5	Low
Silty and Gravelly Sands	SW - SM	2.0 - 5.0	1.5 - 6.0	Low to High
Silty and Gravelly Sands	SM	5.0 - 9.0	6.0 - 9.0	High
Clayey and Silty Sands	SM - SC & SC	9.5 - 35.0	5.0 - 7.0	High
Silts and Organic Silts	ML - OL	23.0 - 33.0	1.1 - 14.0	Low to High
Silts and Organic Silts	ML	33.0 - 45.0	14.0 - 25.0	Very High
Clayey Silts	ML - CL	60.0 - 75.0	13.0	Very High
Gravelly and Sandy Clays	CL	38.0 - 65.0	7.0 - 10.0	High
Lean Clays	CL	65.0	5.0	High
Lean Clays	CL - OL	30.0 - 70.0	4.0	High
Fat Clays	CH	60.0	0.8	Very Low

Groundwater

Seasonal fluctuations of the water table (most commonly in spring and winter) can be a significant source of water (FHWA, 1992). If the analysis shows that groundwater will be a factor in the performance of the pavement, the designer should seek assistance from geotechnical specialists. Rarely is a pavement subsurface drainage system the most efficient way of handling water other than infiltrated or meltwater (AASHTO, 1986).

Computation of Infiltrated Water

Two methods have been used extensively in evaluating surface infiltration: the infiltration ratio method (Cedergren et al., 1973) and the crack infiltration method (Ridgeway, 1976). The infiltration ratio method is highly empirical and depends on both the infiltration ratio and rainfall rate. The crack infiltration method is based on the results of infiltration tests. It has been found that the infiltration is directly related to cracking. A large difference in infiltration predicted from these two methods has been observed. Since the crack infiltration method is more rational and is based on field measurements, it is used more often in determining the surface infiltration; however, the infiltration ratio method can be used as a check. If necessary, the larger of the two results may be used in the design inflow.

Infiltration Ratio Method

The infiltration ratio method is a simplistic method of estimating water inflow. The method assumes that a fixed portion of rain falling on a pavement will enter the pavement. Thus, all that is needed is an infiltration ratio and rainfall rate. For application the 1-hour duration, 2-year frequency rainfall is recommended (FHWA, 1992). Cedegren (1974) has recommended infiltration ratios varying from 0.50 to 0.67 for PCC pavements and 0.33 to 0.50 for AC pavements. The equation for the inflow is:

$$q_i = CRF \qquad \text{Eq. 4-15}$$

where:

q_i = Pavement infiltration, $m^3/day/m^2$ ($ft^3/day/ft^2$)
C = Infiltration ratio
R = Rainfall rate mm/hr (in/hr)
F = Conversion factor, 2.0 for in/hr, 0.24 for mm/hr; (these factors are included automatically in the DRIP program)

Crack Infiltration Method

Ridgeway (1976) recommended an inflow rate estimated by the water-carrying capacity of a pavement crack or joint and by an estimated joint or crack length. Ridgeway's research indicated that the condition of the crack or joint (i.e., sealed or unsealed and debris filled, wide or narrow cracks or joints) and the type of base layer underlying the

pavement surface (i.e., open-graded or dense-graded) both play a role in defining the infiltration capacity of the joint/crack. For high capacity joints/cracks, high intensity, short duration storms are important. For low capacity joints/cracks, storm duration is more important than intensity (Crovetti and Dempsey, 1993).

The design approach presented in the FHWA Drainage Manual (Moulton, 1980) uses the crack infiltration method, and Demonstration Project 87 and the NHI Course No. 131026 present it as the preferred method. An equation to compute the infiltration rate for "normal" conditions of uncracked pavement is:

$$q_i = I_c \left[N_c/W + W_c/(WC_s)\right] + k_p \qquad \text{Eq. 4-16}$$

where:

q_i = Rate of pavement infiltration, $m^3/day/m^2$ ($ft^3/day/ft^2$)
I_c = Crack infiltration rate, $m^3/day/m$ ($ft^3/day/ft$)
N_c = Number of longitudinal cracks
W_c = Length of contributing transverse joints or cracks, m (ft)
W = Width of permeable base, m (ft)
C_s = Spacing of contributing transverse joints or cracks, m (ft)
k_p = Pavement permeability, m/day (ft/day)

A value of I_c = 0.223 $m^3/day/m$ (2.4 $ft^3/day/ft$) is suggested for computations based on studies of saturated joints/cracks (Ridgeway, 1976). This suggested value approximates the average infiltration rate measured through cracks in AC surfaces underlain by open-graded materials.

Design of Permeable Base

There are two basic concepts to design permeable bases. One concept is that the permeable base should have a steady flow capacity equal to or greater than the inflow from the design rainfall. The solution for steady inflow, as developed by Moulton (1979), presents the thickness of the permeable base as a function of permeability (k), slope, (S), length of drainage (L_R), and rate of uniform inflow (q_i). The base thickness should equal or exceed the computed depth of flow. The equations for depth flow are:

Case 1 where: $\left(S^2 - 4\,q_i/k\right) < 0$

$$H_1 = \sqrt{\frac{q_i}{k}} L_R \left[\left\{ \frac{S}{\sqrt{\frac{4q_i}{k - S^2}}} \right\} \left\{ \tan^{-1} \frac{S}{\sqrt{\frac{4q_i}{k - S^2}}} - \frac{\pi}{2} \right\} \right] \qquad \text{Eq. 4-17}$$

Case 2 where: $\left(S^2 - 4q_i/k\right) > 0$

$$H_1 = \sqrt{\frac{q_i}{k}} L_R \left[\frac{S - \sqrt{S^2 - 4q_i/k}}{S + \sqrt{S^2 - 4q_i/k}} \right]^{\frac{S}{2\sqrt{S^2 - 4q_i/k}}} \qquad \text{Eq. 4-18}$$

Case 3 where: $\left(S^2 - 4q_i/k\right) = 0$

$$H_1 = \sqrt{\frac{q_i}{k}} L_R^{-1} \qquad \text{Eq. 4-19}$$

where H_1 is the depth of water at the upper end of the flow path.

Moulton also developed a chart for the solution of the equations 4-17 through 4-19. This chart, which has been widely used, is presented in Figure 4-2. The use of this Figure permits the determination of the maximum depth of flow, H_{max}, in a drainage layer when values of the design inflow rate, q_i, the permeability of the drainage layer, k, the length of the flow path, L, and the slope of the drainage layers, S, along the flow path are known. Conversely, it is possible to determine the required coefficient of permeability, k, of the drainage layer, if the maximum depth of flow, H, and the other parameters are known. The chart is presented as being the maximum depth of water, i.e., values from the chart assume $H_1 = H_{max}$ where H_{max} is the maximum depth of flow. The chart is presented as being the maximum depth of water; in other words, values from the chart assume $H_1 = H_{max}$ where H_{max} is the maximum depth of flow.

The second approach for design of the permeable base, advocated by Casagrande and Shannon (1952), selects a specific time to obtain a specified degree of drainage for a saturated base. Solutions for time-to-drain conditions have been presented by both Casagrande and Shannon (1952) and by Barber and Sawyer (1952). The equations developed by Casagrande and Shannon are:

$$T = \left(1.2 - 0.4/S_1^{1/3}\right)\left\{S_1 - S_1^2 \ln\left(\frac{S_1 + 1}{S_1}\right) + S_1 \ln\left[\frac{2S_1 - 2US_1 + 1}{(2 - 2U)(S_1 + 1)}\right]\right\} \qquad \text{Eq. 4-20}$$

for the case where $U > 0.5$ and

$$T = \left(1.2 - 0.4/S_1^{1/3}\right)\left\{2US_1 - S_1^2 \ln\left(\frac{S_1 + 2U}{S_1}\right)\right\} \qquad \text{Eq. 4-21}$$

for the case where $U \leq 0.5$.

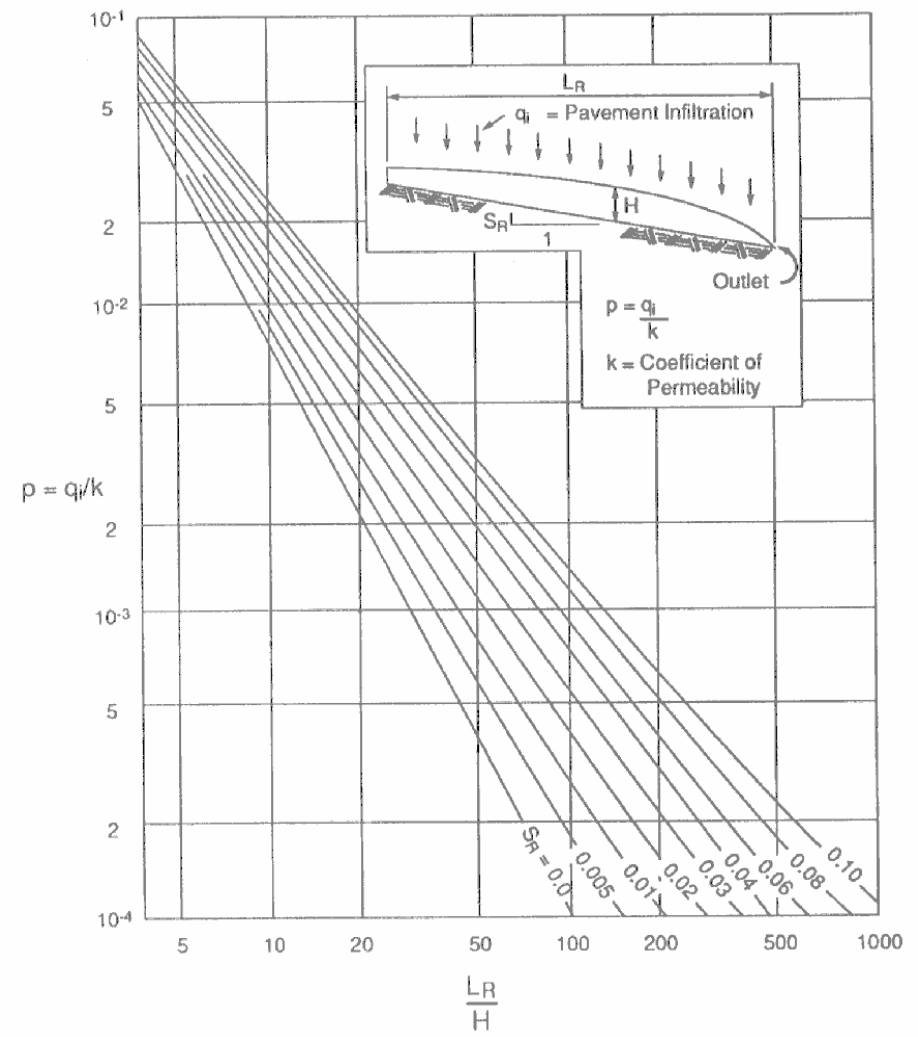


Figure 4-2. Moulton chart for depth-of-flow (Moulton, 1980)

where:

U = Percent drainage (expressed as a fraction, e.g., 1 percent = 0.01)
S_1 = Slope factor = H/(LS)
H = Thickness of granular layer
L = Width of granular layer being drained
S = Slope of granular layer
T = Time factor = tkH/n_eL^2
t = Time for drainage, U, to be reached
k = Permeability of granular layer
n_e = Effective porosity of granular material

The Barber and Sawyer (1952) equations are:

$$T = 0.5S_1 - 0.48S_1^2\log\left(1 + 2.4/S_1\right) + 1.15S_1\log\left[\frac{S_1 - US_1 + 1.2}{(1-U)(S_1 + 2.4)}\right] \qquad \text{Eq. 4-22}$$

for the case where $0.5 \le U \le 1.0$ and

$$T = US - 0.48 S_1^2 \log\left(1 + 4.8\, U/S_1\right) \qquad \text{Eq. 4-23}$$

for the case where $0 \le U \le 0.5$.

where:

U = Percent drainage (expressed as a fraction, e.g., 1 percent = 0.01)
S_1 = Slope factor = H/DS
H = Thickness of granular layer
D = Width of granular layer being drained
S = Slope of granular layer
T = Time factor = $(tkH)/(n_e L^2)$
t = Time for drainage, U, to be reached
k = Permeability of granular layer
n_e = Effective porosity of granular material

The solution by Casagrande and Shannon has been developed into a chart shown in Figure 4-3. This chart has been more widely used than the original equations.

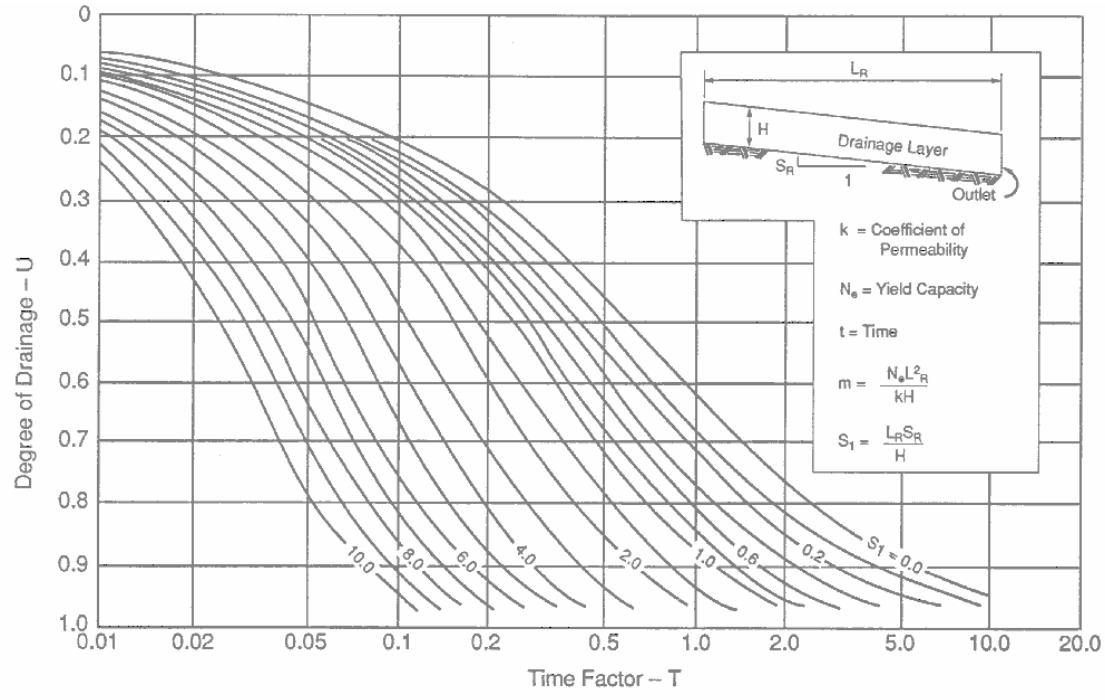


Figure 4-3. Casagrande and Shannon chart (Cassagrande and Shannon, 1952)

Casagrande and Shannon (1952) recommended a criterion of 50 percent drainage in 10 days. Unfortunately, their criteria and reference are applied without regard to the background for the recommendations. The study conducted by Casagrande and Shannon was in connection with problems with flexible military airfields in the northeastern

United States, where the severe saturation of the base was due to freeze-thaw of base and subgrade. The criterion proposed was primarily for drainage of a saturated base of flexible pavements due to thaw of ice lenses. There is no reason to expect the Casagrande and Shannon relationship to adequately solve other problems of pavement drainage. Consider that drainage of the thick base of a flexible pavement is quite a different problem from drainage to prevent pumping of the base of a rigid pavement. Thus, in setting criteria for drainage, both the pavement and the problem must be considered. In fact, the NHI Course 131026 (FHWA, 1999) lists a set of criteria to judge of quality of permeable bases under highways, which is quite different from those of Casagrande and Shannon.

Although the design criteria (time of drainage and degree of drainage) are the most critical factors in the design process, setting these criteria has been rather arbitrary because policy sets the design criteria. The designer can only consider the permeability, thickness, slope, length of drainage path, and effective porosity in the design to achieve the target values. The slope and length of drainage path are set by the geometry of the pavement over which, in most situations, the designer will have no control. For most highways, the slope and length of the drainage path will change continuously along the pavement length, posing the designer with the problem of selecting the appropriate design parameters. The time for drainage is not sensitive to the thickness, so the design problem in regard to time for drainage involves selecting the material for the permeable base to provide adequate permeability. The two methods can be combined such that the permeable base is required to meet the criteria of both depth-of-flow and time-to-drain.

Materials Requirements for Permeable Base

The quantification of drainage material parameters plays an important role in determining drainage capacity. Porosity and effective porosity define an aggregate material's ability to store and give up water. Effective porosity, the coefficient of permeability, and percentage of saturation are required in the calculation of the time to drain. Among all these drainage parameters, the coefficient of permeability is the most important in the quantification of the depth of flow in the permeable base and its time to drain. The influence of various factors (pore fluid and temperature, grain size, void ratio, and structure and stratification) on the permeability of soils has been studied (Huang, 1993).

Gradation

The gradation of aggregates comprising the permeable base has the greatest influence on permeability. Typical gradation specifications used by some State highway agencies are shown in Table 4-2. The recommended minimum coefficient of permeability is 1000 ft/day for use in high-type highways. The gradations in Table 4-2 are considered to provide permeabilities on the order of 1000 to 5000 ft/day in the unstabilized form. However, the AASHTO No. 57 and AASHTO No. 67 gradations shown in the table are typically modified with either asphalt or cement. Other typical gradations used in asphalt-stabilized applications are shown in Table 4-3, and those used in cement-stabilized applications are shown in Table 4-4.

Table 4-2. Typical unstabilized permeable base gradations (FHWA, 1999).

State	Percent Passing Sieve Size											
	2 in	1 ½ in	1 in	¾ in	½ in	3/8 in	No. 4	No. 8	No. 16	No. 40	No. 50	No. 200
AASHTO #57		100	95-100		25-60		0-10	0-5				
AAHSTO #67			100	90-100		20-55	0-10	0-5				
Iowa			100					10-35			0-15	0-6
Minnesota			100	65-100		35-70	20-45			2-10		0-3
New Jersey		100	95-100		60-80		40-55	5-25	0-12		0-5	
Pennsylvania	100			52-100		33-65	8-40		0-12			0-5

Table 4-3. Typical asphalt-stabilized permeable base gradations (FHWA, 1999).

State	Percent Passing Sieve Size					
	1 in	½ in	3/8 in	No. 4	No. 8	No. 200
California	100	90-100	20-45	0-10		0-2
Florida	100	90-100	20-45	0-10	0-5	0-2
Illinois	90-100	84-100	40-60	0-12		
Kansas	100	90-100	20-45	0-10	0-5	0-2
Ohio	95-100			25-60	0-10	
Texas	100	95-100	20-45	0-15	0-5	2-4
Wisconsin	95-100	80-95	25-50	35-60	20-45	3-10
Wyoming	90-100	20-50		20-50	10-30	0-4

Table 4-4. Typical cement-stabilized permeable base gradations (FHWA, 1999).

State	Percent Passing Sieve Size						
	1 ½ in	1 in	¾ in	½ in	3/8 in	No. 4	No. 8
California	100	88-100	X $\pm$ 15		X $\pm$ 15	0-16	0-6
Virginia		100		25-60		0-10	0-5
Wisconsin		100	90-100		20-55	0-10	0-5

Design of Separator Layer

The separator layer may be a granular base material or an appropriate geotextile. The separator layer must (a) prevent fines from pumping up from the subgrade into the permeable base, (b) provide a stable platform to facilitate the construction of the permeable base and other overlying layers, (c) provide a shield to deflect infiltrated water over to its edgedrain, thereby providing protection for the subgrade, and (d) distribute live loads to the subgrade without excessive deflection. Only an aggregate separator layer can satisfactorily accomplish (b) and (d). The granular separator layer is preferred to the fabric since the granular layer will provide the construction platform and distribution of loads to the subgrade. When geotextiles are used as separator layers, they are most often used in connection with stabilized subgrades, which provide the construction platform and load distribution. Both granular and geotextile materials can prevent pumping of fines if they satisfy the filter requirements. The thickness of the granular separator is dictated by construction requirements and can range from 4 to 12 inches.

Material Requirements for Separator Layer

Aggregate Separator Layer

Most SHA's use dense-graded separator layers typical of the gradation shown in Table 4-5. Permeability requirements are not applied to the separator layer, but they must meet filter requirements. The maximum percent of fines passing the No. 200 sieve should not exceed 12 percent, and the coefficient of uniformity should be between 20 and 40.

Table 4-5. Typical gradation requirements for separator layer.

Sieve Size	Percent Passing
$1^1/_2$ in	100
$^3/_4$ in	95 – 100
No. 4	50 – 80
No. 40	20 – 35
No. 200	5 – 12

To ensure that the gradation of the separator layer will prevent subgrade fines from migrating up, and to ensure that fines in the separator layer do not move into the permeable base, the following criteria are imposed:

At the separator and subgrade interface:

$$D_{15} \text{ (separator layer)} \leq 5\ D_{85} \text{ (subgrade)} \qquad \text{Eq. 4-24}$$

$$D_{50} \text{ (separator layer)} \leq 25\ D_{50} \text{ (subgrade)} \qquad \text{Eq. 4-25}$$

At the separator and permeable base:

$$D_{15}\ (\text{base}) \leq 5\ D_{85}\ (\text{separator layer}) \qquad \text{Eq. 4-26}$$

$$D_{50}\ (\text{base}) \leq 25\ D_{50}\ (\text{separator layer}) \qquad \text{Eq. 4-27}$$

The aggregate separator layer should consist of durable, crushed, angular aggregate. The aggregate should meet requirements equivalent to Class C aggregate in accordance with AASHTO M 283 (this standard has been discontinued). The Los Angeles abrasion wear should not exceed 50 percent as determined by AASHTO T 96. The soundness should not exceed 12 or 18 percent loss as determined by the sodium sulfate or magnesium sulfate tests, respectively, following AASHTO T 104. Compacted density should be 95 percent of the maximum density in accordance with AASHTO T 180.

Geotextile Separator Layer

For geotextiles as separator layers, the following criteria have been recommended where steady-state flow is anticipated (generally the case when used as a separator layer) (FHWA, 1998):

$$\text{AOS or } O_{95\ (\text{geotextile})} \leq B\ D_{85\ (\text{soil})} \qquad \text{Eq. 4-28}$$

where:

AOS = Apparent opening size, mm
O_{95} = Opening size in the geotextile for which 95 % are smaller, mm
AOS ≈ O_{95}
B = Dimensionless coefficient
D_{85} = Soil particle size for which 85 % are smaller, mm

The coefficient B ranges from 0.5 to 2.0 and is a function of the soil type to be filtered, soil density, uniformity coefficient C_u if soil is granular, and geotextile type (woven or non-woven). For sands, gravelly sands, silty sands, and clayey sands (less than 50 percent passing 0.075 mm), B is a function of C_u.

for:

$C_u \leq 2$ or ≥ 8, then $B = 1$
$2 \leq C_u \leq 4$, then $B = 0.5\ C_u$
$4 < C_u < 8$ then $B = 8/C_u$

where:

$$C_u = D_{60}/D_{10} \qquad \text{Eq. 4-29}$$

Sandy soils, which are not uniform, tend to bridge across the openings; thus, the larger pores may actually be up to twice as large as the larger soil particles because two particles cannot pass through the same hole at the same time. Therefore, use of B = 1 would be conservative for retention. For silts and clays, B is a function of the type of geotextile:

for woven geotextiles	B = 1;	$O_{95} \leq D_{85}$
for nonwoven geotextiles	B = 1.8;	$O_{95} \leq 1.8\ D_{85}$
and for both	AOS or	$O_{95} \leq$ 0.3 mm

To ensure that the geotextile will survive the construction process, certain minimum geotextile strength and endurance properties are required (FHWA, 1998). These minimum requirements are presented in Table 4-6. Note that these values are not based on any systematic research but were derived from empirical observations of satisfactorily

Table 4-6. Geotextile strength property requirements for drainage geotextiles (Holtz et al., 1998).

Property	**ASTM Test Method**	**Units**	**Geotextile Class 2[1]**	
			Elongation [2] < 50%	**Elongation [2] > 50%**
Grab Strength	D 4632	N	1100	700
Sewn Seam Strength[3]	D 4632	N	990	630
Tear Strength	D 4533	N	400	250
Puncture Strength	D 4833	N	400	250
Burst Strength	D 3786	kPa	2700	1300

1 The geotextile class is based on the AASHTO M 288 specification.
2 As measured in accordance with ASTM D 4632.
3 When seams are required.

performing geotextiles used in drainage applications. They are not intended to replace site-specific evaluation, testing, and design.

Design of Edgedrains

Edgedrains can be designed for (FHWA, 1992):

- Pavement infiltration flow rate.
- Peak flow from the permeable base.
- Average flow rate during the time to drain the permeable base.

For design based on the pavement infiltration flow rate, the design flow capacity of the edgedrain is:

$$Q = Q_p \times L_o = (q_i\ W)\ L_o \qquad \text{Eq. 4-30}$$

For design based on peak flow, the design flow capacity is:

$$Q = Q_p \times L_o = (kS_xH)\, L_o \qquad \text{Eq. 4-31}$$

For design based on average flow to drain the permeable base, the design flow capacity is:

$$Q = Q_p \times L_o = (WHn_eU(24/t))\, L_o \qquad \text{Eq. 4-32}$$

where,

Q = Pipe flow capacity, m^3/day (ft^3/day)
Q_p = Design pavement discharge rate, m^3/day/m (ft^3/day/ft)
q_i = Pavement infiltration, m^3/day/m^2 (ft^3/day/ft^2)
W = Width of the granular layer, m (ft)
L_o = Outlet spacing, m (ft)
k = Permeability of granular layer, m^3/day (ft^3/day)
U = Percent drainage (as 1 percent = 0.01)
S_x = Transverse slope, m/m (ft/ft)
H = Thickness of granular layer, m (ft)
t = Time for drainage, U, to be reached, days
n_e = Effective porosity of granular material

Although there are three methods for computing the required capacity of the edgedrains, good engineering requires that the capacity of the drainage system should increase as the water flows through the system. Thus, good engineering would dictate that, at a minimum, the capacity of the edgedrain should be equal to the peak capacity of the permeable base.

In designing the edgedrain it is usually assumed that all the flow is to be handled by the pipe. For systems having very permeable backfill in the edgedrain trench, this will result in conservative designs that can provide a factor of safety against settlement of material in the pipes. The capacity of a pipe edgedrain is computed using the Manning (Daugherty and Ingersoll, 1954) equation:

$$Q = \frac{K}{n} S^{1/2} R^{2/3} A \qquad \text{Eq. 4-33}$$

where:

Q = Pipe flow capacity
S = Slope of the pipe invert
n = Pipe coefficient of roughness
A = Pipe cross-sectional area
K = $1\ \frac{\sqrt[3]{meter}}{\sec ond}$

$$R = \frac{A}{P} = \frac{D}{4}$$

P = Wetted perimeter of pipe
D = Pipe diameter

Therefore,

$$Q = (K/n)S^{1/2}(D/4)^{2/3}\pi(D/2)^2 \qquad \text{Eq. 4-34}$$

where

Q is in m^3/sec
D is in meters
K is in $(meter)^{1/3}$/sec

Converting to English units:

$$Q = (53.01/n)\ S^{1/2}\ D^{8/3} \qquad \text{Eq. 4-35}$$

where

Q = ft^3/day
D = inches

The suggested value (FHWA, 1992) for the coefficient of roughness for smooth pipe is 0.012, and the suggested value for corrugated pipe is 0.024.

In examining the design process it is seen that only certain properties, i.e., pipe diameter, pipe type, and outlet spacing can be controlled. The selections between pipes are very limited, and usually within an organization a single pipe type and size are used; thus, the design process is reduced to determining the distance between outlets. By setting the pipe capacity, Q, equal to the design pavement discharge per unit length, Q_p, equations for the distance, L, between outlets are developed. By setting the pipe capacity equal to the discharge per unit length, Q_p, times the distance between the outlets, L_o, the following equations are developed:

$$Q_p \times L_o = Q \qquad \text{Eq. 4-36}$$

For infiltration flow:

$$L_o = Q/(q_i W) \qquad \text{Eq. 4-37}$$

For peak flow:

$$L_o = Q/kS_xH \qquad \text{Eq. 4-38}$$

For average flow:

$$L_o = (Q\ t)/(24WHN_eU) \qquad \text{Eq. 4-39}$$

Although the distance between outlets and pipe size can be computed based on theory, the actual outlet spacing used in the field may be dictated by good engineering practice. Many agencies specify maximum spacing of outlets and minimum pipe size based on maintenance requirements. It is common to specify a maximum spacing of 75 to 100 m (250 to 300 ft) for outlets and a minimum pipe diameter of 75 to 100 mm (3 to 4 in.).

Filter Requirements for Edgedrains

The filter material must be fine enough to prevent the adjacent soil from piping or migrating into the edgedrains but coarse enough to allow the passage of water with no significant resistance. To meet the filter criteria, it may be necessary to use several different aggregates, one placed adjacent to the other. This procedure is difficult to construct without contamination and can be replaced by using geotextiles.

Geotextiles may be used as an envelope for trench drains, a wrapping for pipe drains, or as a filter for permeable bases. A geotextile can be selected to satisfy the filter criteria and replace the aggregate filter. Due to the relative ease of installation (as compared to the difficulty of placing a filter aggregate and a coarse aggregate in separate layers without contamination), the use of geotextiles may be more cost-effective.

The filter criteria (clogging/permeability criterion) for aggregates were originally developed by Betram (1940) based on the ratio of the grain size of filter material to the size of soil. The clogging criterion ensures that the filter material is fine enough to prevent the adjacent finer material from piping or migrating into the filter material, and the permeability criterion ensures the material is coarse enough to allow flow of water. The work of Betram was later expanded by the U.S. Army Corps of Engineers (1955).

Unlike the filter criteria used in the gradation analysis of aggregates, a variety of filter criteria have been developed by a number of organizations and researchers. Based on a review of these criteria, the FHWA *Geotextile Engineering Manual* (FHWA, 1995) suggested the use of more stringent criteria when the hydraulic loadings are severe or the performance of the drainage system is critical to the protection of roadways and pertinent structures. The retention or pumping resistance criteria, the permeability criteria, and the clogging criteria for selecting the required AOS (apparent opening size) of geotextiles have been specified in ASTM (ASTM, 1989).

The filter criteria for pipes are also required when perforated or slotted pipes are used for the collection and removal of water. The material in contact with the pipes must be coarse enough that no appreciable amount can enter into the pipes. The current filter criteria used in selecting pipes are based on the U.S. Army Corps of Engineers criteria (1955).

Prefabricated Edgedrains

Koerner (1991) provided recommended requirements for prefabricated edgedrain filters, as shown in Table 4-7. Koerner states the following design considerations for prefabricated edgedrains:

- The core must be capable of sustaining a certain amount of stress.
- The core must have a required flow rate.
- The geotextile must be capable of passing the flow.
- The geotextile must be capable of retaining the adjacent soil.
- The geotextile must sustain the normal stress between core protrusion locations.

Recent findings (NCHRP, 1994) indicated poor performance by prefabricated geocomposite edgedrains, including problems with soil retention and excessive clogging. The study recommended that the geocomposite prefabricated drains should be installed to the shoulder side of the trench with the pavement side backfilled with a suitable sand. This is shown in Figure 4-4.

Design of Outlet Drain

Design of the outlet drain mainly consists of checking the capacity of the outlet pipe to ensure the capacity of this pipe is at least as great as the edgedrain. The slope is dictated by the roadway geometry, but if possible it should not be less than 3 percent. The capacity of outlet pipes is checked by using Manning's formula.

Retrofit Edgedrains

There are differences of opinion as to the effectiveness of various remedial pavement drainage techniques and how these should be designed. These differences may be due to a lack of good documentation to substantiate the various opinions and because of the many variables that affect pavement drainage. A study (FHWA, 1989) conducted to evaluate the design requirements and effectiveness of edgedrains concluded:

- The edgedrain should be located under the shoulder immediately adjacent to the pavement/shoulder joint.
- By eliminating the filter fabric at the subbase/edgedrain interface, eroded fines cannot clog the filter fabric.
- Trench backfill should be permeable enough to transmit water to the longitudinal edgedrain pipe; asphalt or cement treated backfill increases stability with little or no loss of permeability.
- The most commonly used trench width was 12 in; locating the top of the pipe at the bottom of the layer to be drained was recommended.
- Outlet spacing should not exceed 500 ft; additional outlets should be provided at the bottom of sag vertical curves.

Table 4-7. Recommended properties for prefabricated edgedrains (Koerner, 1991).

Requirement	Method	Value
Core Strength	GRI GG4	≥ 9,600 lbf/in^2
Core Flow Rate	ASTM D4716	≥ 15 gal/min - ft
Geotextile Permeability	ASTM D4491	≥ 0.001 cm/sec
Geotextile AOS	ASTM D4751	≥ No. 100 sieve
Geotextile Puncture	ASTM D3787	≥ 75 lb
Geotextile Grab Strength	ASTM D4632	≥ 180 lb
Geotextile Tear Strength	ASTM D4533	≥ 75 lb

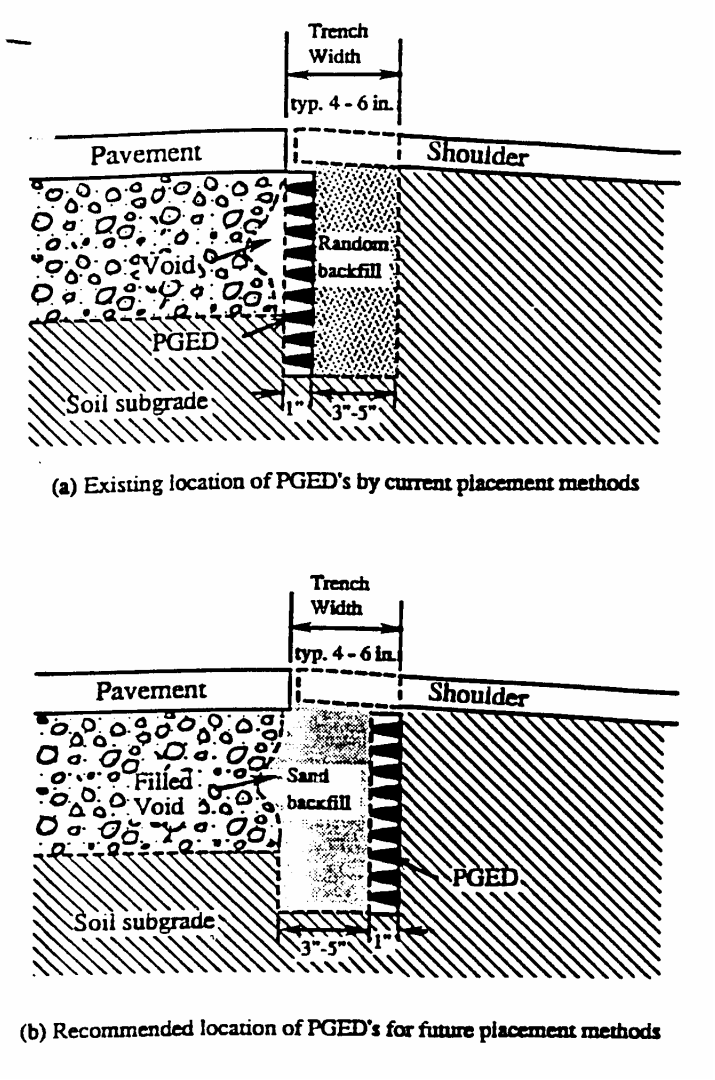


Figure 4-4. Recommended installation of prefabricated geocomposite edgedrains (NCHRP, 1994)

- Because of the tendency of flexible corrugated plastic pipe to curl, use of rigid PVC pipe was recommended for outlet laterals; rigid PVC pipe helps maintain proper outlet pipe grade and provides protection from crushing.
- Headwalls protect the outlet pipe from damage, prevent slope erosion, and ease in the locating of the outlet pipe.

Dempsey (1993) reported on retrofit prefabricated edgedrains used in a flexible runway pavement. Measurements indicated that 25 to 45 percent of the rainfall infiltrated the pavement and passed through the retrofit edgedrains. It was observed that water flow from the pavement joints and cracks ceased once the system was installed. Surface seepage and frost heave problems did not occur after the subdrainage installation.

Flow in Geocomposite Fin-Drains

The flow longitudinally in the core of geocomposite fin-drains has been and is being determined by two basic laboratory test procedures. The flow rate test that most manufacturers and testing laboratories use is ASTM D-4716 *Constant Head Hydraulic Transitivity (In-Plane Flow) of Geotextile and Geotextile Related Products*. This test method was developed to test geocomposite drains for use in geotechnical application and is not particularly applicable to pavements. In this test method, the test specimen is placed horizontally, as shown in Figure 4-5.

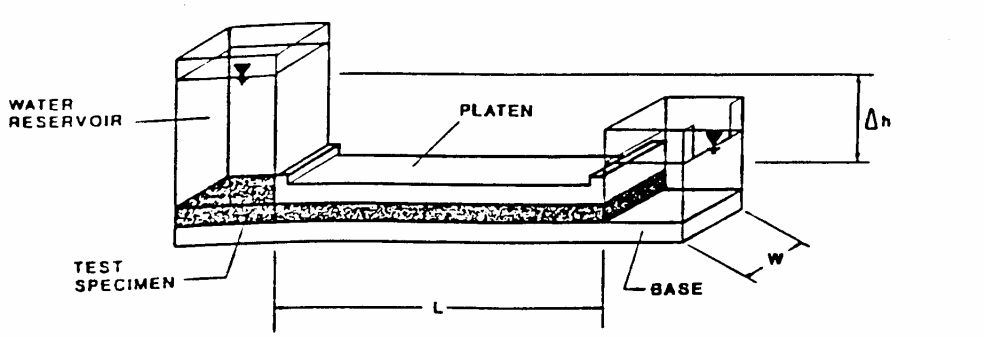


Figure 4-5. Constant head hydraulic transitivity testing device.

Koerner (1991) states that this test is not a particularly good simulation of the edgedrain situation, primarily because the core lies horizontally and flows full instead of being positioned vertically and only flowing in the lower flow zone. According to Koerner, Dempsey (1988) has developed a more accurate test. The problem Koerner had with the test developed by Dempsey is that it required 30 ft of floor space; thus, in Koerner's test the ASTM D-4716 test method was used.

The main equipment components for the test method developed by Dempsey (1988) consist of the 20-ft flow channel that contains the geocomposite or fin drain material and a weir box for measuring the volume of water flow. A schematic diagram of the laboratory equipment is shown in Figure 4-6. Using the equipment shown in Figure 4-6,

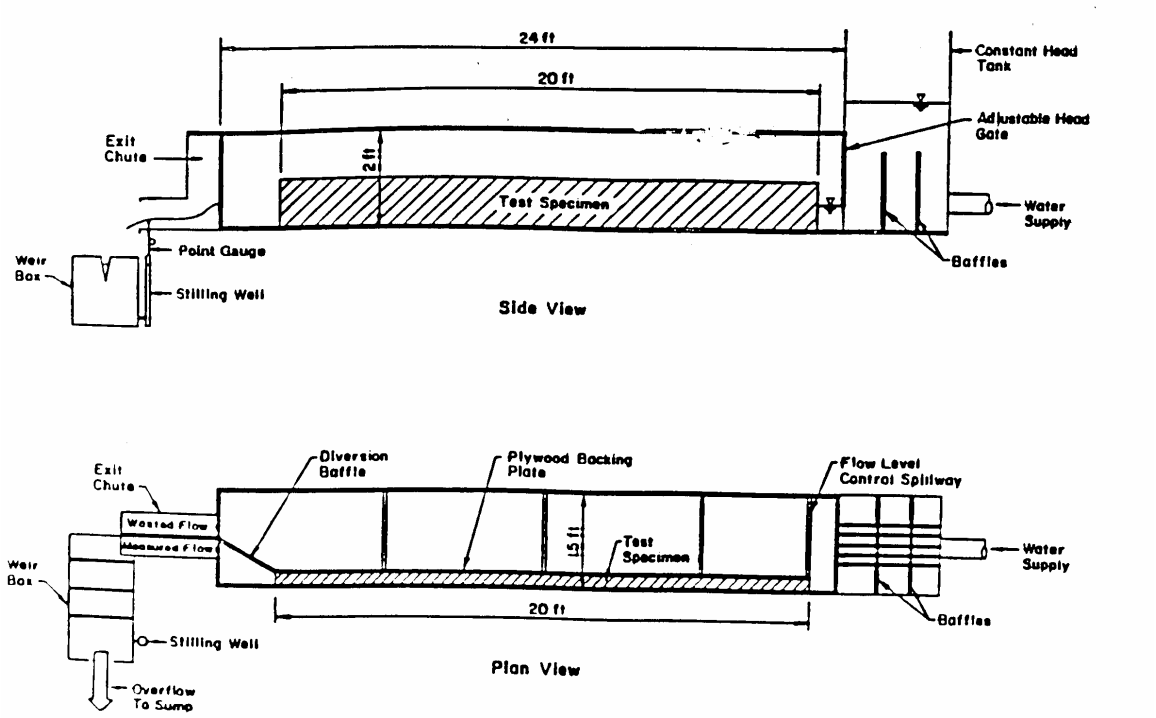


Figure 4-6. Schematic of the equipment to determine fin-drain flow (Dempsey, 1988).

Dempsey conducted tests for a number of fin-drain materials. Table 4-8 contains the characteristics of the different materials tested. The results of the test are given in Table 4-9. Dempsey assumed the flow in a fin-drain to be similar to the flow in an open channel such that Manning's equation would be applicable to develop the flow equation.

$$Q = CD\,G^{1/2} \qquad \text{Eq. 4-40}$$

where:

Q = Flow in ft^3/day
C = Fin-drain flow factor in ft^3/day/inch
G = Total hydraulic gradient (in the test G = S + H/L)
S = Trench slope
H = Difference in height of water entering and height of water at exit
D = Depth of water flow in inches

The values of C were determined and reported in English units of ft^3/day/inch. To convert to metric units of m^3/day/mm, multiply the value in English units by 0.001115. The flow factors of some of the tested products are (FHWA, 1990):

Product	C Value, ft^3/day/inch	C value, m^3/day/mm
Hydraway	1333	1.486
Akwadrain	528	0.589
Hitek 20	584	0.651
Hitek 40	2030	2.263
Miradrain 6000	250	0.279
Stripdrain 100	1390	1.550

Table 4-8. Description of geocomposite fin-drain materials tested (Dempsey, 1988).

Core Data				Fabric Data		
Fin-Drain Material	**Structural**	**Material**	**Thickness mm (in.)**	**Material**	**Fabrication**	**Core Attachment**
Hitek 20	Cuspated	HDPE	20 (0.78)	Polypropylene	Nonwoven	Loose Wrapped
Hitek 40	Cuspated	HDPE	40 (1.57)	Polypropylene	Nonwoven	Loose Wrapped
Akwadrain	Cuspated	HDPE	25 (1.00)	Polypropylene	Nonwoven	Adhesive Bond One Side, Loose One Side
Miradrain 6000	Dimpled Sheet	HIPS	10 (0.389)	Polypropylene	Nonwoven, Needle Punched	Adhesive Bond Two Sides
Hydraway	Columns	LLDPE	25 (1.00)	Polypropylene	Nonwoven, Needle Punched, Calendered	Adhesive Bond to Columns, Heat Bond Backing
J-Drain	Net	LDPE	6.4 (0.25)	Polypropylene	Nonwoven	Linear Adhesive Bond Line Both Sides

HDPE - High Density Polyethylene; HIPS - High Impact Polystyrene; LLDPE - Linear Low Density Polyethylene; LDPE - Low Density Polyethylene

Table 4-9. Laboratory flow volumes as a function of channel slope and entrance head (Dempsey, 1988).

Fin-Drain Material	**Entrance Head, mm (in)**	**Flow Volume, gal/hr for Indicated Channel Slope, %**				
		0	**1**	**2**	**3**	**4**
Hitek 20*	157 (6.2)	110	158	189	223	249
Hitek 40*	160 (6.3)	387	550	670	782	892
Akwadrain*	160(6.3)	98	133	154	189	215
Miradrain 6000	160(6.3)	45	67	79	93	108
Hydraway	155 (6.1)	270	357	407	495	564
J-Drain	163 (6.4)	21	30	39	47	55
Hitek 20*	310 (12.2)	305	380	435	495	536
Hitek 40*	312 (12.3)	1065	1281	1444	1601	1787
Akwadrain*	318 (12.5)	273	336	380	423	468
Miradrain 6000	310 (12.2)	147	170	191	220	237
Hydraway	315 (12.4)	655	794	892	990	1080
J-Drain	318 (12.5)	66	92	106	114	133
Submerged Entrance						
Hitek 20*	462 (18.2)	517	598	660	703	753
Hitek 40*	470 (18.5)	1692	1875	2026	2163	2284
Akwadrain*	470 (18.5)	443	490	541	564	584
Miradrain 6000	467 (18.4)	218	252	273	295	318
Hydraway	465 (18.3)	997	1137	1235	1350	1390
J-Drain	470 (18.5)	123	141	153	165	178

* Two-sided flow

Koerner (1991) determined the flow characteristics of nine different fin-drains using ASTM Test Method D-4716. Koerner recognized that flow characteristics as determined by the ASTM test method were an index and did not attempt to compute edgedrain flow but chose to arbitrarily set performance criteria. The criteria seem to be set to allow use of most of the existing geocomposites. The performance criteria established for flow capacity are 15 gal/min at a normal pressure of 1,500 lbf/ft^2 and 0.1 gradient. Of the nine fin-drains evaluated, seven exceeded the flow criteria. Koerner made no attempt in the 1991 paper to extend the study to the development of a flow equation (such as was done by Dempsey).

In considering the construction of fin-drains, the flow in fin-drains could be represented by Manning's equation or by Darcy's equation, but most likely it should be somewhere between the two conditions. It certainly appears that Dempsey had the best available data on flow in fin-drains and that his analysis of the data must be accepted. It is interesting to note the difference in the two equations. For the Dempsey equation, the flow is related to the square root of the hydraulic gradient. In Darcy's equation, shown below, the flow is related to the hydraulic gradient to the first power:

$$Q = kAi \qquad \text{Eq. 4-41}$$

where:

Q = Flow in ft^3/day
k = Coefficient of permeability in ft/day
A = Area of flow in ft^2
i = Slope or hydraulic gradient in ft/ft.

This indicates that Dempsey found the flow in the fin-drain to be less sensitive to changes in hydraulic gradient than Darcy found for flow in soils. The data presented by Dempsey (1988) seems to justify the square root relationship. Consider the Hydraway fin-drain with a 155-mm entrance head in Figure 4-7. At 2 percent slope the flow is approximately 400 gal/hr as compared to 570 gal/hr at 4 percent slope. This would indicate that the relationship between the hydraulic gradient would be less than the first power relationship used in Darcy's equation.

Computation of Field Flow Capacity

A method of computing flow capacity of fin-drains is presented in appendix A of the "DAMP" documentation (FHWA, 1990). The method uses the equation developed by Dempsey (1988). This procedure uses the hydraulic gradient as the trench slope plus the ratio of the fin-drain width to the distance between outlets. The procedure also requires the depth of flow. The problem is that both hydraulic gradient and the depth of flow vary along the length of fin-drain. Moulton obtained a solution for the governing differential equation for the flow in the base material that could be applied if Darcy's equation were used for flow. However, based on the available data, it seems best to use Dempsey's equation.

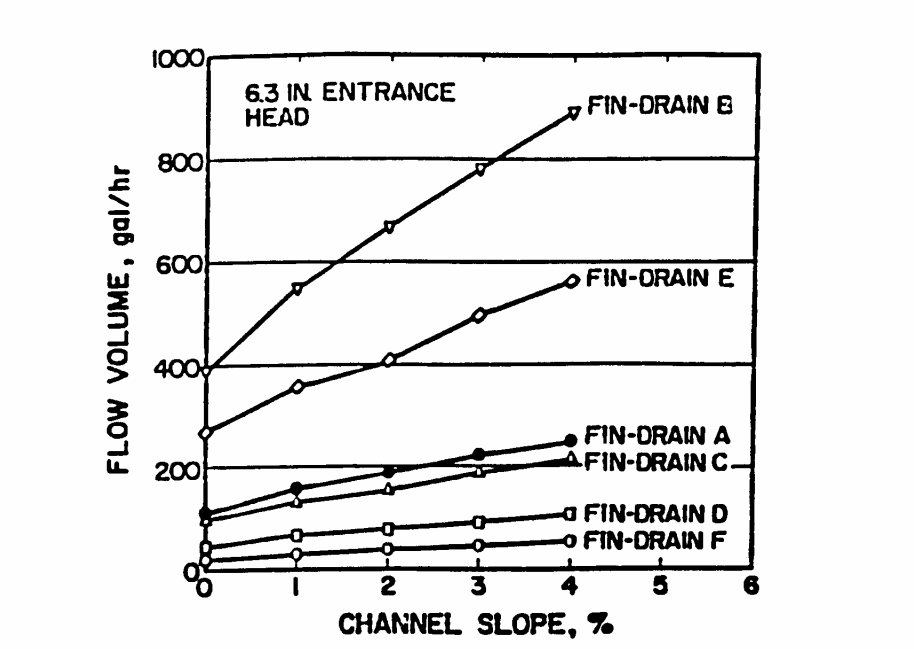


Figure 4-7. Relationships between core flow capacity and channel slope at 6.3-in average entrance head (Dempsey, 1988).

The problem in using Dempsey's equation is how to define the hydraulic gradient and the depth of flow. Typically, a fin-drain is installed with a flow zone and freeboard (see Figure 4-8). It should be assumed that flow would occur within the flow zone. Also, it should be assumed there will be an outlet pipe that will flow at some depth. If it is assumed that the hydraulic gradient is constant between the upper end and the outlet, as shown in Figure 4-9, then the hydraulic gradient (G) is:

$$S + \frac{(D_1 - D_2)}{L} \qquad \text{Eq. 4-42}$$

where:

S = Slope of trench, m/m (ft/ft)
D_1 = Depth of flow zone, mm (in)
D_2 = Depth at the outlet or the diameter of the outlet pipe, mm (in)
L = Distance between outlet, m (ft)

For most cases the slope of the trench (S) may be large compared to H/L; thus, the main unknown would be the depth of flow. The depth of flow varies along the flow path and is very difficult to define.

Since the inflow into fin-drains is computed with a high degree of uncertainty, accepting the gross assumptions in Figure 4-9, the depth of flow can be assumed to be the average depth of flow. In this case the capacity (Q) would be computed by:

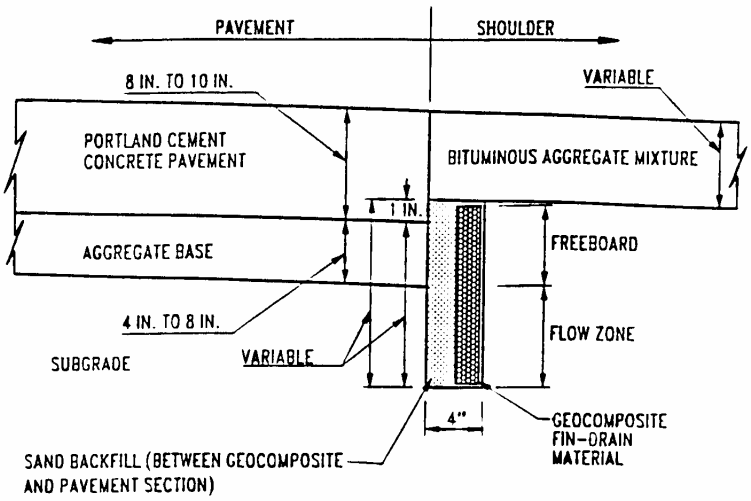


Figure 4-8. Typical fin-drain system showing freeboard and flow zone areas.

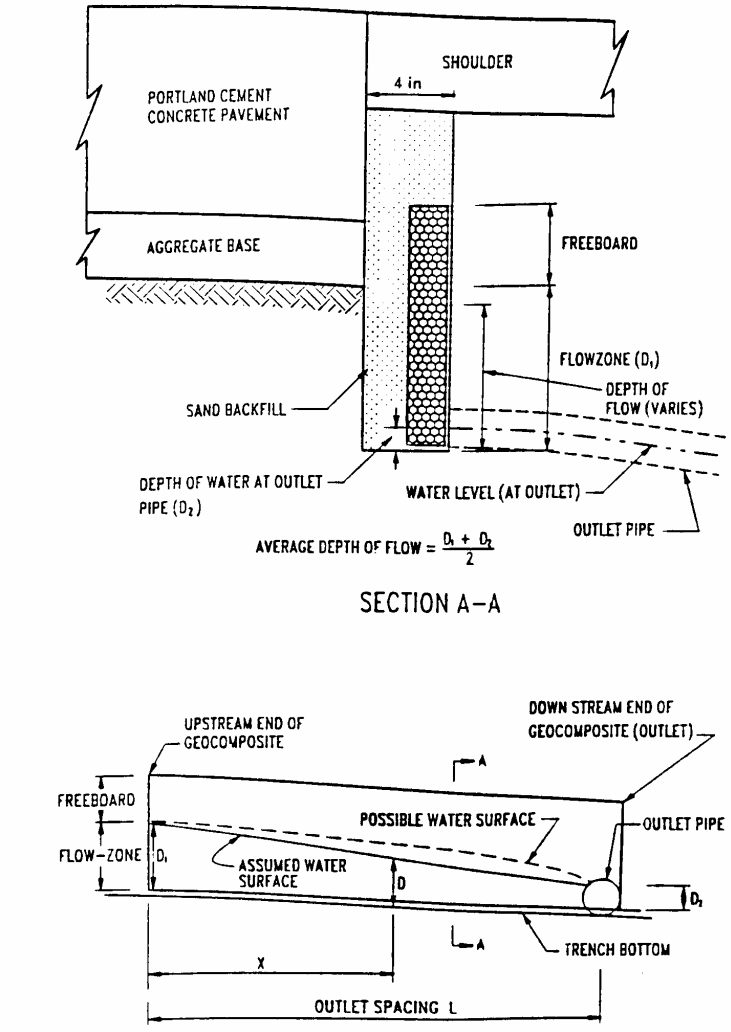


Figure 4-9. Schematic for computing flow.

$$Q = CD\left[S + \frac{(D_1 - D_2)}{L}\right]^{1/2} \qquad \text{Eq. 4-43}$$

where:

C = Fin-drain flow constant, m^3/day/mm (ft^3/day/in)
D = Average depth of flow, i.e., $(D_1 + D_2)/2$, mm (in)
D_1 = Depth of flow zone, m (ft)
D_2 = Ddepth at outlet, m (ft)
L = Distance between outlet, m (ft)
S = Slope of trench, m/m (ft/ft)

This approach is likely to lead to very conservative estimates of the flow capacity. A less conservative estimate would be to use D_1 as the depth of flow. The estimated flow capacity using this method is probably sufficiently accurate for design purposes.

CHAPTER 5 - EXAMPLE PROBLEMS

This chapter contains sample exercises that acquaint the user with the operation of DRIP.

EXAMPLE PROBLEM NUMBER 1

Given

A pavement section consists of two 12-ft (3.66-m) lanes of 9-in- (225-mm-) thick PCC pavement with 10-ft (3.05-m) AC shoulders on each side with a uniform cross slope (not crowned), and the width of the permeable base is the same as the PCC pavement. The transverse joint spacing is 20 ft (6.1 m). The slope in both the longitudinal (S) and transverse (S_x) directions is 2 percent. The permeable base is made up of AASHTO #57 material and has a unit weight of 100 pcf (1600 kg/m^3), specific gravity of 2.65, and a minimum permeability of 3000 ft/day (914 m/day). The thickness of the permeable base is 4 in (100 mm), based on construction considerations. Assume a unit weight of 162 pcf (2595 kg/m^3) for the PCC material. The subgrade is Georgia Red Clay, which is actually a well-graded clayey-silt. Laboratory tests indicate the particle gradation shown in Table 5-1 for the subgrade material and a permeability of 0.0033 ft/day (0.001 m/day). Corrugated pipe edgedrains having 4-in (100-mm) diameter are used on the project.

Table 5-1. Sieve analysis of Georgia Red Clay subgrade.

Sieve No.	Percent Passing
# 4	92
#10	67
#20	55
#50	42
#200	31

Determine

Use the crack infiltration method to determine inflow. Check the adequacy of the permeable base using the depth-of-flow approach to determine flow conditions. Determine the need for an aggregate separator layer and the adequacy of the 4-in (100-mm) pipe.

Solution

Prior to starting the analysis, the user needs to select the type of units in which to perform the analysis. This problem will be solved using English units. This system of units is the default option in DRIP and can be selected by checking English under the *Options* | *Units* menu command. Once selected, this system of units will be retained throughout the analysis unless the user makes a change. Similarly, the mode of program execution (Expert or Normal) can also be selected from the *Options* menu. The default is the Normal mode, and that will be used in this example.

The problem solution is presented under several different sections. The arrangement of these sections follows the logical left-to-right approach emphasized in Chapter 3. An experienced user may, however, solve the problem using a different sequence of steps.

Pavement Geometry

Step 1: Select the ***Roadway Geometry*** tab (this is the default program tab) to access the corresponding property page. Select a uniformly cross-sloped pavement section by clicking on the Geometry B radio button.

Step 2: Enter the value of b as 24 ft (2 lanes of 12 ft each). Since the problem statement assumes that the width of the permeable base is same as that of the PCC layer, enter the value of c as 0. Clicking the calculator icon for width of the permeable base W results in a computed value of 24 ft.

Step 3: Enter the longitudinal and transverse slopes in the S and S_X edit boxes, respectively. Click the calculator icons for both S_R (resultant slope) and L_R (resultant length) to compute these parameters. The calculations should yield the following values: $S_R = 0.0283$ ft/ft and $L_R = 33.94$ ft/ft.

The completed screen is shown in Figure 5-1. The values entered and computed in this property page will be saved and carried forward for later use. Note that as soon as the computations are completed on this page, the respective values are displayed on the left side of the main DRIP client window. This screen can be exited by clicking on another tabbed property page.

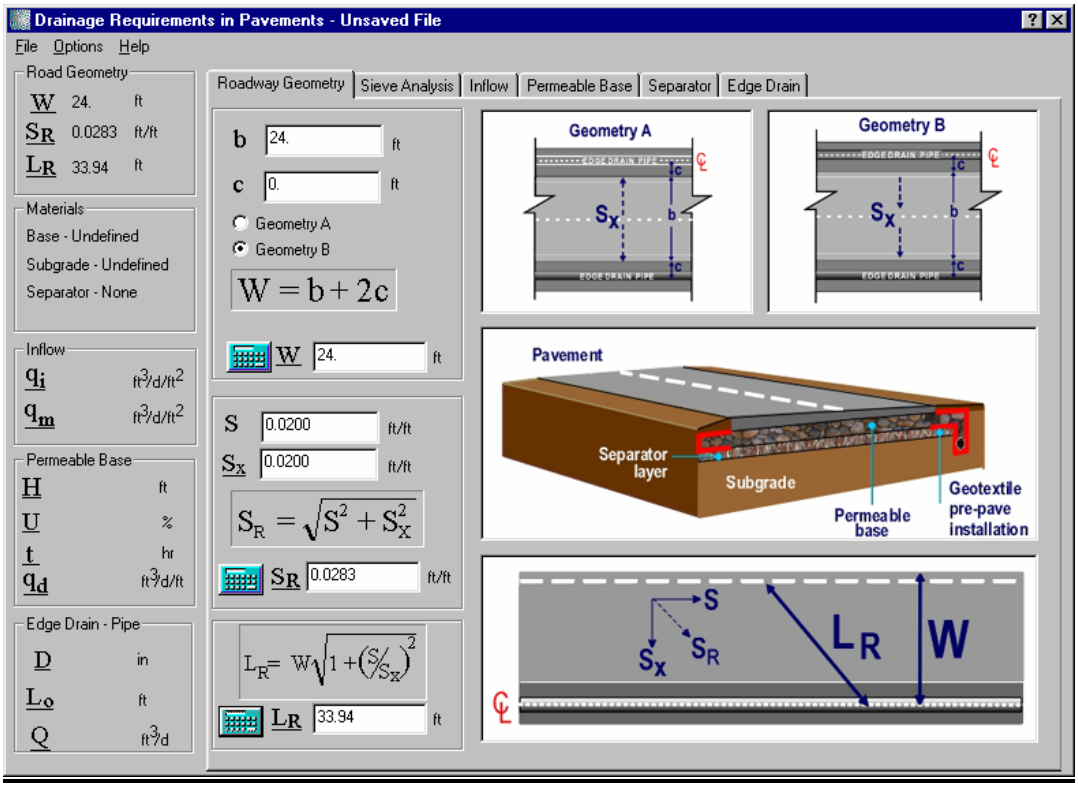


Figure 5-1. Computation of roadway geometry.

Inflow Computation (Crack Infiltration Method)

Step1: Select the ***Inflow*** tab to access the corresponding property page. Click on the Crack Infiltration Method radio button (since this method was required to be chosen to estimate inflow).

Step 2: Retain the default values of 2.4 ft^3/day/feet for I_c and 0 for pavement permeability k_p. Also retain the values for W_c and W that have been automatically carried forward from the calculations performed on the ***Roadway Geometry*** page.

Step 3: Enter the number of longitudinal cracks, N_c, as 3 (N_c = the number of contributing lanes + 1 = 2 + 1 = 3). Enter the given transverse spacing of contributing transverse joints C_s = 20 ft.

Step 4: Click the calculator icon to compute inflow q_i. This should yield a value of 0.42 ft^3/day/ft^2.

The values entered and computed in this screen will be stored and carried forward to other screens where they are needed. The completed ***Inflow*** screen is shown in Figure 5-2. The computed inflow value is updated in the summary page.

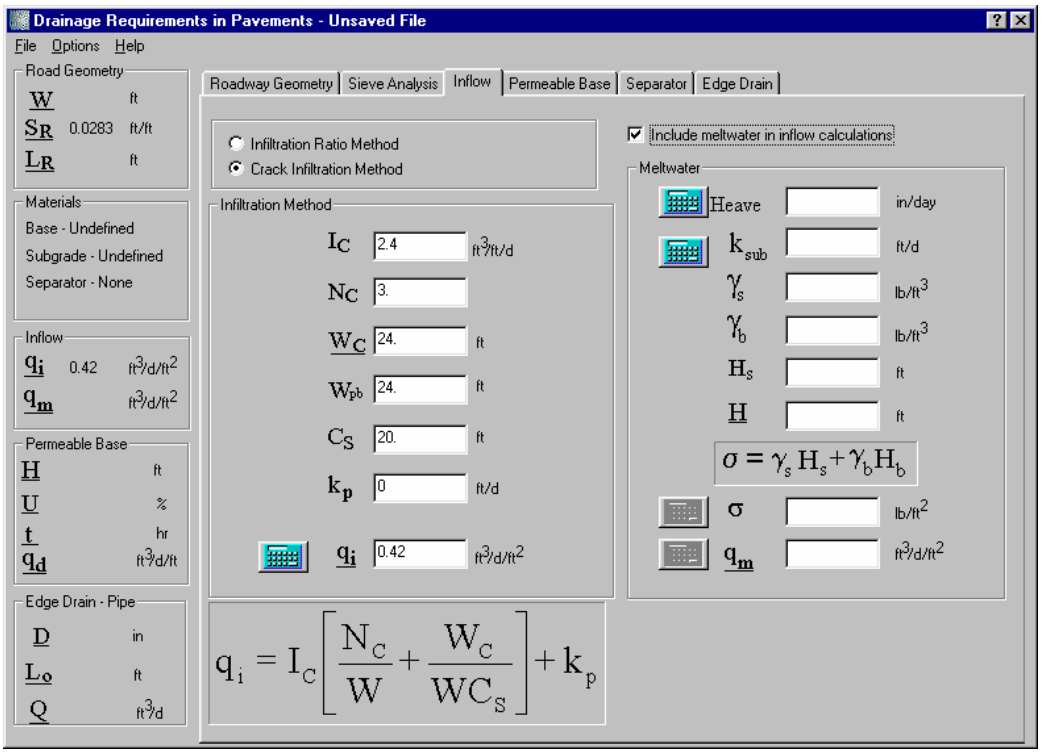


Figure 5-2. Crack infiltration computation.

Meltwater Computation

Step 1: Activate the *Meltwater* sub-screen in the ***Inflow*** property page by clicking on the "Include Meltwater in the inflow calculations" checkbox.

Step 2: The heave rate (*Heave*) for the clayey-silt subgrade soil can be determined by clicking on the calculator button located to the left of the variable. This action calls up the heave rate table. The heave rate table shows that the value for clayey-silt soil is 0.51 in/day. This value can either be entered manually in the edit box on the *Meltwater* sub-screen or entered automatically by selecting the row corresponding to clayey-silt soil type.

Note : For materials with large heave rates, the mid-point values may be entered.

Step 3: Enter the given values for the subgrade permeability (k_{sub} = 1 ft/day), unit weight of the pavement surface (γ_p = 162 lb/ft^3), the unit weight of the base material above the subgrade (γ_b = 100 lb/ft^3), the thickness of pavement surface (H_s = 9 in.), and the thickness of the base material (H = 4 in.) in the appropriate boxes.

Step 4: Click on the calculator icon next to the variable σ to compute the stress imposed by the pavement on the subgrade. This will yield a value of 154.8 lb/ft^2.

Step 5: Click the calculator icon for determining the quantity of meltwater (q_m). Moulton's meltwater chart appears on the screen. On this screen a horizontal red line appears marking the heave rate of the subgrade (0.51 in/day). Use the mouse to slide the vertical tick line along the horizontal red line (0.51 in/day line) to an approximate location for a stress of 154.8 psf. The value for $q_m/(k_{sub})^{0.5}$ will appear in the appropriate box. When satisfied that the mouse is positioned at the proper stress value, click the left mouse button to produce a computed value of q_m. For this example, the mouse is positioned to indicate a value of $q_m/(k_{sub})^{0.5}$ of 0.91 ft^3/day/ft^2. A click of the left mouse button produces a value for q_m of 0.05 ft^3/day/ft^2. Press OK to return to the ***Inflow*** property page.

The values entered and computed in this screen will be retained and carried forward. The Moulton's meltwater chart is shown in Figure 5-3, and the completed meltwater screen is shown in Figure 5-4. The computed meltwater quantity (q_m) is updated in the summary page.

Permeable Base Design (Depth-of-Flow)

Step 1: Select the ***Permeable Base*** tab to access the corresponding property page. Click on the Depth of Flow Method radio button. Most of the variables such as q_i+q_m, S_R, L_R, and H already have values carried forward from pervious screens.

Note: The term q_i+q_m is a summation of the inflow from rainfall and meltwater.

Step 2: Enter the coefficient of permeability of the base (k = 3000 ft/day).

Step 3: Compute the H_{min} by clicking on the calculator icon. A H_{min} value of 0.1437 ft is reported, which is lower than the selected permeable base thickness (H) of 0.3333 ft. Therefore, the design is satisfied.

Note: If Hmin were much greater than H, the designer would make adjustments to the design by changing design variables such as base thickness or permeability. If the base thickness H can be revised, this parameter must be changed to be at least equal to the Hmin.

Step 4: Compute flow capacity of the permeable base (q_d) by clicking on the appropriate calculator button. This yields a value of 44.811 ft^3/day/ft. The flow capacity is estimated from Moulton's chart.

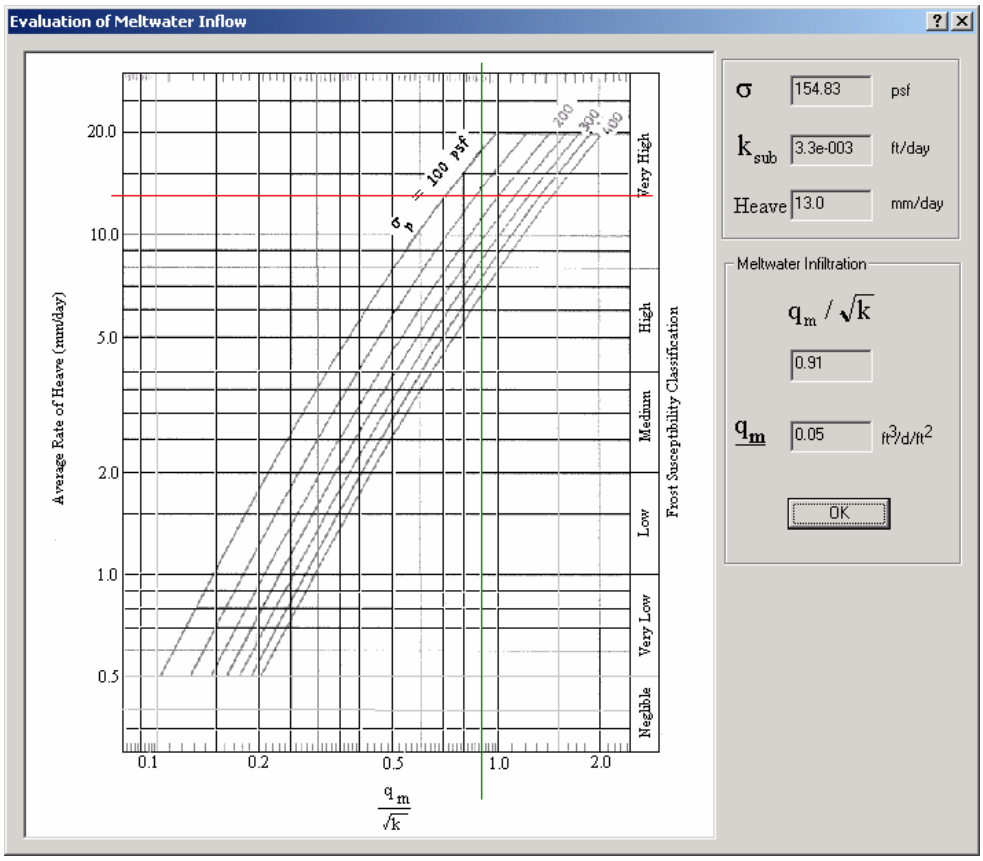


Figure 5-3. Moulton's meltwater chart.

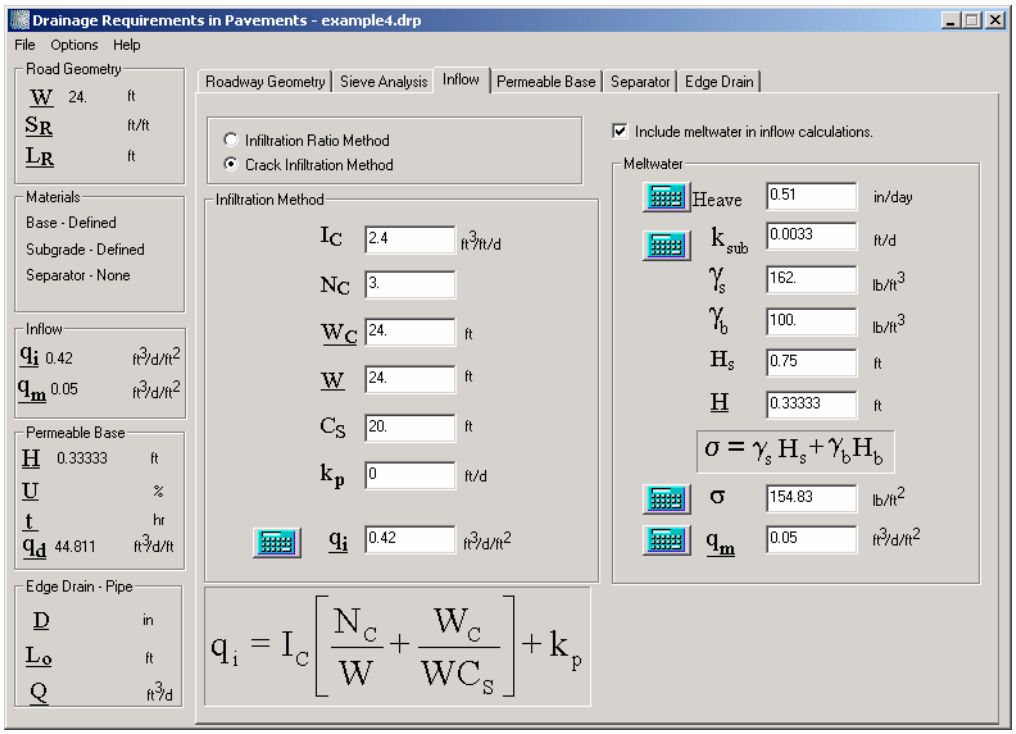


Figure 5-4. Meltwater computation.

A completed design screen for the depth-of-flow design is shown in Figure 5-5. The values computed here are carried forward to other screens. The summary box on the DRIP client window is also updated accordingly.

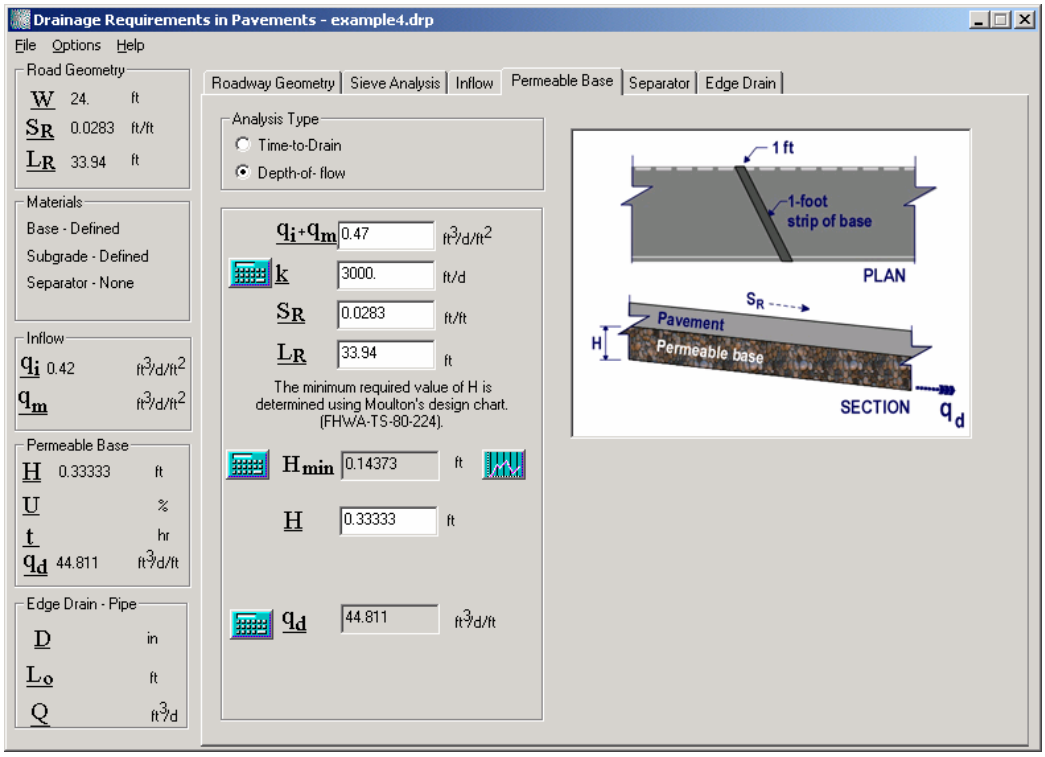


Figure 5-5. Permeable base depth-of-flow design.

Additional Discussion on Depth of Flow Design

If the user wishes to perform a sensitivity analysis to see the influence of different parameters on the required thickness, the graph icon to the right of $H_{\min}$ variable in figure 5-5 can be clicked. DRIP internally performs the calculations over a pre-selected range of the independent parameter (in this case the required base thickness) and computes and plots the dependent variables. The charts are plotted using the DripPlot. The DripPlot window appears as soon as the graph icon next to the H_{min} variable is clicked and the following sensitivity plots are displayed:

- Required Base Thickness (H_{min}) vs. Pavement Inflow (q_i or $q_i + q_m$).
- Required Base Thickness (H_{min}) vs. Base Course Permeability (k).
- Required Base Thickness (H_{min}) vs. Resultant Slope (S_R).
- Required Base Thickness (H_{min}) vs. Resultant Length (L_R).

The user can control the type of plots to be displayed in the DripPlot window using the *Options* | *Sensitivity* menu command prior to clicking the graph icon. An example sensitivity plot of required base thickness versus permeability is shown in Figure 5-6.

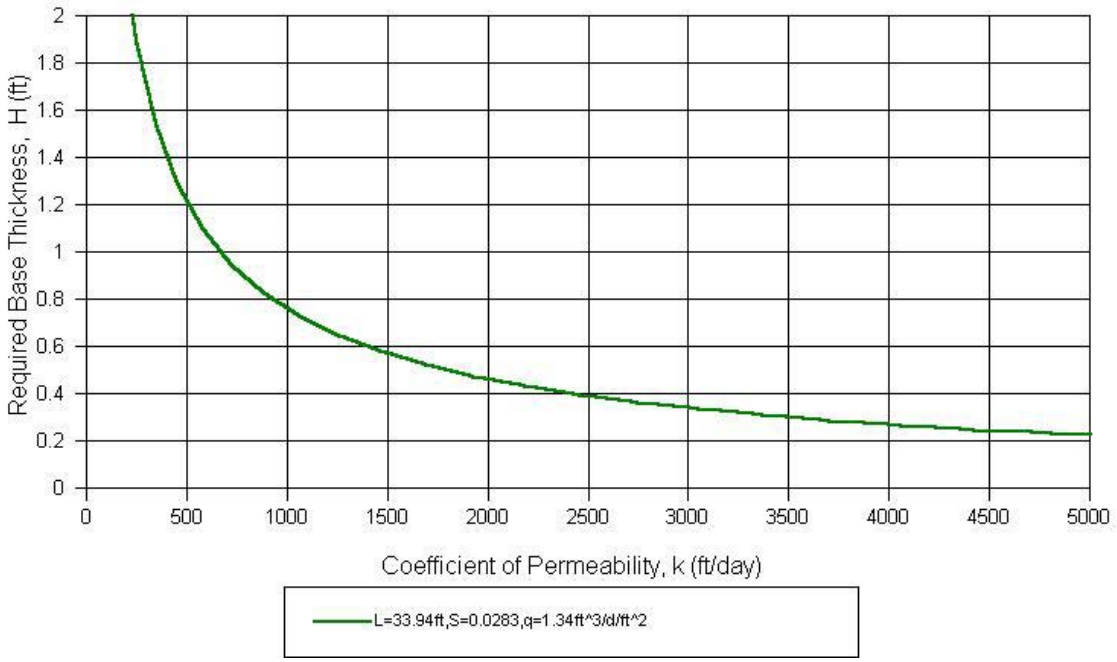


Figure 5-6. Depth-of-flow sensitivity analysis example (*H* vs *k*).

The generated plots can be directly saved as image files (jpeg or dib formats) using the appropriate options under of the *File* menu. Hard copy outputs can also be generated using the *File* | *Print* command or using the printer icon on DripPlot.

Separator Layer Design

Step 1: Select the ***Separator Layer*** tab. Select the No Separator radio button to evaluate the need for a separator layer.

Step 2: Click on the calculator icon next to the *Base Course* variable. This shifts the user to the ***Sieve Analysis*** property page. The permeable base is made up of the AASHTO #57 material. The gradation for this material is already in the sieve analysis library. To initialize this gradation to the program, click on the drop-down material library list box and select AASHTO #57. Click on the calculator icon to determine the particle sizes for D_{15} and D_{50}.

Step 3: Select the ***Separator Layer*** tab again. The values of D_{15}=0.2529 in. and D_{50}=0.5484 in. appear for the *Base Course.*

Step 4: Click on the calculator icon next the *Subgrade* variable to compute the subgrade particle sizes. The user is returned to the ***Sieve Analysis*** property page again and the Subgrade radio button is automatically activated. Select the Value radio button and enter the subgrade gradation in the grid on the left-hand side of the property page. Compute the D_{50} and D_{85} by clicking on the particle size calculator icon.

Step 5: Return to the separator layer property page by selecting the ***Separator*** tab. The values of D_{50}=0.0253 in. and D_{85}=0.1498 in. are returned for the subgrade.

Step 6: On the ***Sieve Analysis*** property page, check the filtration and uniformity criteria at the subgrade/base interface by clicking on the balance icon on the right-hand side. Both the criteria generate a *Pass* rating, which implies that no separator layer is required.

The completed separator layer screen is shown in Figure 5-7. Note that the summary page on the right side of the DRIP screen shown in the figure now states that the base and subgrade materials have been defined.

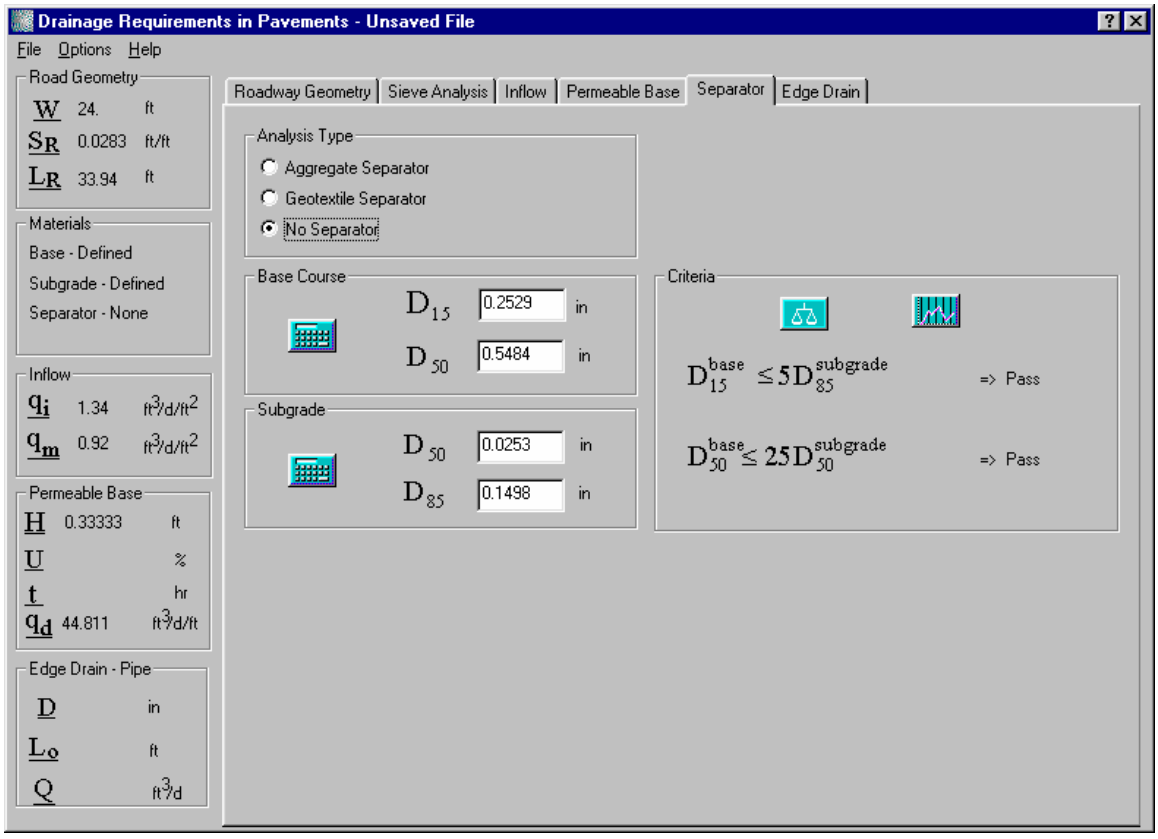


Figure 5-7. Checking separation criteria.

Edgedrain Design

Step 1: Select the ***Edgedrain*** tab.
Step 2: Select the Pipe Edgedrain radio button. Click the "Corrugated" checkbox and a value of $n_{manning}$ = 0.024 is displayed. Type in a value of D = 4 in.
Step 3: The calculator icon is enabled for calculating the pipe capacity (Q). The computed pipe capacity should read 12,594 ft^3/day.
Step 4: Click on the L_o button to compute the outlet spacing. This gives an L_o value of 391.6 ft. However, this value is based on the default selection of the *Pavement Infiltration* method for the pavement discharge rate (see under "Discharge Rate Approach" option list). Two other methods are given to compute the maximum outlet spacing: *Permeable Base* and *Time-to-Drain*. Since the time-to-drain

method was not used for designing the permeable base we will not examine this approach. For computing the outlet spacing L_o based on the *Permeable Base* approach, select the appropriate radio button from the "Discharge Rate Approach" options. Our previously computed base discharge q_d of 44.81 ft^3/day/ft appears automatically. This results in a maximum outlet spacing of 281 ft. Thus, the permeable base discharge result is the critical value, so the user should specify an outlet spacing of 281 ft.

The final edgedrain design screen is shown in Figure 5-8. Note the updated summary on the left side of the screen shown in the figure. A printed output summary can be obtained by clicking on *File* | *Print Summary* menu option.

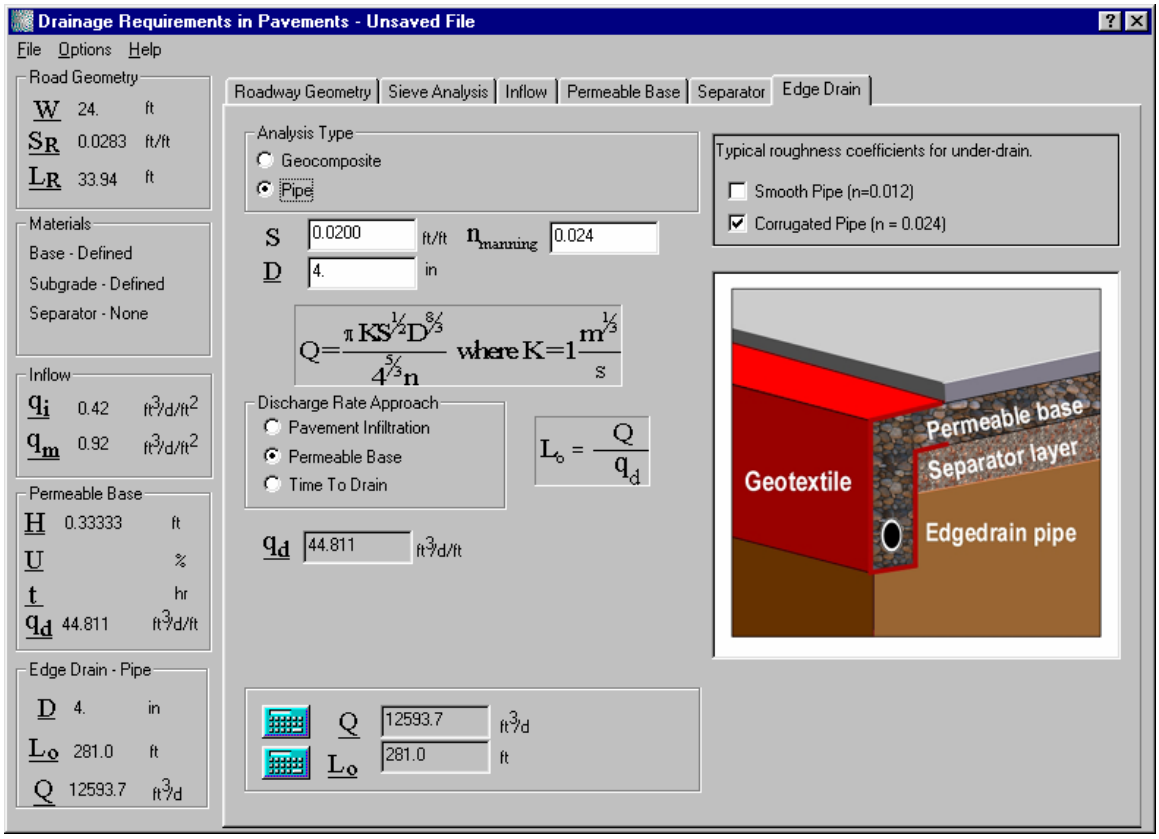


Figure 5-8. Pipe edgedrain design and outlet spacing computation

EXAMPLE PROBLEM NUMBER 2

Given

The input data are the same as Example Problem No. 1, except that a woven geotextile is used for the separator layer and a Hydraway geocomposite edgedrain is present. Permeability conditions are critical.

Determine

Calculate the time to drain of the permeable base. Design the geotextile separator layer. Calculate the outlet spacing for the geocomposite edgedrain.

Note: The roadway geometry and inflow calculations do not have to be performed again.

Solution

Sieve Analysis

Step 1: Click on the ***Sieve Analysis*** tab in the DRIP client window. Select the Base radio button. The AASHTO #57 gradation configured in the previous example should appear automatically in the grid on the left side of the screen.
Step 2: Enter the given values for the *Unit Weight* (130 pcf) and *Specific Gravity* (2.65) of the base.
Step 3: Compute the porosity $n = 0.214$ by clicking on the calculator icon.
Step 4: Select the Water Loss Method radio button to compute the effective porosity. This selection is justified since AASHTO #57 is a coarse gradation. Immediately, the "Water Loss" table pops up. On this screen, an extrapolated passing # 200 value of 0.5% is displayed. Select the Silt radio button for the type of fines. This produces a Water Loss value of 76% for gravel. Select this value with a cursor and click OK to transport this value to the ***Sieve Analysis*** screen.
Step 5: Click on the calculator icon adjacent to the effective porosity n_e on the ***Sieve Analysis*** screen to compute this value. The program computes $n_e = 0.163$.

The final screen for computation of the permeable base material properties is shown in Figure 5-9.

Permeable Base Design (Time-to-Drain)

Step 1: Click on the ***Permeable Base*** tab to access the corresponding property page. Select the Time-to-Drain radio button. The values for the design inputs, n_e, k, S_R, L_R, and H should already be present from the analyses done as part of the previous example and this session so far.
Step 2: The time-to-drain factor t can be determined based on 50-percent drained or the 85-percent saturation criteria. The former is the more conservative for permeable bases, so it will be used. Enter U = 50%.
Step 5: Click on the calculator icon adjacent to the variable t to compute it. A value of 0.55 hr is returned if the Barber/Sawyer equation is used (default). The Casagrande/Shannon equation yields a value of 0.52 hr. Both these results fit the "Excellent" drainage category.

The final ***Permeable Base*** design screen in shown in Figure 5-10.

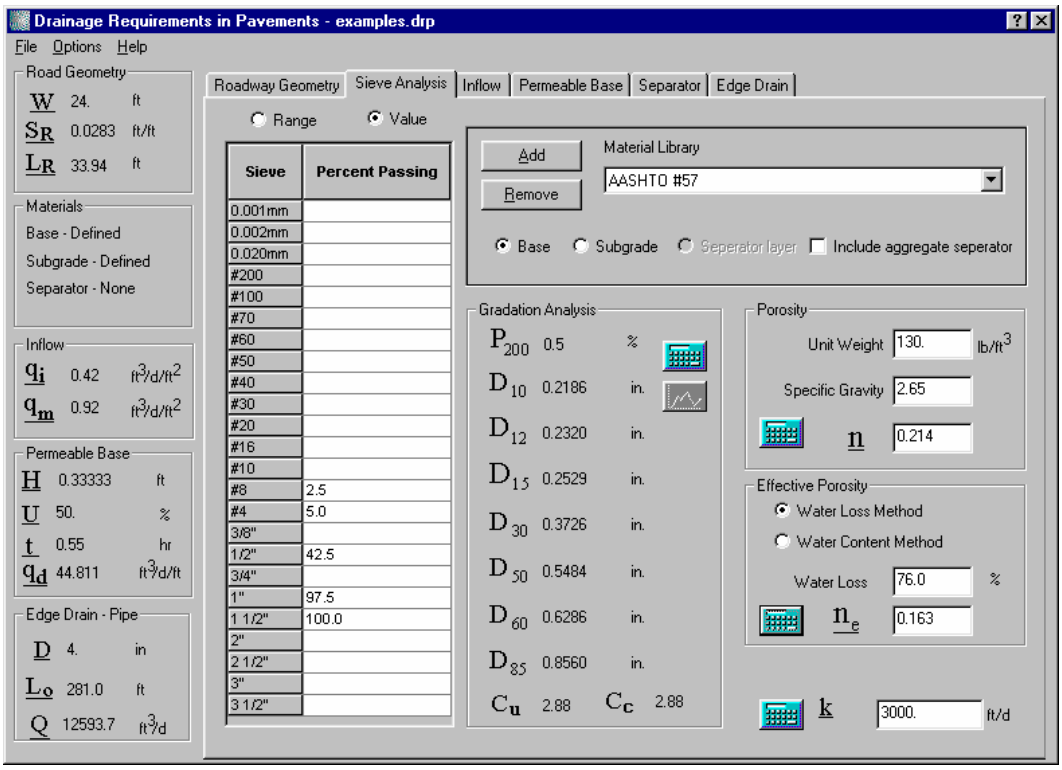


Figure 5-9. Performing particle size analysis of the permeable base.

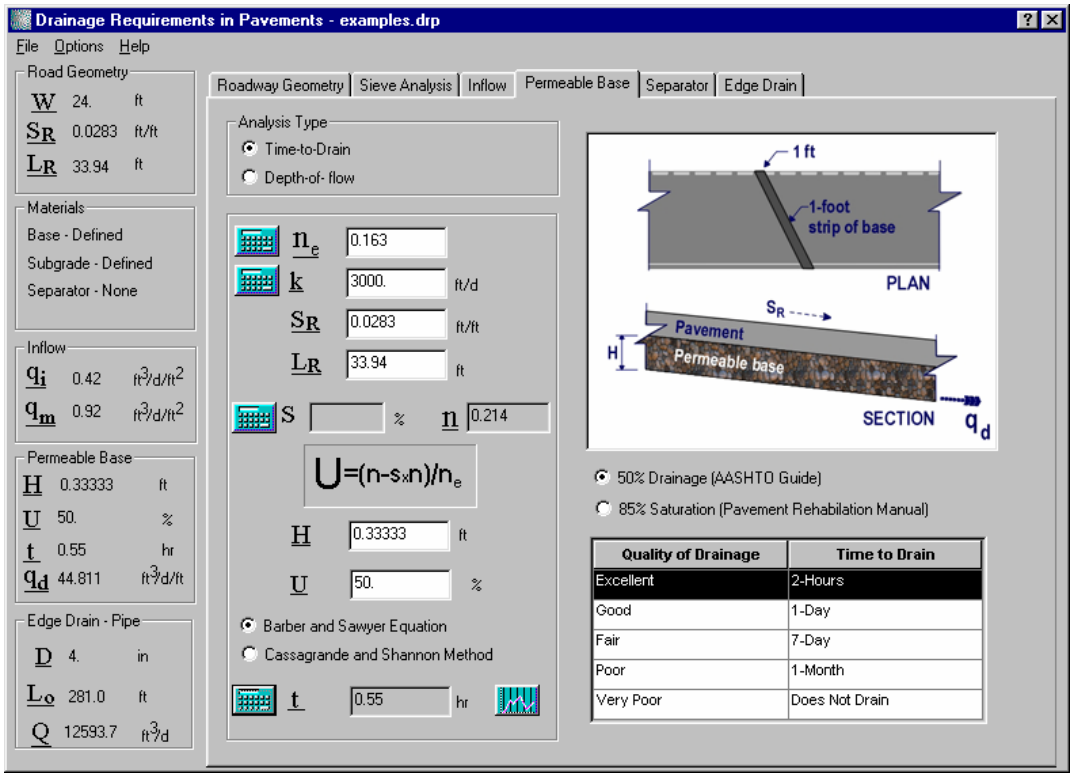


Figure 5-10. Time-to-drain computations for permeable base.

Additional Discussion

Clicking on the graph icon to the right of the time to drain variable *t* generates the following sensitivity plots:

- Time to drain (*t*) versus Degree of drainage (*U*).
- Time to drain (*t*) versus Resultant length (L_R).
- Time to drain (*t*) versus Resultant slope (S_R).
- Time to drain (*t*) versus Coefficient of permeability of base (*k*).
- Time to drain (*t*) versus Base thickness (H).
- Time to drain (t) versus Effective porosity (ne).

Separator Layer Design

Step 1: Click on ***Separator*** tab to access the property page. Click on the Geotextile Separator radio button.
Step 2: For conservatism, click the *Dynamic Flow* radio button for "Soil Retention Criteria." Also, click the *Critical* radio button for permeability criteria.
Step 3: The P_{200}, k_{sub}, C_U, D_{15}, and D_{85} should be retained from the previous screen. If these values are not present, click on the calculator icon in the "Subgrade" category box, enter the Georgia Red Clay gradation, compute the particle sizes, D_{xx}, and C_U, and enter the given k_{sub} value. Then click on the ***Separator Layer*** tab to return to the separator layer property page.
Step 4: Once all the necessary computations are made, the separator property page should have the following values for the variables: P_{200} = 31%, k_{sub} = 1 ft/day, C_U = 211.73, and D_{15} = 5.88e-04 in, D_{85} = 0.1498 in. Click on the Woven Geotextile radio button in the "Geotextile Separator" category box. Click on the calculator icon to compute *AOS* = 0.0785 in. and *k* = 10 ft/day.
Step 5: Suppose a woven geotextile with *AOS* of 1/6 in. and a permeability of 100 ft/day can be found, type in k_{sep} = 100 ft/day. Click on the calculator icon to compute t_{max} = 0.069 in. for the geotextile. This is the maximum thickness of the geotextile. The percent open area should be equal or greater than 4 percent, as noted close to the bottom right of the screen.
Step 6: Finally, click on the balance icon on the right hand side of the screen to see if the chosen geotextile passes all the necessary criteria. All the criteria checks generate a *Pass* rating for the selected geotextile.

The final screen for the geotextile separator layer design is shown in Figure 5-11.

Edgedrain Design

Step 1: Click on ***Edgedrain*** tab to access the property page. Click on the Geocomposite radio button.
Step 2: Select the row for the Hydraway edgedrain from the table on the right side. The value of C_g = 1333 ft^3/day is automatically returned to the appropriate edit box.

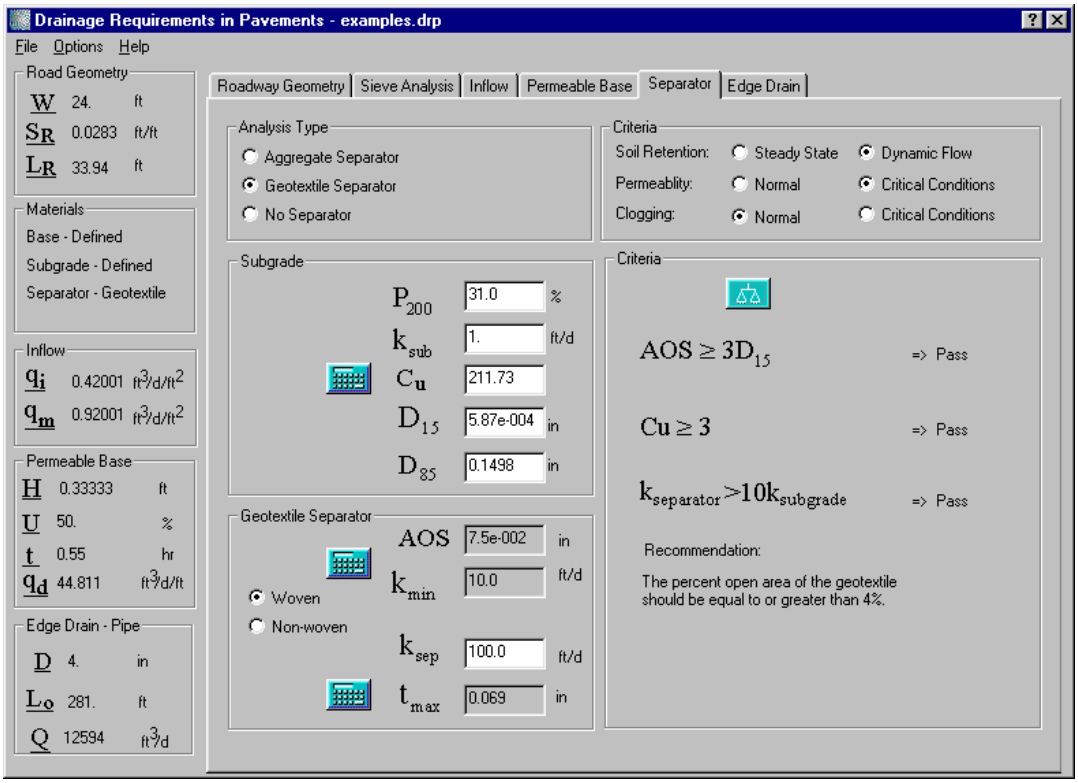


Figure 5-11. Geotextile separator layer design.

Step 3: Type in a value of 12 in. for the height of flow zone D_1 and 4 in. for the diameter of the pipe D_2.

Step 4: Use the time-to-drain method for outlet pipe spacing by clicking on the Time-to-Drain radio button on the "Discharge Rate Approach" category box. All the necessary time to drain inputs should already appear in the respective variable edit boxes from the earlier computation on the ***Permeable Base*** screen.

Step 5: Click the calculator icon to compute Q and L_o. The program returns Q = 1691.1 and L_o = 59.4 ft.

The final screen for the geocomposite edgedrain design is shown in Figure 5-12.

EXAMPLE PROBLEM NUMBER 3

Given

The gradations of a permeable base and a proposed aggregate separator layer to be used in a project are given in Table 5-2. Also given is the gradation of the subgrade soil at the project location.

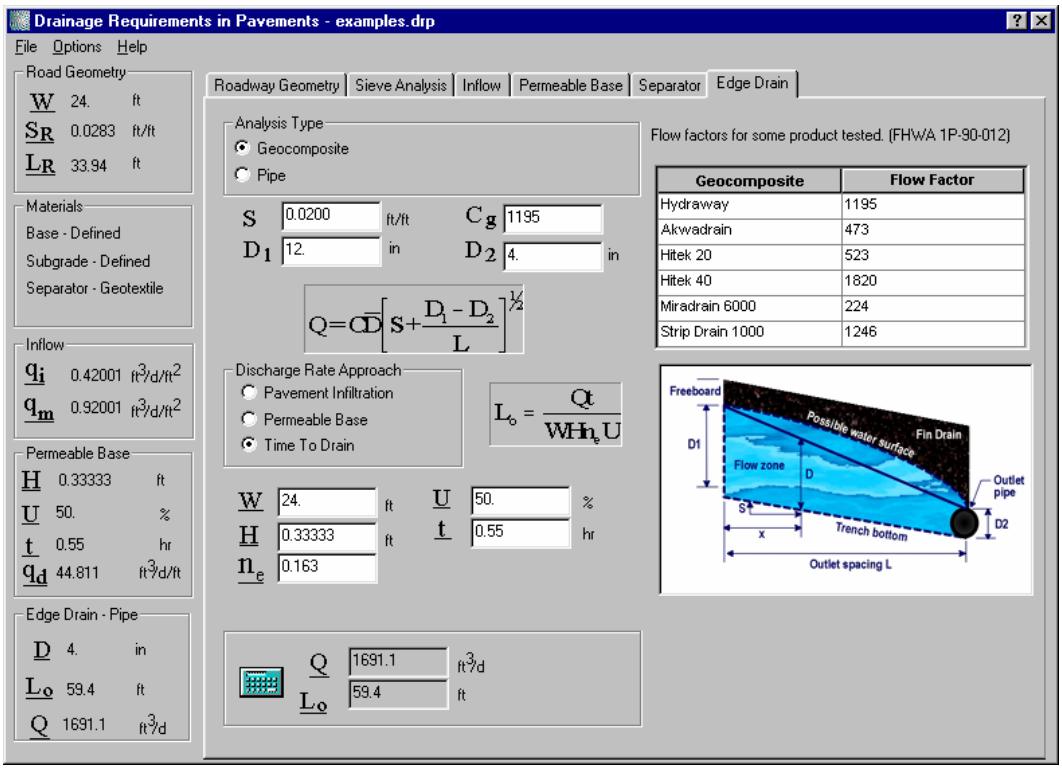


Figure 5-12. Design of geocomposite edgedrain.

Table 5-2. Gradations of pavement materials.

Sieve Sizes	Permeable Base	Subgrade	Proposed Separator Layer
1 1/2 in	100		
1 in	97.5		100
3/4 in			
1/2 in			85
3/8 in	70		
No. 4	47.5		65
No. 8	15	100	
No. 16	4		40
No 30		88	
No 40			
No. 50	2.5	68	
No. 100			
No. 200		45	11
0.001 mm (hydrometer)		4	

Determine

Determine the need to place a separator layer between the permeable base and native subgrade. If there is a need, determine whether the proposed separator layer is adequate.

Solution

Step 1: Click on the ***Sieve Analysis*** tab to enter and store the given base, subgrade, and separator layer gradations.
Note: Step-by-step instructions on saving custom gradations are on page 3-19.

Step 2: Click the "Include aggregate separator" check box.

Step 3: To enter and save the gradation of the given permeable base, click on the *Base* radio button on the ***Sieve Analysis*** page. Enter the percent passing information for the permeable base given in table 5-2 in the grid provided on the left side of the screen after selecting the *Value* radio button. After all the information is filled in, click on the "Add" button under the Material Library category box and save the entered gradation. Now, by clicking on the calculator icon under the Gradation Analysis category box, the user can compute the percent passing the No. 200 sieve, P_{200}, the particle sizes, D_{xx} (e.g., D_{10}, D_{12}, D_{15}), and the C_U and C_C values for the permeable base.

Step 4: Repeat the data entry and analysis performed in Step 3 for the separator and subgrade layers.

Step 5: Once all the gradations are entered and the corresponding properties computed, click on the ***Separator*** tab to access this property page. All the relevant D_{xx} values for each of the layers should already appear here. Under the separator layer property page select the No Separator option by clicking on the radio button. Then check the permeable base/subgrade interface by clicking on the balance symbol under the Criteria category box. The program indicates that the uniformity criterion has not been satisfied. This implies that a separator layer is required. Figure 5-13 displays the program screen generated from this calculation.

Step 6: Now choose the Aggregate Separator radio button. Check the criteria again by clicking on the balance icon. This results in the program generating a Pass rating for all the criteria. Therefore, the chosen separator layer is adequate. The final program screen for this computation is shown in Figure 5-14.

Step 7: A plot showing the gradations of the subgrade, permeable base, and the separator layer can be obtained by clicking on the graph icon next to the balance icon. On this plot, the upper and lower bounds of the gradation band within which the proposed separator layer has to fit to be considered acceptable also appear. These bounds are basically a graphical representation of the design criteria. The plot can be generated on a FHWA power 45 chart by selecting *Options* | *Plot Scale* | *Power 45* command from the Options menu. Alternately, selecting *Options* | *Plot Scale* | *Semi-log* command from the Options menu will result in a semi-log plot.

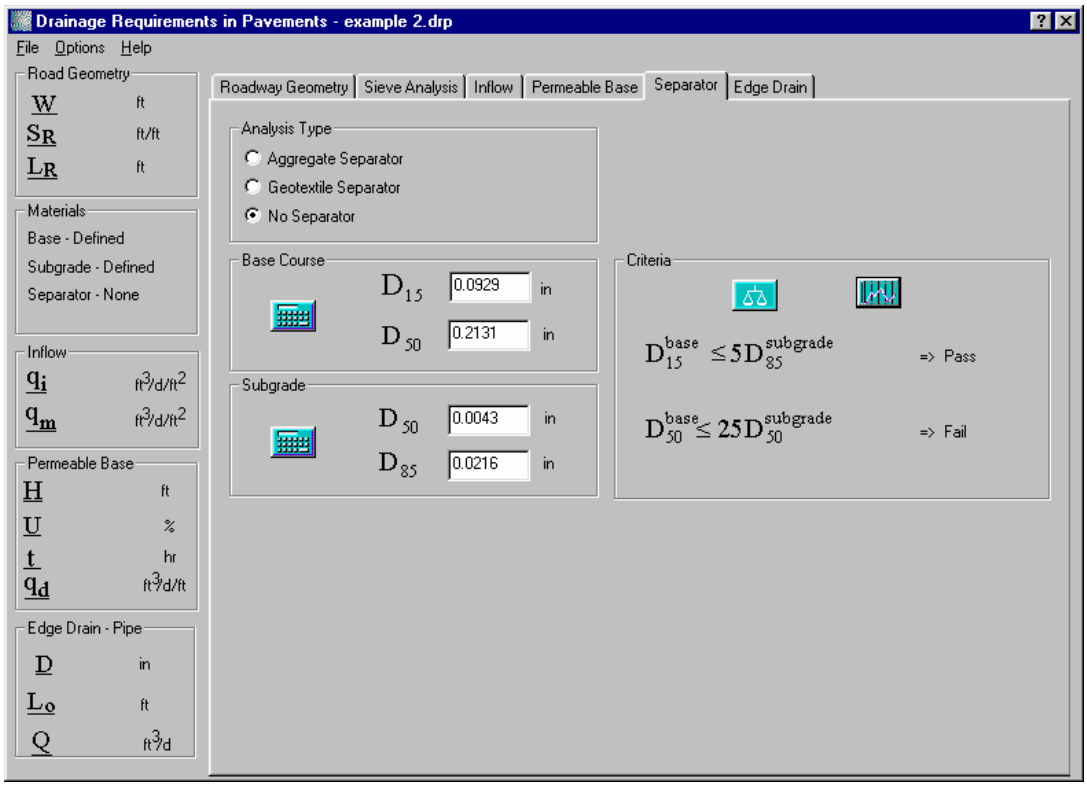


Figure 5- 13. Final program screen for the No Separator option.

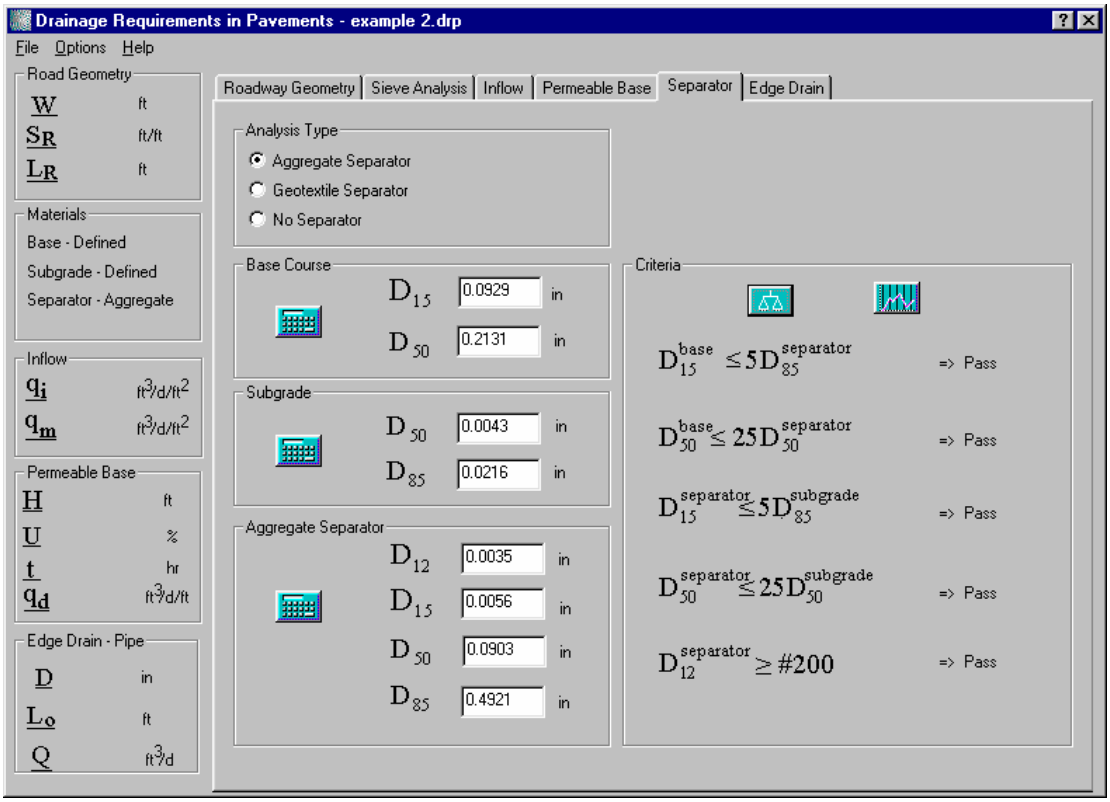


Figure 5-14. Final program screen for the Aggregate Separator option.

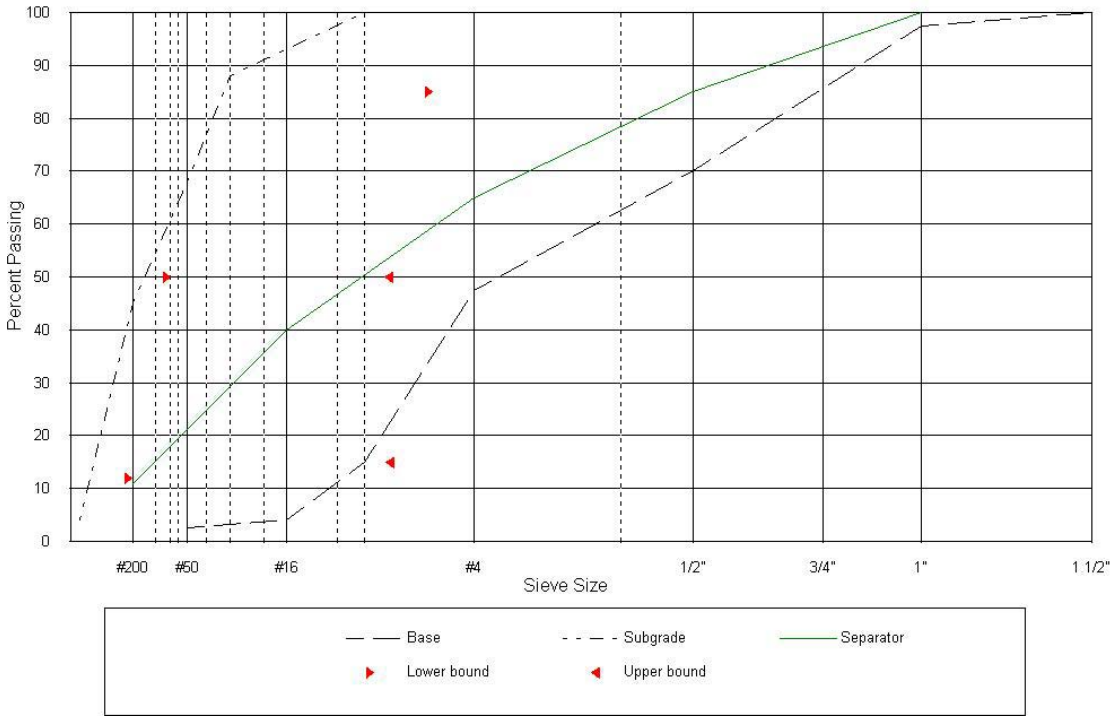


Figure 5-15. Separator layer design shown on an FHWA power 45 plot.

Figure 5-15 presents a gradation plot for the design example solved above on an FHWA power 45 chart. Figure 5-16 presents a semi-log plot of the same example in metric scale for comparison. Semi-log plots are useful in visualization when the gradations range from very fine to very coarse material. However, the D_{xx} values computed in DRIP are based on the power 45 charts.

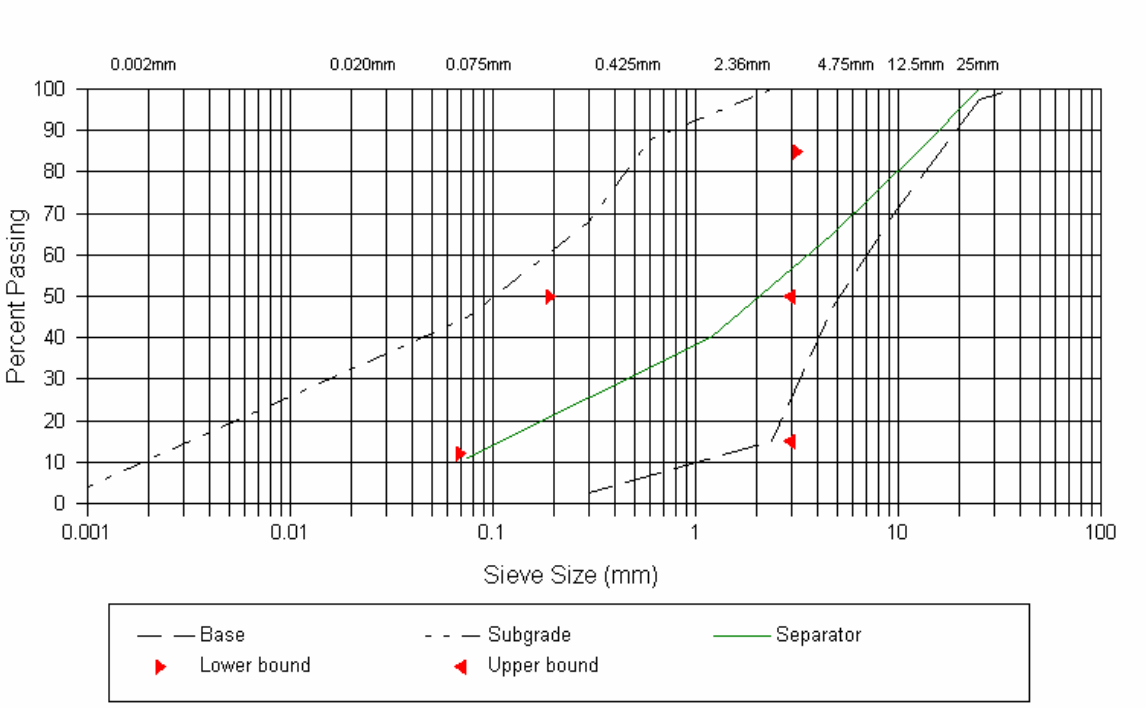


Figure 5-16. Separator layer design shown on a semi-log plot.

CHAPTER 6 - SENSITIVITY ANALYSIS

Time-to-Drain

The following plots were developed using the sensitivity plotting functionality of the ***Permeable Base*** property page for the Time-to-drain method. The sensitivity plots presented here can be generated by the clicking the graph icon after the time-to-drain parameter *t* has been computed.

Porosity

In Figure 6-1 it can be seen that the effect of effective porosity is linear. This means that if the effective porosity is doubled, the time to drain is doubled. This is logical since twice the amount of water will be released from the base course. However, engineers should not yield to the temptation of reducing the effective porosity to reduce the time to drain. It must be remembered that the goal of drainage is to remove as much water as possible from the base course.

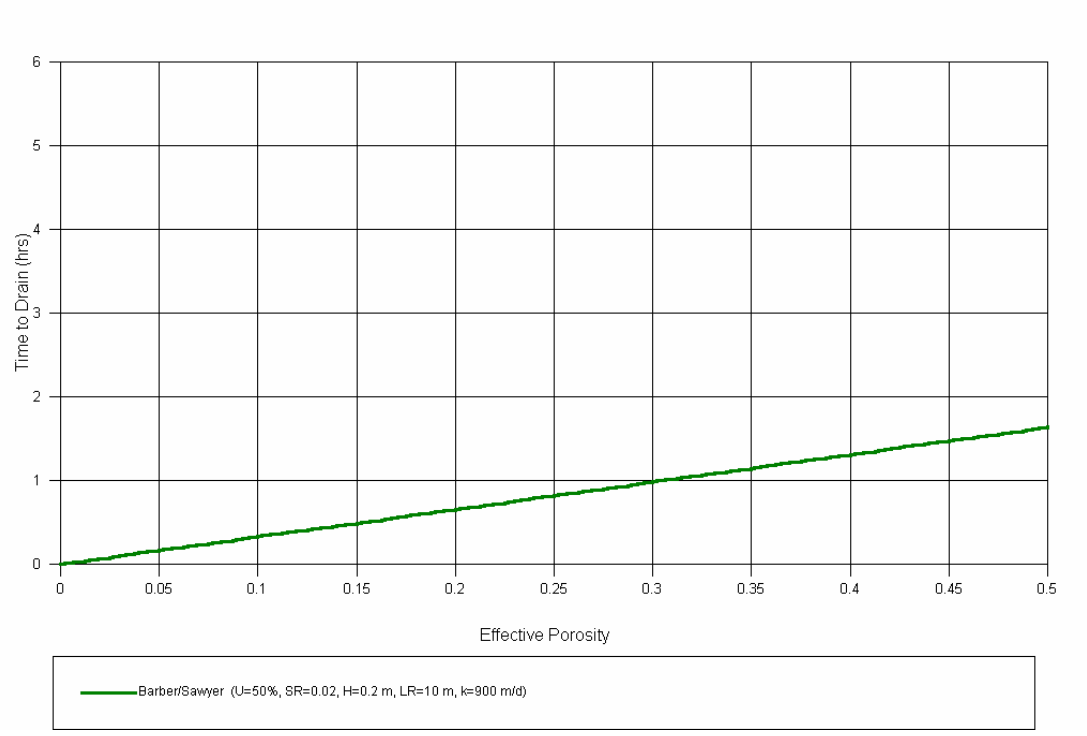


Figure 6-1. Time to drain versus effective porosity.

Permeability

In Figure 6-2, it can be seen that the effect of the coefficient of permeability is inversely proportional to the time to drain. The more permeable the material, the faster the base material will drain. Also, the effect of permeability on the time-to-drain parameter decreases with increasing permeability.

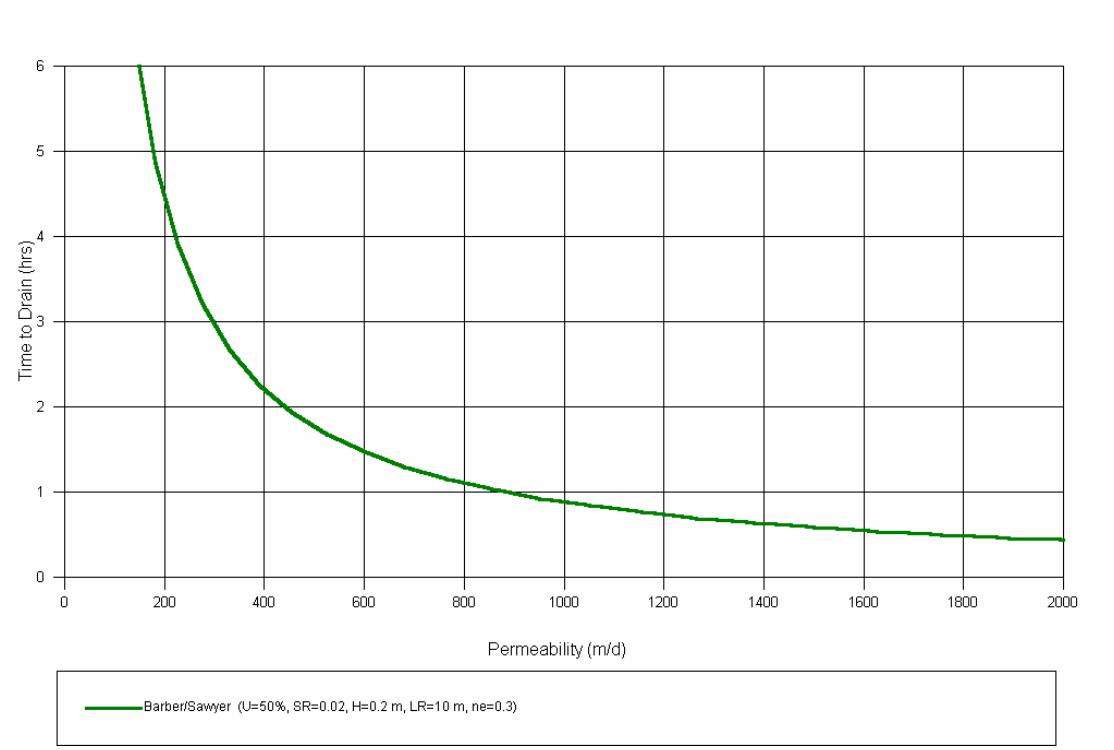


Figure 6-2. Time to drain versus coefficient of permeability.

Resultant Slope

As shown in Figure 6-3, the design procedure is sensitive to the resultant slope, with the time to drain decreasing as the slope increases. This is logical; the steeper the slope, the faster water will drain. The time to drain continues to decrease over the entire range of slopes presented. Theoretically, the base will drain even if the slope is flat; however, it is questionable practice to apply the design procedure to flat slopes.

Resultant Length

Figure 6-4 shows the effect of resultant length of drainage path on the time-to-drain parameter. The relationship is quite linear in the reasonable range of L_R (4 m and greater).

Thickness

The effect of base thickness is plotted in Figure 6-5. The time to drain is reduced by increasing the layer thickness. While there is large sensitivity to changes in H when the value is very small, the curve tends to reach a point where subsequent increases in H no longer have much effect on the time to drain.

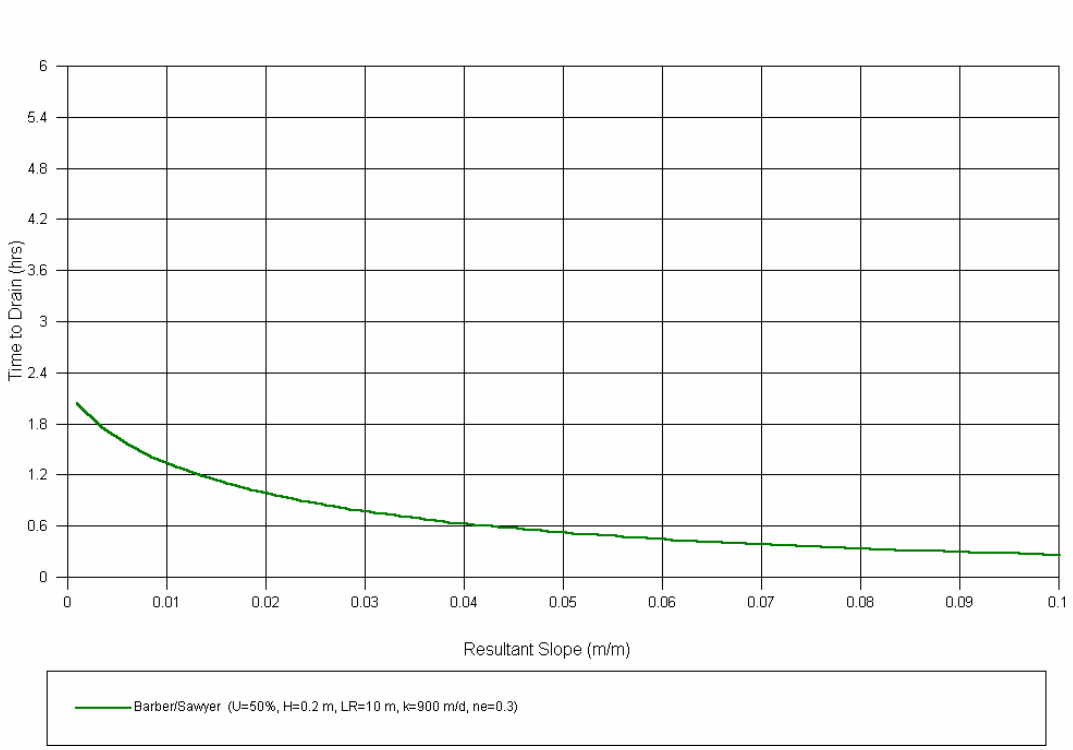


Figure 6-3. Time to drain versus resultant slope.

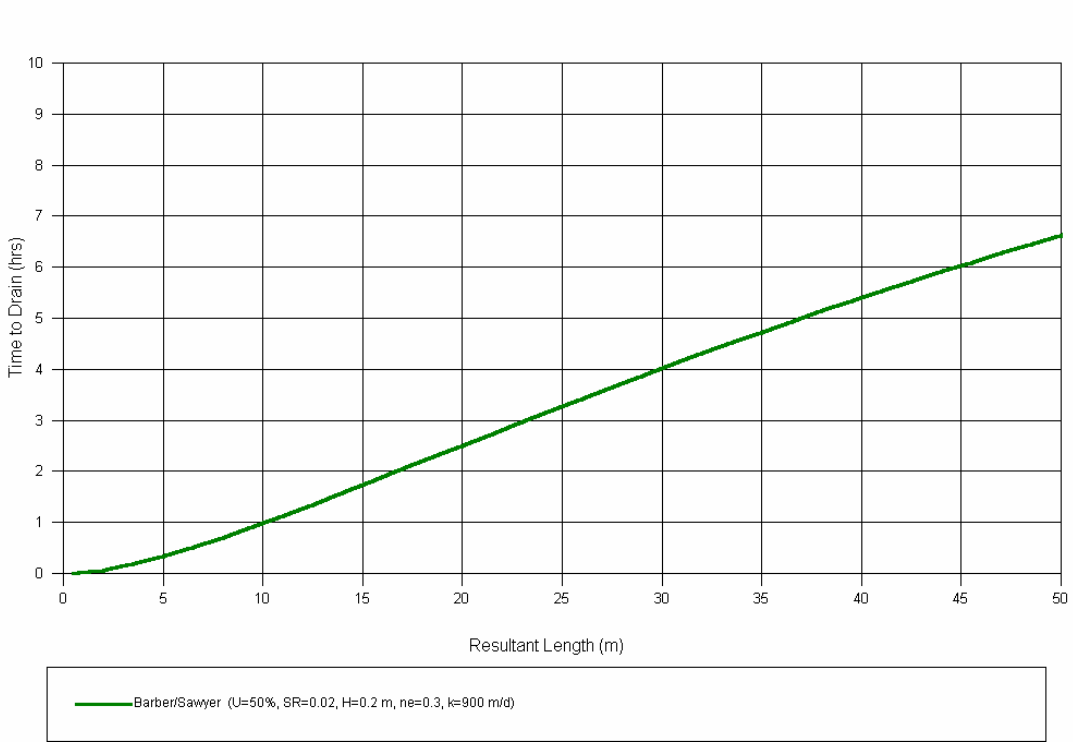


Figure 6-4. Time to drain versus resultant length of drainage path.

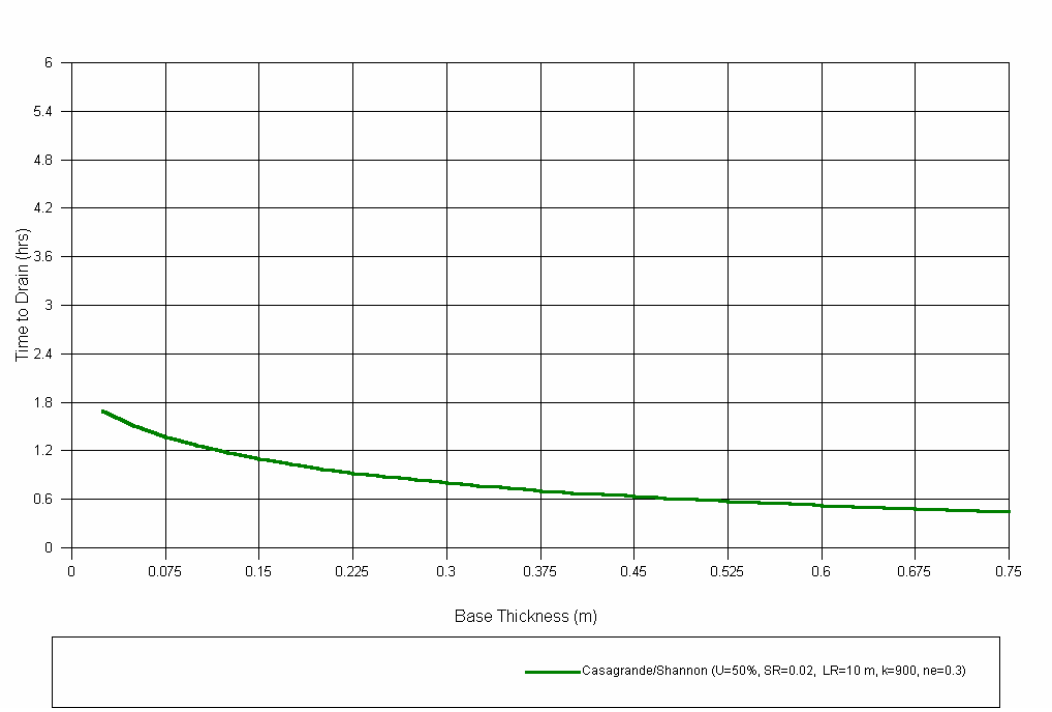


Figure 6-5. Time to drain versus thickness of permeable base.

Methodology

Figure 6-6 shows the recognizable plot of time to drain versus percent drainage for both the Casagrande/Shannon and Barber/Sawyer methods. Note that they are very similar, actually crossing each other at approximately U=55%. This is true in most cases.

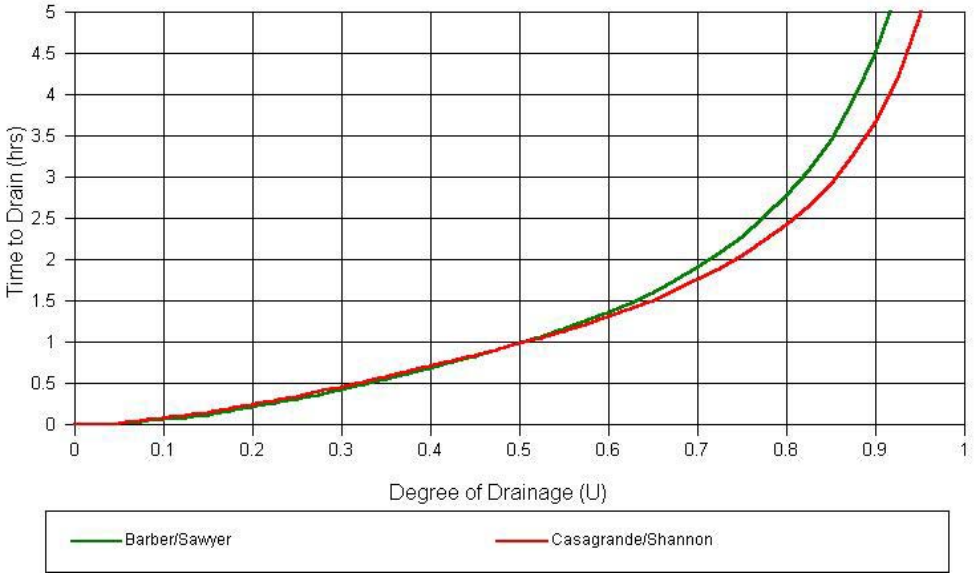


Figure 6-6. Time to drain versus degree of drainage for Barber/Sawyer and Casagrande/Shannon methods.

The major difference in the two methods is shown in Figure 6-7, which plots time to drain versus base thickness for the same data set using each method. Note the wider variation at smaller values of *H*. For most reasonable values for base thickness, however, the two methods will yield similar results.

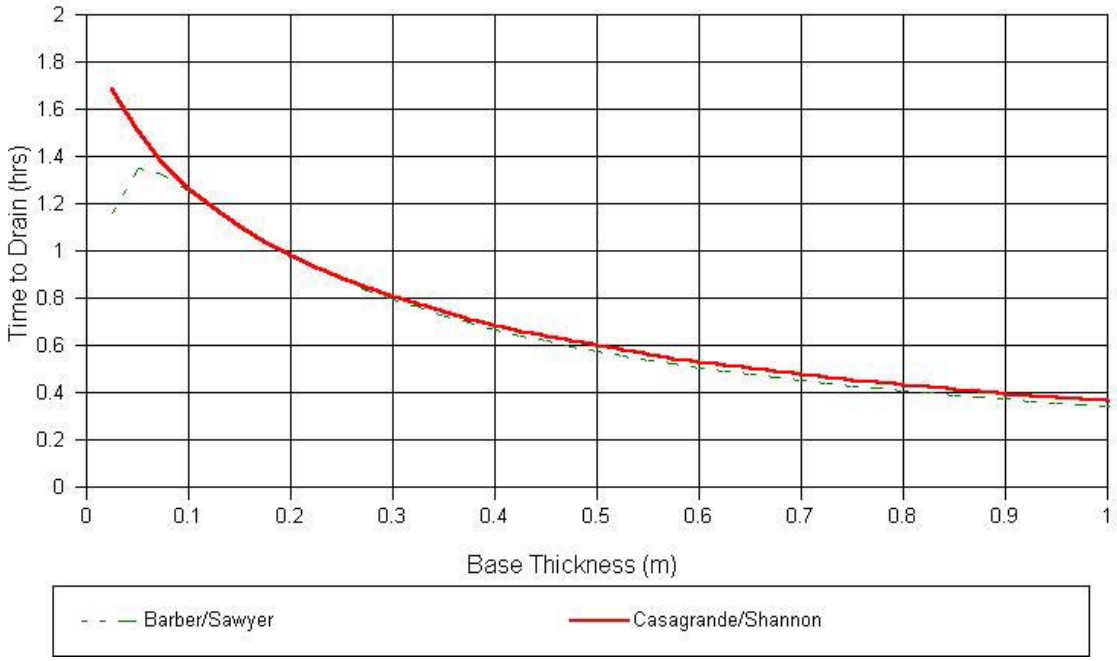


Figure 6- 7. Time to drain versus base thickness using Casagrande/Shannon and Barber/Sawyer methods.

Base Thickness

The following plots were developed using the sensitivity plotting functionality of the ***Permeable Base*** screen for the *Depth-of-Flow* method. The sensitivity plots presented here can be generated by the clicking on the graph icon after the required minimum base thickness, H_{min}, has been computed.

Permeability

In Figure 6-8, it can be seen that the effect of the coefficient of permeability is inversely proportional to the required minimum base thickness. As the permeability of the material increases, the base will drain faster and thus a thinner permeable base can be used. As the permeability increases, the required minimum base thickness decreases at a decreasing rate.

Resultant Slope

As shown in Figure 6-9, the design procedure is sensitive to slope with the required base thickness decreasing as the slope increases. As is the case for the time to drain, the flatter

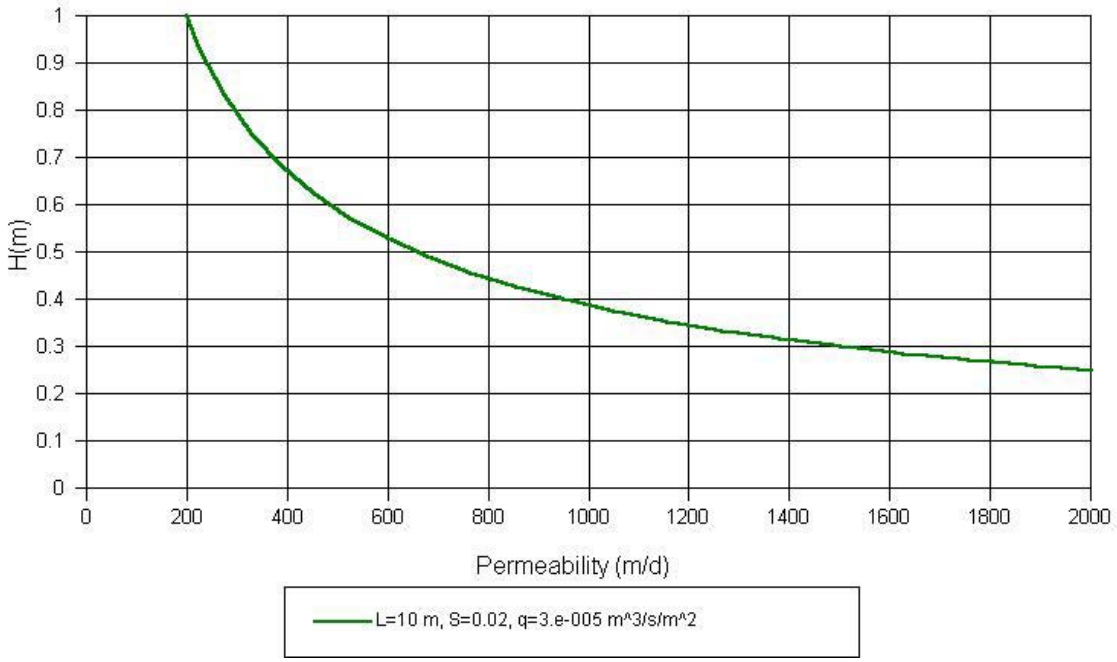


Figure 6-8. Minimum base thickness versus coefficient of permeability.

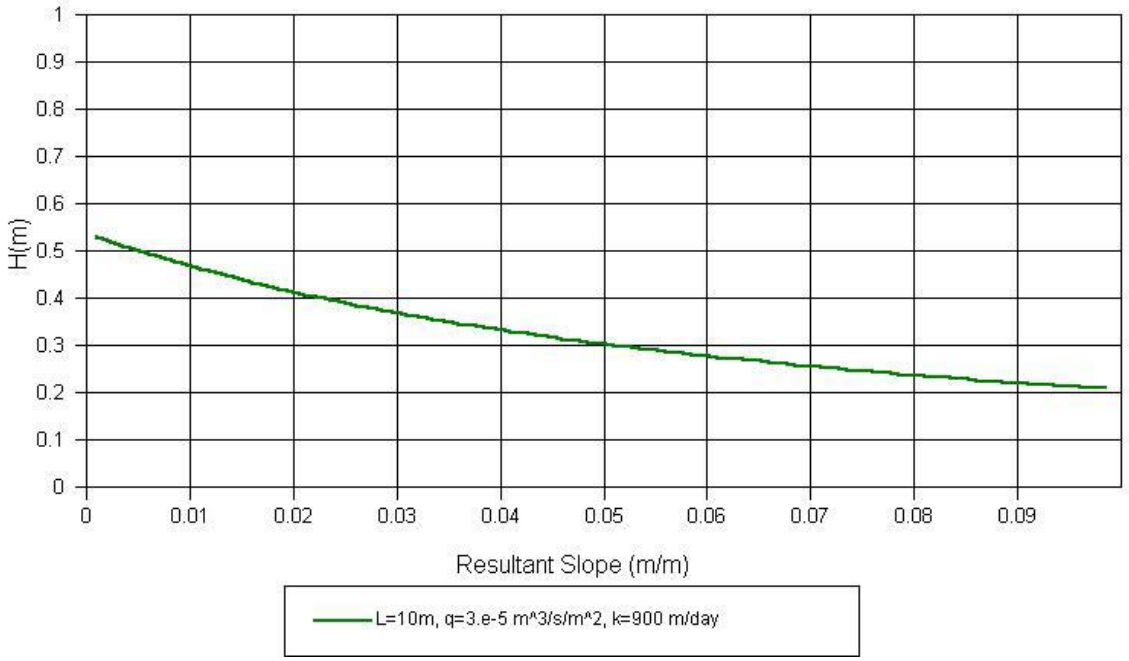


Figure 6- 9. Minimum base thickness versus resultant slope.

the slope, the slower the water will drain, and thus a thicker base is required to contain all the water. The depth required continues to drop over the entire range of slopes presented.

As was stated previously, the base will drain even if the slope is flat; however, it is questionable practice to apply the design procedure to flat slopes.

Resultant Length

Figure 6-10 shows the effect of resultant length of drainage path. The relationship is linear, meaning that if the resultant length is doubled, the required base thickness is doubled. This is logical, since twice the amount of water will need to be contained in the base course.

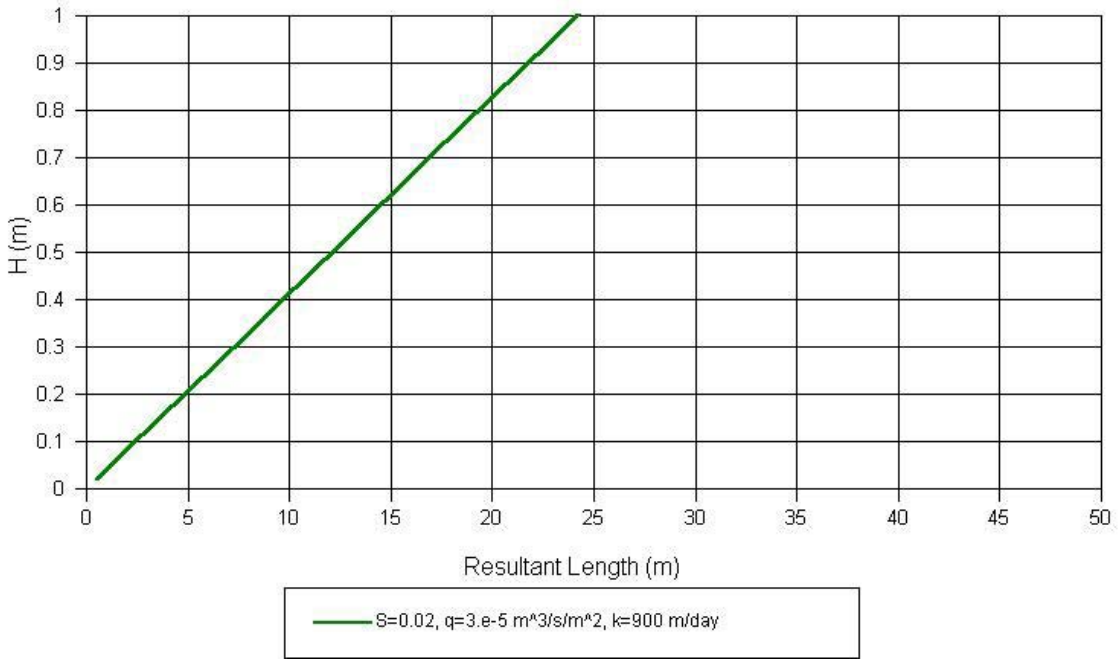


Figure 6-10. Minimum base thickness versus resultant length of drainage path.

Infiltration Rate

Figure 6-11 shows that the required base thickness is sensitive to the rate of infiltration, with the required thickness increasing as q_i increases, as would be expected. While there is large sensitivity to changes in q_i when the value is very small, the sensitivity becomes more linear after H reaches a more reasonable value (greater than 0.15 m).

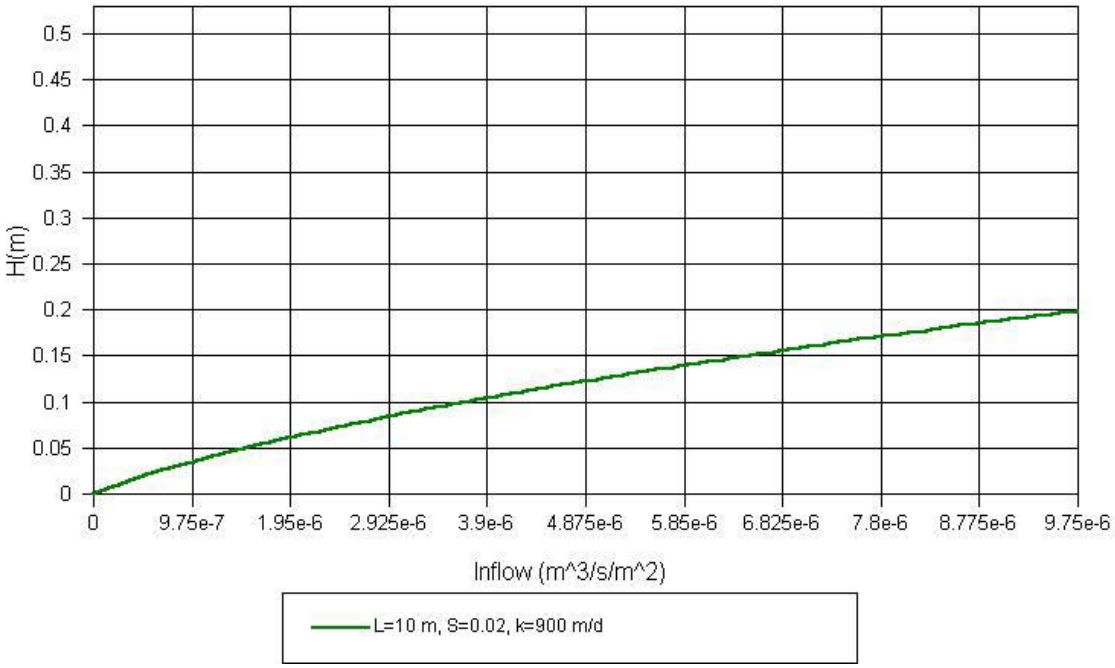


Figure 6-11. Minimum base thickness versus infiltration rate.

CHAPTER 7 - REFERENCES

AASHTO, *Guide for Design of Pavement Structures*, Volume 2, American Association of State Highway and Transportation Officials, 1986.

ASTM, *Annual Books of ASTM Standards, Road and Paving Materials: Traveled Surface Characteristics*, Vol. 04.03, American Society for Testing and Materials, 1989.

Barber, E. S. and C. L. Sawyer, "Highway Subdrainage," *Proceedings, Highway Research Board*, pp. 643-666, 1952.

Betram, G. E., "An Experimental Investigation of Protective Filters," Publication No. 267, Graduate School of Engineering, Harvard University, 1940.

Casagrande, A., and W. L. Shannon, "Base Course Drainage for Airport Pavements," *Proceedings of the American Society of Civil Engineers*, Vol. 77, pp. 792-814, 1952.

Cedergren, H. R., J. A. Arman, and K. H. O'Brien, "Development of Guidelines for the Design of Subsurface Drainage Systems for Highway Pavement Structural Sections," Report No. FHWA-RD-73-14, Federal Highway Administration, 1973.

Cedegren, H. R., *Drainage of Highway and Airfield Pavements*, John Wiley and Sons, New York, NY, 1974.

Cedergren, H., "America's Pavements: World's Longest Bathtubs," *Civil Engineering*, pp. 56-58, 1994.

Crovetti, J. A., and B. J. Dempsey, "Hydraulic Requirements of Permeable Bases," Transportation Research Record No. 1425, Transportation Research Board, 1993.

Daugherty, R. L. and A. C. Ingersoll, *Fluid Mechanics With Engineering Applications*, McGraw Hill book Co., 1954.

Dempsey, B.J., "Core Flow Capacity Requirements of Geocomposite Fin-Drain Materials Used in Pavement Subdrainage," *Transportation Research Board, Record No. 1159*, 1988.

Dempsey, B. J., "Performance of Prefabricated Geocomposite Subdrainage System in an Airport Runway," Federal Aviation Administration Report DOT/FAA/RD-93/23, 1993.

FHWA Report, "Experimental Project No. 12, Concrete Pavement Drainage Rehabilitation," 1989.

FHWA-IP-90-012, "Highway Subdrainage Design by Microcomputer: (DAMP)," 1990.

FHWA-SA-92-008, “Demonstration Project No. 87, Drainage Pavement System Participant Notebook,” 1992.

FHWA, “Geotextile Engineering Manual, Course Text,” Publication No. FHWA-HI-89-050, Federal Highway Administration, 1995.

FHWA-HI-95-038, “Geosynthetic Design and Construction Guidelines,” NHI Course No. 13213, Federal Highway Administration, April, 1998.

FHWA-HI-99-028, “Pavement Subsurface Drainage Design,” NHI Course No. 131026, Federal Highway Administration, April, 1999.

Haung, Y., *Pavement Analysis and Design*, Prentice-Hall, 1993.

Koerner, R. M. and B. Hwu, “Prefabricated Highway Edge Drains,” Transportation Research Record No. 1329, Washington, DC, 1991.

Moulton, L. K., *Groundwater, Seepage, and Drainage: a Textbook on Groundwater and Seepage Theory and its Application*, 1979.

Moulton, L. K., “Highway Subsurface Design,” Report No. FHWA-TS-80-224, Federal Highway Administration, 1980.

NCHRP Report 367, “Long-term Performance of Geosynthetics in Drainage Applications,” 1994.

Ridgeway, H. H., “Infiltration of Water Through the Pavement Surface,” *Transportation Research Record 616*, Transportation Research Board, pp. 98-100, 1976.

U.S. Army Corps of Engineers, "Drainage and Erosion Control-Subsurface Drainage Facilities for Airfields," Part XIII, Chapter 2, *Engineering Manual*, Military Construction, 1955.

RELATED REFERENCES

Transportation Research Record 1425, “Performance Evaluation of Retrofit Edge Drain Projects,” 1991.

Transportation Research Record 1425, “Comparison of Compaction Methods in Narrow Subsurface Drainage Trenches,” 1991.

Rixner, J. J. and S. R. Kraemer, “Prefabricated Vertical Drains,” FHWA/RD-86.168, Federal Highway Administration, October, 1986.

Grogan, William P., “User’s Guide: Subsurface Drainage For Military Pavements,” FEAP-UG-92/09, Facilities Engineering Applications Program, Ft. Belvoir, VA, 1992. “Techniques For Pavement Rehabilitation,” NHI Course No. 13108, Federal Highway Administration, October, 1987.

Moulton, Lyle K., “Prediction of the Depth of Frost Penetration - A Literature Review,” March, 1969.

“Geocomposite Pavement Drain Systems 1991,” Transportation Research Record No. 1329, 1991.

Transportation Research Record 1434, “Subsurface Drainage, Soil-Fluid Interface Phenomena, and Management of Unpaved Surfaces,” 1994.

Moulton, Lyle K. and Roger K. Seals, “Determination of the In-Situ Permeability of Base and Subbase Courses,” FHWA-RD-79-88, Federal Highway Administration, May, 1979.

Christopher, Barry R. and Holtz, Robert D., “Geotextile Engineering Manual,” Federal Highway Administration, Mar, 1985.

Department of Army, Engineering Technical Letter, “Permeable bases For Pavements,” ETL 1110-3-435, May, 1992.

Christopher, B. R., and R. D. Holtz, “Geotextile Engineering Manual,” DTFH 61-83-C00150, Federal Highway Administration, Washington, DC, 1985.

EM 1110-2-1906, *Laboratory Soils Testing*, Appendix VII, Permeability Tests.

National Highway Institute, NHI Course No. 13108, “Techniques For Pavement Rehabilitation - A Training Course,” FHWA-HI-90-022, October, 1987.

Baumgardner, R.H. and Mathis, D.M., "Concrete Pavement Drainage Rehabilitation: State of the Practice Report," U.S. Department of Transportation, Experimental Project No. 12, April 1989.

Dempsey, B.J., Carpenter, S.H. and Darter, M.I., "Improving Subdrainage and Shoulders of Existing Pavements," Final Report FHWA/RD-81/078, Federal Highway Administration, 1982.

Dempsey, B.J., "Performance of Prefabricated Geocomposite Subdrain System in an Airport Runway," Federal Aviation Administration Report DOT/FAA/RD-93/23, October 1993.

Federal Highway Administration, "Technical Guide Paper on Subsurface Pavement Design," Technical Paper 90-01, Office of Engineering, Pavement Design, October 1990.

Hall, Jim, Barker, Walter, and Wyatt, Tim, "Subsurface Drainage Design for Highway Pavements: A Literature Review," Applied Research Associates, Vicksburg, MS, June 1995.

Koerner, R.M., Koerner, G.R., Fahim, A.K., and Wilson-Rahmy, R.F., "Long-Term Performance of Geosynthetics in Drainage Applications," Report 367, National Cooperative Highway Research Program, Geosynthetic Research Institute, Drexel University, 1994.

Moulton, L.K., "Problem No. 1 - Steady State Unconfined Flow Above A Sloping Impervious Boundary - With Infiltration," Handwritten Notes, June 10, 1974.

U.S. Department of Transportation, "Drainable Pavement Systems: Participant Notebook, Demonstration Project 87." Publication No. FHWA-SA-92-008, Federal Highway Administration, March 1992.

Baumgardner, R. H. and D. M. Mathis, “Experimental Project No. 12, Concrete Pavement Drainage Rehabilitation, State of the Practice,” Federal Highway Administration, Pavement Division and Demonstration Projects Division, Washington, DC, 1989

Crovetti, J. A., and B. J. Dempsey, “Pavement Subbases,” University of Illinois Report UILU-ENG-91-2005, 1991.

Federal Highway Administration, “Subsurface Pavement Drainage”, FHWA Technical Paper 90-01, 1990.

Forsyth, R. A., G. K. Wells, and J. H.Woodstrom, “Economic Impact of Pavement Subsurface Drainage,” Transportation Research Record 1121, pp. 77-85, 1987.

Taylor, Donald W., Soil Mechanics, John Wiley and Sons, Inc., 1965.

AASHTO, Guide for Design of Pavement Structures, American Association of State Highway and Transportation Officials, 1986.

Ridgeway, H. H., “Pavement Subsurface Drainage System, Synthesis of Highway Practice 96,” Transportation Research Board, 1982.

Army TM 5-820-2 (Air Force AFJMAN 32-1016), Technical Manual-Subsurface Drainage For Pavements (Draft), 1994.

Baumgardner, Robert H., “Overview of Pavement Drainage Systems for Concrete Pavements,” Road Base Seminar, Reston, Virginia, September, 1994.

Reed, Christine M., “Impact of Open-Graded Permeable bases on the Construction of Concrete Pavements in Illinois,” Paper No. 950316, Transportation Research Board, 74th Annual Meeting, January, 1995.

Dempsey, B. J., S. H. Carpenter, and M. I. Darter, "Improving Subdrainage and Shoulders of Existing Pavements." Final Report FHWA/RD-81/078. Federal Highway Administration, 1982.

APPENDIX A – STANDARDIZED NOMENCLATURE

ROADWAY GEOMETRY

Symbol	Item	English	SI
S	Longitudinal slope	ft/ft	m/m
S_X	Cross slope	ft/ft	m/m
S_R	Resultant slope	ft/ft	m/m
L_R	Resultant length of flow through base	ft	m
W	Width of permeable base	ft	m
A	Angle between roadway cross slope and resultant slope		

PAVEMENT INFILTRATION

q_i	Rate of pavement infiltration	$ft^3/d/ft^2$	$m^3/s/m^2$
C	Infiltration ratio		
R	Rainfall rate	in/hr	mm/hr
I_C	Crack infiltration rate	$ft^3/d/ft$	$m^3/s/m$
N_C	Number of longitudinal joints or cracks		
W_C	Length of contributing transverse joints or cracks	ft	m
C_S	Spacing of contributing transverse joints or cracks	ft	m
W	Width of permeable base	ft	m
k_p	Pavement permeability	ft/day	m/sec
N	Number of contributing traffic lanes		

PERMEABLE BASE DISCHARGE

q_d or Q_p	Permeable base discharge rate	$ft^3/d/ft$	$m^3/s/m$

OUTLET SPACING

Q	Pipe flow	ft^3/day	m^3/s
L	Longitudinal length of contributing roadway	ft	m
W	Width of contributing roadway	ft	m

SOILS

Symbol	Item	English	SI
C_u	Coefficient of Uniformity		
D_{10}	Effective size		mm
D_{XX}	Soil particle size		mm
γ_d	Dry unit weight of material	lbs/ft^3	kN/m^3
	Unit weight of water	62.4 lbs/ft^3	9.81 kNm^3
G_{SB}	Bulk specific gravity		
N or n	Porosity		
N_e or n_e	Effective porosity		
V_V	Volume of voids		
V_W	Volume of water		
V_T	Total volume		
WL	Water loss		
U	Percent drained		
S	Percent saturation		

DARCY'S LAW

Q	Flow capacity of base	cu ft/day	m^3/s
k	Coefficient of permeability	ft/day	m/d
i	Hydraulic gradient	ft/ft	m/m
A	Cross sectional area of flow	sq ft	m^2
H	Thickness of permeable base	ft	mm
V_S	Seepage velocity	ft/day	m/s
V	Discharge velocity	ft/day	m/s

TIME TO DRAIN

t	Time to drain	hrs	hrs
T	Time factor		
m	"m" factor		
S_1	Slope factor		

GEOTEXTILE

O_{95}	Opening size of geotextile in which 95% of the the openings are smaller		mm
O_{XX}	Opening size of geotextile		mm

PIPE FLOW

Symbol	Item	English	SI
Q	Pipe capacity	cu ft/day	m^3/s or l/s
D	Pipe diameter	in	mm
S	Slope	ft/ft	m/m
n	Manning's coefficient		
A	Flow area	sq ft	m^2
P	Wetted perimeter	ft	m
R	Hydraulic radius	ft	m
K	Conveyance		
V	Velocity	ft/sec	m/s