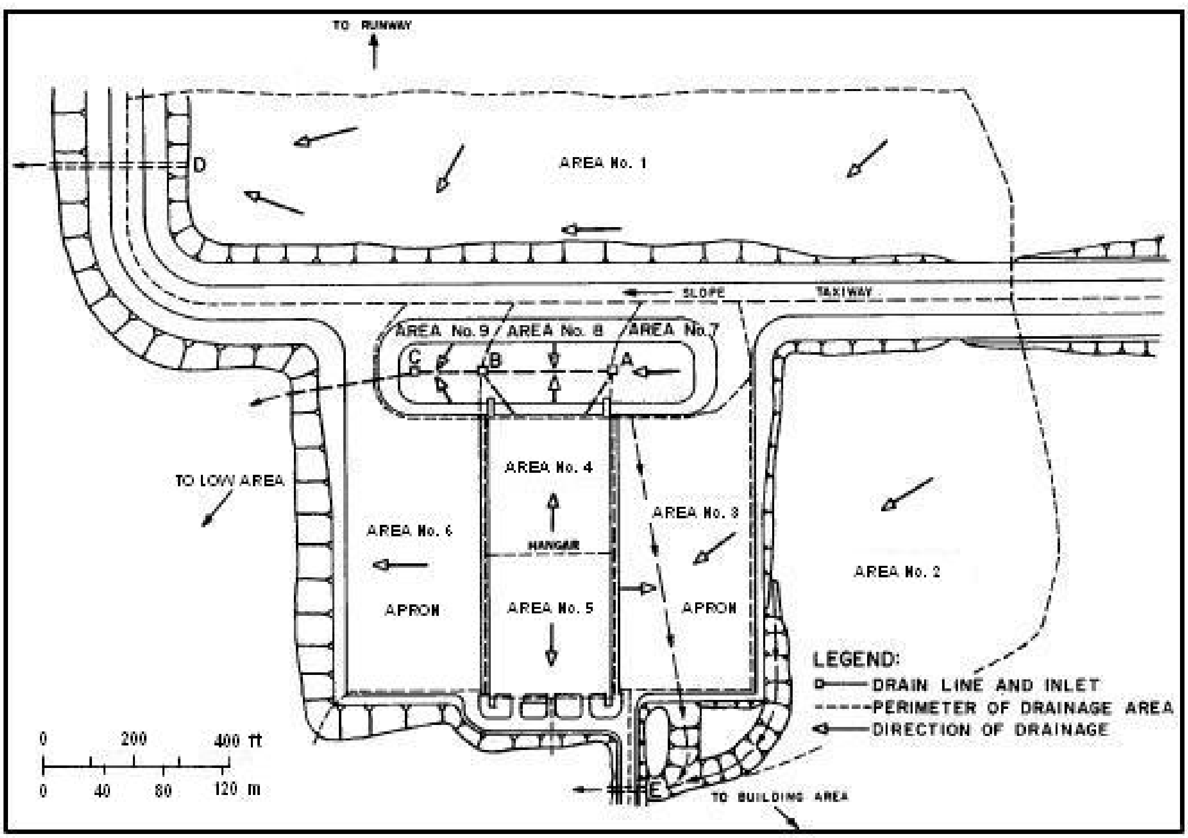
APPENDIX C

DESIGN EXAMPLES

C-1 ARCTIC AND SUBARCTIC DRAINAGE

C-1.1 **Preliminary Layout**. Prepare a map (scale 1 in. = 200 ft or larger) showing the outline of runways, taxiways, parking aprons, paved shoulders, facility areas, and roads. Superimpose on this network 1-ft-interval contours that will show the finished airfield or heliport. Insure that grades conform with current safety criteria as set forth in TM 5-803-4 for Army facilities of AFM 88-6, Chapter 1 for Air Force facilities unless waiver approvals are secured. If the airfield is also to be used for civil aviation, coordinate the site selection with the District Airport Engineer of the Federal Aviation Administration and the state aviation agency. Indicate locations of test pits, soil borings, and probings, and designate significant items clearly.

Figure C-1. Drainage Problem: Airfield in Subarctic Region-Hangar, Taxiway and Apron



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C-1.2 **Profiles**. Profiles of all runways, taxiways, helipads and parking areas, so that elevations and controlling grades can be ascertained for any point.

C-1.3 **Drain Outlets**. With general consideration of the limiting grade elevations and feasible channels for the disposal of storm runoff and snow melt, select locations that are considered most suitable for outlets of drains serving various portions of the field. With this information, select a tentative layout for primary storm drains. In general, the most economical and efficient design is obtained by maximum use of open ditches in preference to underground drains and by maintaining the steepest hydraulic gradient feasible in the main trunk drain, while making laterals on each side approximately equal in length, insofar as practicable.

C-1.4 **Cross-sectional Profiles of Intermediate Areas**. Assume lines for cross-sectional profiles of intermediate areas, plot data showing controlling elevation, and indicate the tentatively selected locations for inlets by means of vertical lines. In some cases, the projection of runways, taxiways, helipads, or aprons should be shown on the profiles, to facilitate a comparison of elevations of intermediate areas with those of paved areas. Generally, one cross-sectional profile should follow each line of the underground storm drain system and others should pass through each of the inlets at approximately right angles to paved runways, taxiways, helipads or aprons.

C-1.5 **Correlation of Controlling Elevations and Limiting Grades**. Beginning at points corresponding to controlling elevations, such as the crown or edges of a runway, sketch in the ground profile from the given points to the respective drain inlets, making the grades conform to limiting slopes for the areas involved. Review the tentative grading and inlet elevations and adjust the locations of drain inlets and grading details as necessary to obtain the most satisfactory general plan.

C-1.6 **Determination of Drainage Area**. Using the completed grading plan, sketch the boundaries of drainage areas tributary to the respective drain inlets and compute the area of paved and unpaved areas tributary to the respective inlets.

C-1.7 **Ponding Basins**. Avoid the use of ponding basins in arctic and subarctic areas.

C-1.8 **Average Retardance Coefficient**. Assign values of n to various turfed, bare, frozen ground, or paved subareas as explained in Section 2-7, and compute average roughness factors for overland and channel flow. See columns 6 and 20, and note 2 in Table C-1.

C-1.9 **Average Slope**. Estimate the average slope of overland and channel flow conditions for each inlet drainage area using the data indicated on the grading plan.

C-1.10 **Effective Length**. From the grading plan determine the effective length of flow, giving due consideration to the occurrence of overland and channelized flow. By use of Figure 2-5, convert the measured lengths of flow to equivalent lengths of flow in 10-ft increments which correspond to S = 1.0 percent and n = 0.40. For actual lengths

Table C-1

Table C-2

exceeding 600 ft, divide by any convenient factor and determine corrected length therefore, then multiply by this factor to find the corrected length for the full distance. For example, if actual length is 700 ft, determine corrected length for 350 ft and multiply by 2. See also columns 8-10 of Table C-1.

C-1.11 **Project Design Storm**. By use of Figure 2-1 and the known geographic location of the airfield or heliport, select a project design storm of the specified frequency of occurrence.

C-1.12 **Snowmelt**. Add an amount of 0.05 to 0.1 in 1 hour for snowmelt to the project design storm (see C-1.11 above).

C-1.13 **Infiltration**. If the airfield or heliport site is located in the Arctic, assume that the infiltration rate is zero. If in the Subarctic, determine average infiltration rates from local studies but not higher than 0.3 in./hr.

C-1.14 **Standard Supply Curves**. Standard supply curves for areas with zero infiltration loss will be the same as the standard rainfall plus snowmelt curves (Figure 2-3). Where infiltration losses occur, the standard supply curve number corresponding to a given standard rainfall plus snowmelt curve number is computed by subtracting the estimated 1-hour infiltration value from the 1-hour rainfall plus snowmelt quantity. See columns 11-14 of Table C-1.

C-1.15 **Weighted Standard Supply Curve**. Determine a weighted standard supply curve for the composite drainage area proportional to the standard supply curves for the various subareas. See column 15 of Table C-1.

C-1.16 **Determination of Drain-Inlet Capacities**. With reference to Figures 2-7 through 2-12, select the two graphs with supply curve numbers closest to the weighted standard supply curve determined above. The following procedure is carried through on both graphs and interpolated for the weighted standard supply curve. The critical duration of supply t_c (col. 16, Table C-1) and the maximum rate of runoff q_d (col. 17) for the individual inlet drainage area can be read directly from the graph for the given value of effective length. Value of t_c should not be less than the minimum values of 10 minutes for paved for bare areas and 20 minutes for turfed areas (Section 2-7). In order for the maximum rate of flow to be attained at a given point in a drainage system during a supply of uniform intensity, the storm must last long enough to produce a maximum rate of inflow into each upstream drain inlet and to permit the inflow to travel through the drain from the “critical inlet” to the given point. The duration of supply necessary for this purpose is referred to herein as t'_c and is given approximately by the equation

$$t'_c - t_c + t_d \qquad \text{(eq. C-1)}$$

in which t_c is the duration of supply that would provide the maximum design storm runoff from the area tributary to the critical drain inlet and t_d is the time required for water to flow from the critical drain inlet to the point under consideration. The critical drain inlet to the point under consideration. The critical inlet can normally be assumed to be the inlet located the greatest distance upstream from the given point. To simplify the determination of drain-inlet capacities, the computed values of t'_c can be rounded off to the nearest 5 minutes as shown in column 19 of Table C-1. The procedure for computing values of t'_c is described in Chapter 2. Inspection of Figures 2-7 through 2-12 will show that for large values of effective length and low values of supply curve, the maximum rate of runoff is approximately constant after a duration of supply equal to t_c. Under these conditions, it will facilitate the design computations to use the constant value q_d for t_c duration of supply for all durations of supply in excess of t_c.

C-1.17 **Computation of Pipe Sizes and Cover**. The size and gradient of storm drain required to discharge storm runoff may be determined by using Mannings' formula or the charts provided in Chapter 3. In any case, calculated capacities should be liberal to provide a safety factor against high flows during spring thaw and possible clogging due to icing (Section 2-8). It is recommended that minimum pipe diameter be at least 18 in. and preferably larger, even where the calculated runoff may require a smaller size. In selecting proposed inlet elevations and slope of pipelines, minimum cover required for the various pipe materials and strengths should be in accord with Chapter 4. At each site, prior to design, the suitability of embedment depths should be confirmed by field investigations.

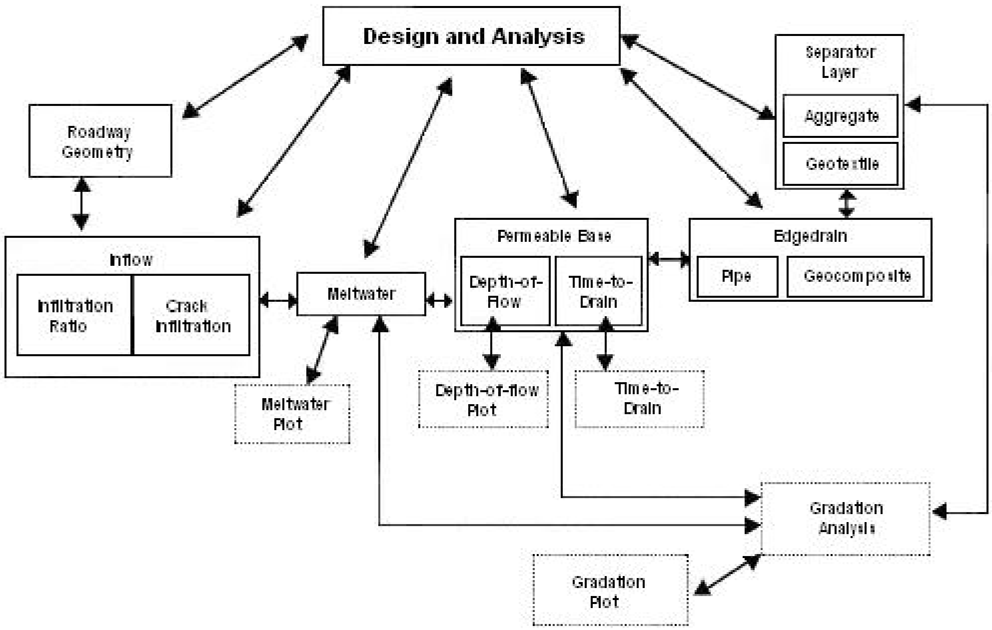
C-1.18 **Determination of Ditch Sizes**. The ditch should be large enough to accommodate the storm runoff with liberal allowances for blockage or flow retardation due to formation of icing or accumulation of debris. The shape of ditches depends on airfield or heliport lateral clearance safety criteria, snow removal and storage practices, susceptibility to icing, erosion and debris control, and local environmental conditions.

C-2 SUBSURFACE DRAINAGE DESIGN USING DRIP

C-2.1 **Introduction**. The microcomputer program *Drainage Requirements in Pavements (DRIP)*, developed under an FHWA contract (Wyatt et al. 1998a), is designed to assist engineers in designing subsurface drainage systems for highway pavements. The modular framework of DRIP is illustrated in Figure C-2. Each of these modules can be accessed either individually to perform a specific design task or sequentially as part of an overall design process. The Design and Analysis node is central to the program and controls the flow of information between modules. Not all of the modules presented in Figure C-2 is required to perform the design of the drainage systems recommended in this manual. Therefore, only the relevant modules and their design windows are presented in this example.

C-2.2 **System Requirements**. DRIP was developed to run under Windows 3.1. The program has been fully tested and verified to run error-free under Windows 95 and NT. Other than the Windows operating system, DRIP does not have any special requirements. However, a 16-color display with small fonts and at least 800×600 resolution is recommended because of the graphical nature of the program.

Figure C-2. Modular Framework of the DRIP Program



C-2.3 **Getting Started**. The opening screen of DRIP is shown in Figure C-3. From this screen you can either start a DRIP session by clicking on the *Begin* button or quit the program by clicking on the *Close* button.

C-2.4 **Design and Analysis Window**. The *Design and Analysis* window is shown in Figure C-4. This window is the central node of the program. The items listed on the left side of the window—*Roadway Geometry, Inflow, Permeable Base, Separator,* and *Edgedrain*—each correspond to a specific design module. The DRIP design modules may be accessed either by clicking on the respective icons or using the *Go To* list box. Prior to accessing the design modules, however, you need to suitably configure the design options by clicking on the check boxes located on the left side of the window.

C-2.4.1 **Permeable base**: Select *Time-to-Drain Method* for the design of permeable base. This is the analysis method used in the guide.

C-2.4.2 **Separator**: Check *Use Separator Layer* to evaluate separator layer materials.

C-2.4.3 **Edgedrain**: Select *Pipe* edgedrain. For airfield applications, the guide recommends pipe edgedrains.

Figure C-3. The Opening Screen of DRIP

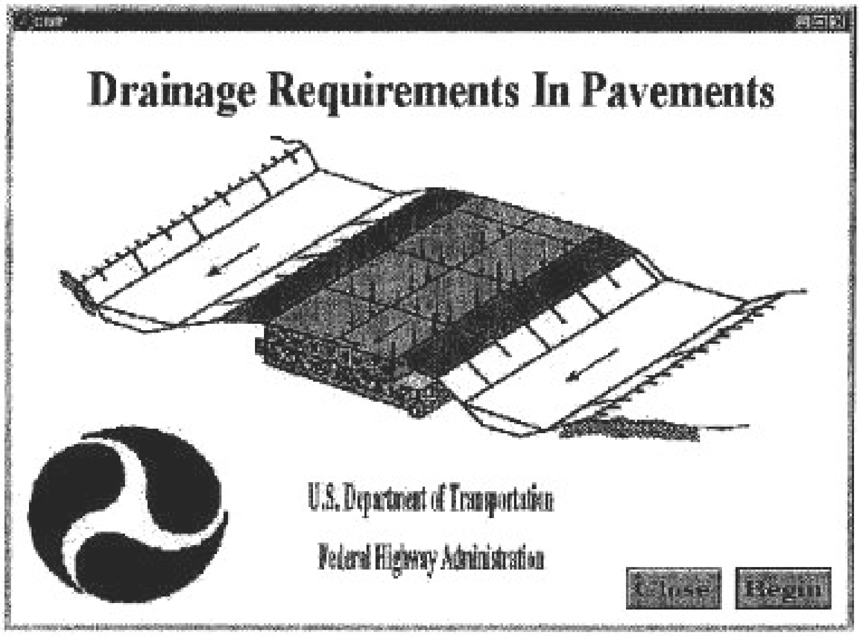
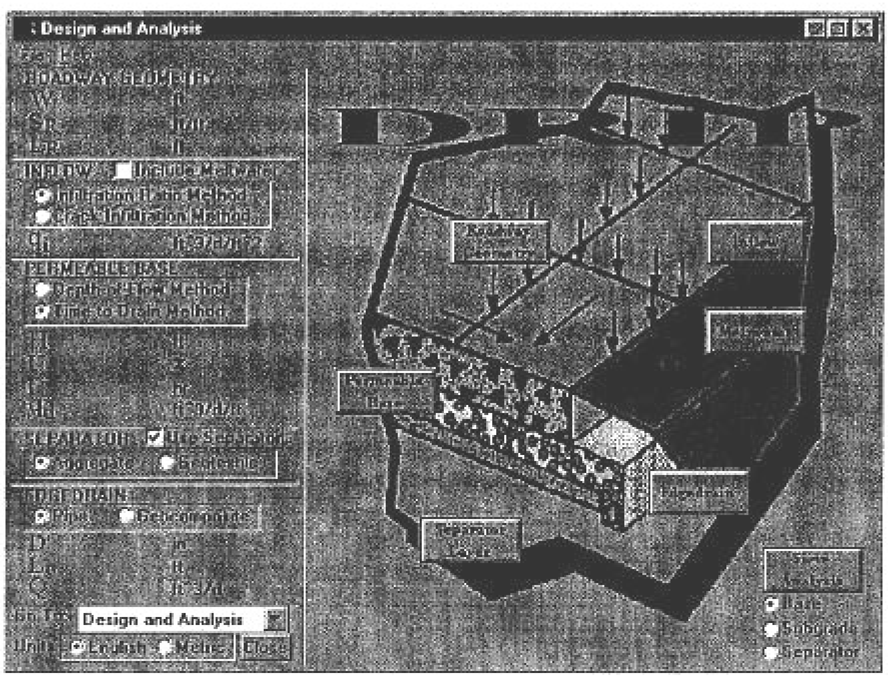


Figure C-4. The Design and Analysis Window



C-2.4.4 **Units**: Select the desired unit system. You have the option to set the unit system for each module, but the unit system selected on the *Design and Analysis* window will be the default.

C-2.5 **Drip Modules**. In this section, the DRIP modules that are relevant to hydraulic design of airfield pavements are explained in detail. Example problems are included to demonstrate the usage of DRIP. DRIP uses the following general convention:

C-2.5.1 When several design modules are executed under the same DRIP session, relevant data are automatically shared between modules.

C-2.5.2 Any window can be closed using the *Close* button at the bottom of the window or by selecting *Exit* from the File menu.

C-2.5.3 Every design window displays a number of inputs and outputs. Also displayed are the equations that related the inputs to the respective outputs. Once all the input data values are for a given equation are entered, a calculator icon next to the output is activated, indicating that the particular output is ready to be computed. Click on the calculator icon to process the input data.

C-2.5.4 If any of the DRIP-calculated fields are entered manually, DRIP issues a warning message. For example, the resultant slope and drainage path is needed for time-to-drain calculation in the *Permeable Base* module. DRIP includes *Roadway Geometry* module for calculating these values. Therefore, DRIP will issue a warning message if these values are entered manually.

C-2.5.1 **Sequence of operation**. DRIP is modular and the sequence of execution of the modules need not follow any particular order. However, the following sequence is recommended:

C-2.5.1.1 **Roadway geometry**: Use the module to determine the resultant slope and drainage path. To access *Roadway Geometry* module click on the *Roadway Geometry* button or select *Roadway Geometry* from the *Go To* drop-down menu.

C-2.5.1.2 **Sieve analysis**: This module is used to calculate the gradation parameters required in various modules. To access this module, click on the *Sieve Analysis* button or select *Sieve Analysis* from the *Go To* drop-down menu.

C-2.5.1.3 **Permeable base**: Perform hydraulic design of permeable base using the time-to-drain method. Choose *Time-to-Drain Method* of analysis under *Permeable Base*, and click on the *Permeable Base* button on the *Design and Analysis* window to access this module. This window requires inputs from the *Sieve Analysis* module for permeable base gradation.

C-2.5.1.4 **Edgedrain**: Perform pipe edgedrain design using the *Edgedrain* module.

C-2-5.1.5 **Separator layer**: Use this module to perform separator layer design. There are two selections for separator layers. Based on the project requirements, the appropriate layer type must be chosen. This module also requires inputs from the *Sieve Analysis* module for subgrade and separator layer gradations (in the case of aggregate separators).

As the design progresses from one step to another, the inputs and outputs of a given module are made available to all modules that are subsequently invoked. However, if a step is inadvertently missed, you need to go back to the module in question and perform the necessary calculations.

C-2.5.2 **Roadway geometry calculations**: The resultant slope, S_R, and the resultant length, L_R, of the flowpath are needed for time-to-drain calculations. The resultant slope is the resultant of the longitudinal slope, S, and cross-slope, S_x, of the pavement; the resultant length is the distance over which water flows within the pavement structure in the direction of the resultant slope. These quantities can be computed using the *Roadway Geometry* module in DRIP.

C-2.5.2.1 **Roadway geometry inputs**

a. Roadway cross-section (crowned or superelevated).

b. Lane and shoulder widths.

c. Longitudinal grade of roadway (S).

d. Cross-slope of roadway (S_x).

C-2.5.2.2 **Roadway geometry outputs**

a. Resultant slope (S_R).

b. Resultant drainage path (L_R).

<u>Example C-2A: Roadway Geometry Design</u>

Determine the resultant slope, S_R, and the resultant length, L_R, for the following crowned runway section:

Cross-slope, S_x:	0.015 ft/ft
Longitudinal slope, S:	0.0015 ft/ft
Pavement width:	150 ft
Shoulder width:	0 ft

Solution

1. Click on *Roadway Geometry* button from the *Design and Analysis* window to access *Roadway Geometry* module.

2. Enter the lane width, b, and the shoulder width, c. The shoulder width, c, is the distance from the pavement edge to the edgedrain. Typically, edgedrain is located at least or 1 or 2 ft away from the pavement edge. Assume c = 2 ft.

3. Choose *Geometry A*.

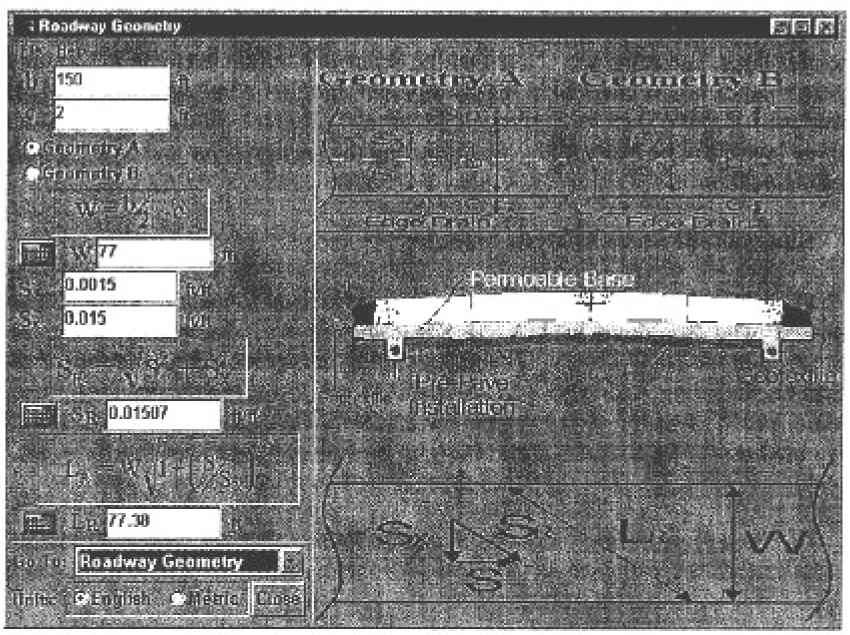
4. The calculator icon next to "W" should now turn blue. Click on the calculator icon to compute the width of the drainage path, "W."

5. Enter values of the slopes S and S_x.

6. The calculator icons next to the quantities S_R and L_R should now turn blue, indicating that the solutions are ready to be computed. Compute L_R and S_R by clicking on the respective icons.

Figure C-5 shows the *Roadway Geometry* design window with the inputs and outputs for this example. The resultant slope is 0.01507 ft/ft, and the drainage path is 77.38 ft.

Figure C-5. Roadway Geometry Design Window



C-2.5.3 **Sieve analysis**. The *Sieve Analysis* module is used to determine gradation parameters for base, separator layer, and subgrade. Three selection buttons are provided under the *Sieve Analysis* button on the *Design and Analysis* window for the selection of the analysis for base, separator layer, and subgrade. Note that the *Separator* button becomes active only if the *Use Separator* check box is checked in the *Design and Analysis* window. The VASDAM (Visual Analysis of Sieve Data for Aggregate Materials) program window corresponding to each of these three layers can be accessed by first selecting the desired layer and then clicking on the *Sieve Analysis* button.

C-2.5.3.1 **Input to the sieve analysis module**

a. Material Name: The name supplied here is used to identify the gradation data being analyzed. The drop-down list box attached to this input can be used to retrieve any gradations saved in the DRIP library. The default DRIP library includes a number of permeable base gradations, including AASHTO # 57, AASHTO # 67, Iowa, Minnesota, New Jersey, Pennsylvania, and Wisconsin. You can save the gradation data that you entered from a DRIP session by clicking on *File* from the *Sieve Analysis* module and then selecting *Save As*. To retrieve previously saved gradation data, click on *File*, then select *Open*.

b. Sieve Data: Select either the *Range* or *Value* selection button. When the *Range* is specified, the gradation parameters are computed for the midpoint of the gradation band.

c. Sieve Number: A sieve size can be entered with the help of the drop-down menu attached to this input. The drop-down menu is activated by clicking on the *Sieve Number* input field. Click on the desired sieve to make the selection.

d. %-Passing: A numeric value indicating the percent of material passing the current sieve number. Enter the appropriate values and click on *Add to Table* button to add the information to the table. To modify the previously entered %-Passing data, select the row to be modified, enter the appropriate values, and click on *Add to Table* button to update the table.

e. Unit Wt: Laboratory determined unit weight of the base material. Guidance for determining unit weight can be accessed by clicking on the *?* button located to the left of this input.

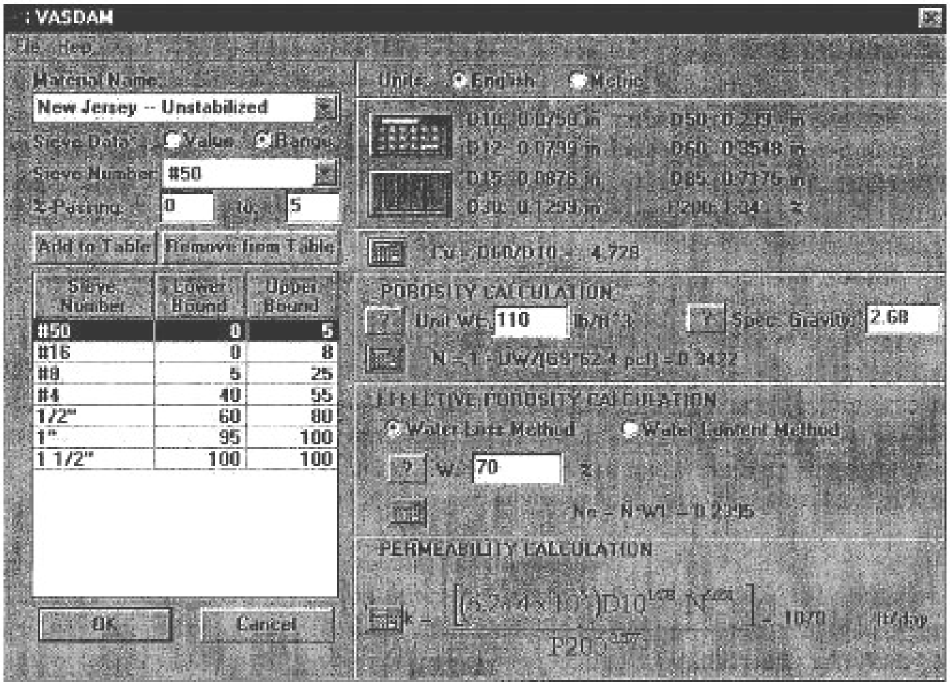
f. Spec. Gravity: Laboratory-determined specific gravity of the base material. Guidance for determining specific gravity can be accessed by clicking the *?* button located to the left of this input.

g. Effective Porosity Calculation: Effective porosity can be calculated using either the *Water Loss Method* or the *Water Content Method*. Select the desired method by clicking on the appropriate selection button.

h. W: The water loss coefficient, W. DRIP provides a table of recommended water loss values based on the type and amount of fines (material passing No. 200 Sieve (0.075-mm) material) present in the material. This table is accessed by clicking on the *?* button located next to the symbol *W*.

The sieve analysis window for permeable bases is shown in Figure C-6. As with other DRIP modules, the calculator icon becomes enabled as the required data are provided. Click on the calculator icon to perform the required calculation.

Figure C-6. Sieve Analysis Window for Permeable Bases



C-2.5.3.2 **Outputs of the sieve analysis module**. The sieve analysis module provides the following output:

a. D_{10}, D_{12}, D_{15}, D_{30}, D_{50}, D_{60}, and D_{85}. These values are needed for checking filter criteria for the separator layer.

b. P_{200} (percent passing the 0.075-mm sieve).

c. Coefficient of uniformity, C_U.

d. Porosity, N.

e. Effective porosity, N_e.

f. Permeability, k. The permeability estimated in this module is based on empirical correlation for fine-grained soils. The permeability of aggregate materials can deviate significantly from this value. Therefore, this value is not recommended for use; a laboratory-estimated value should be used.

C-2.5.4 **Permeable base design**. The *Permeable Base* module can be accessed from the *Design and Analysis* window by clicking the *Permeable Base* button. Ensure that *Time-to-Drain Method* is selected under *Permeable Base on the Design and Analysis* window before entering this module. The design inputs and outputs for this module are as follows:

C-2.5.4.1 **Inputs for permeable base designs based on the time-to-drain method**.

a. n_e: The effective porosity of the base material. The effective porosity can be determined using the *Sieve Analysis* module. If you completed the sieve analysis using DRIP, the value determined from the sieve analysis module should already be shown on the time-to-drain analysis window. Clicking on the calculator icon next to the edit box for n_e will take you to the *Sieve Analysis* module where n_e for the selected gradation can be calculated. Alternatively, n_e determined from laboratory testing can be entered manually.

b. k: The coefficient of permeability of the base material. The value determined by laboratory testing should be used, although the *Sieve Analysis* module can also be used to determine a rough estimate. As with n_e, clicking on the calculator icon next to the edit box for *k* will take you to the *Sieve Analysis* module for estimating *k* using the formula shown on that window.

d. S_R: The resultant slope of the permeable base. This parameter is an output of the *Roadway Geometry* module and automatically appears on this window if that module was previously executed. Otherwise, S_R can be entered manually.

e. L_R: The resultant length of the drainage path. This parameter is also an output of the *Roadway Geometry* module and automatically appears on this window if that module was previously executed in the same DRIP session. Otherwise, L_R can be entered manually.

f. H: Thickness of the permeable base. A fixed value of 6 in. (150 mm) is recommended for airfield pavements.

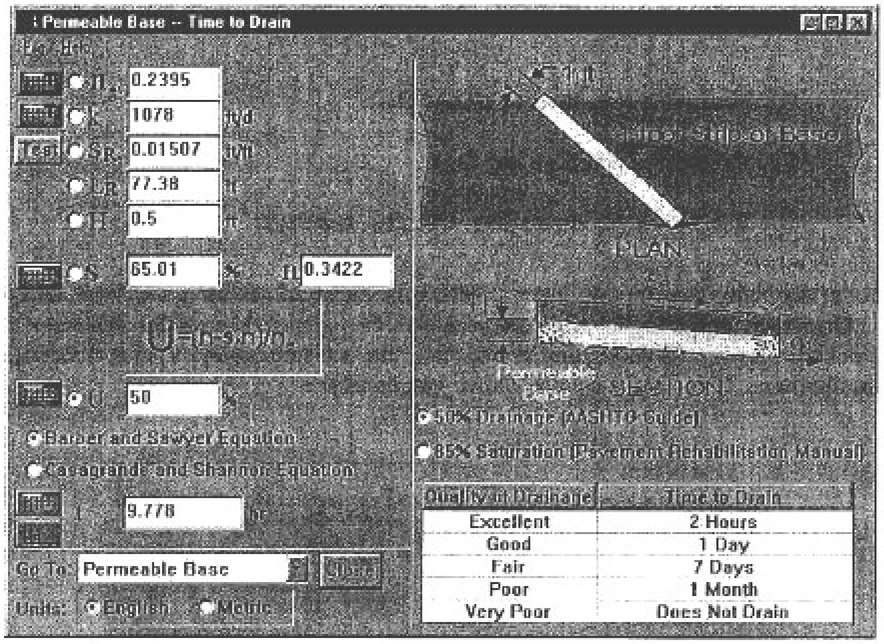
g. Either the target percent saturation, S, or percent drained, U is needed to determine time-to-drain. The drainage criteria used in DM 21.06 is based on the time to 50 percent drainage (i.e., U = 50). The relationship between S and U are shown on *Permeable Base — Time to Drain* window. Once either S or U is entered, the other value can be determined by clicking on the calculator icon next to the input parameter.

C-2.5.4.2 **Outputs of the time-to-drain method for permeable base design**

a. The time required to drain the base to the target percent saturation or percent drained.

b. The drainage history plot. A plot of the percent-drained or percent-saturation of the base with time can be viewed by clicking on the plot icon located immediately below the calculator icon for the time-to-drain calculation (see Figure C-7).

Figure C-7. Time-to-Drain Design Window



Located on the lower right of the *Permeable Base — Time to Drain* window is the quality of drainage assessment table for highway pavements. Note that the time-to-drain requirements for airfield pavements, as specified in this handbook, are less stringent than those for highways. See Table C-3 for the assessment of the quality of drainage for airfield pavements.

Table C-3. Quality of Drainage Rating for Highways and Airfield Pavements

Quality of Drainage	Time to Drain	
	Highways	**Airfields**
Excellent	2 hr	1 day
Good	1 day	7 days
Fair	7 days	15 days
Poor	30 days	30 days

<u>Example C-2B: Time-to-Drain Determination and Permeable Base Design</u>

Determine the time required for 50 percent drainage for the pavement section given in Example C-2A. The permeable base should satisfy the requirements for an *Excellent* quality of drainage as defined in Table C-3 (50 percent drainage in 12 hours or less). New Jersey permeable base gradation with a laboratory coefficient of permeability (*k*) of 1,000 ft/day is proposed as the base material. Assume a unit weight of 110 pcf, specific gravity of 2.68, and a water loss coefficient of 70 percent. Assume a permeable base thickness of 6 in.

Solution

1. Click on *Permeable Base* button from *Design and Analysis* window to access *Permeable Base* module. Be sure that the *Time-to-Drain Method* is selected under *Permeable Base* on the *Design and Analysis* window. If you completed Example C-2A, the *Permeable Base—Time-to-Drain* window should already display the values of the resultant slope (S_R) and resultant length (L_R) calculated from the *Roadway Geometry* window.

2. Click on the calculator icon next to the n_e input box. This opens the VASDAM window (Figure C-6). From the *Material Name* drop-down box, select "New Jersey—Unstabilized." The gradation for this parameter appears and the D_x calculator icon is activated. Click on this icon to compute D_x. Enter the given unit weight, specific gravity, and water loss coefficient in the respective boxes of the VASDAM window. Click on appropriate calculator buttons to calculate the coefficient of uniformity (C_u), porosity (N), and effective porosity (N_e). Click the *OK* button to close the VASDAM window and return to the *Permeable Base — Time-to-Drain* window.

3. Enter the base permeability (k) and base thickness (0.5 ft).

4. Enter the target percentage drained value, U(%) = 50 percent. Click on the calculator icon next to percent saturation, *S*, to see what degree of saturation 50 percent drainage represents.

5. Click on the calculator icon next to *t* (time-to-drain) to determine the time required to drain 50 percent of the drainable water. The plot icon below *t* should also become active when all inputs are entered. Click on this button to view the drainage history plot.

6. Check to see if the chosen gradation meets the design standard.

Figure C-7 shows the DRIP window with all inputs and outputs for this example. The calculated time-to-drain for this example is 9.778 hours. Therefore, the selected permeable base material meets the design standard.

C-2.5.5 **Separator layer design**. The DRIP *Separator Layer* module performs the automated checking of the filter criteria for aggregate and geotextile separator layers. However, the filter criteria for geotextile separator layer incorporated in DRIP is slightly different than the recommendations given in this manual. Therefore, DRIP should be used for checking the filter criteria for aggregate separator layer only.

C-2.5.5.1 **Aggregate separator layer design**. The DRIP window for aggregate separator layer design is shown in Figure C-8. The criteria that need to be satisfied for the design are listed on the right side of the window. The inputs required to compute these criteria are listed to the left of the window.

a. Inputs for Aggregate Separator Layer Design

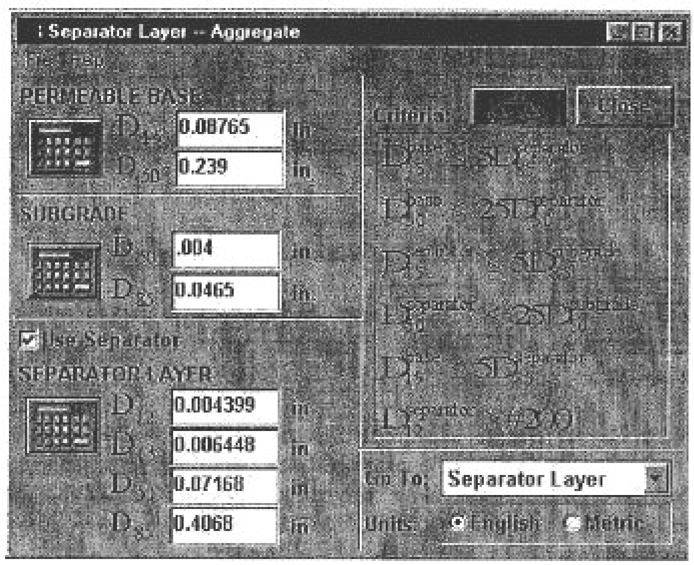
1. Permeable base inputs (D_{15} and D_{50}).

2. Subgrade inputs (D_{50} and D_{85}).

3. Separator layer inputs (D_{12}, D_{15}, D_{50}, and D_{85}).

Click on the calculator icon for each layer to determine these values using the *Sieve Analysis* module. Once the required input values are provided, the balance icon on the *Separator Layer* window becomes active. Click on this icon to see if the selected separator layer material satisfies the required criteria. The results are also shown graphically.

Figure C-8. DRIP Window for Aggregate Separator Layer Design



C-2.5.6 **Edgedrain design**. Pipe edge drains are recommended for use in this handbook. Ensure that *Pipe* radio button is selected under *Edgegrain* on *Design and Analysis* window and click on the *Edgedrain* button to access the *Pipe Edgedrain* window.

Pipe edgedrain design is a two-step process involving the calculation of the pipe capacity, Q, and the outlet spacing, L_o. The output of the first step is an input to the second. Three different options are available for determining the pavement discharge rate: *Pavement Infiltration, Permeable Base*, and *Time-to-Drain*. As explained in this handbook, the permeable base discharge option provides the maximum possible discharge from the base layer, but if the base material is extremely highly permeable, the results may be overly conservative. For very highly permeable base, the *Time-to-Drain* method should be used, with the time-to-drain manually entered to achieve the desired quality of drainage (e.g., enter 12 hr for *Excellent* or 168 hr for *Good* drainage). The inputs and outputs for this module are as follows:

C-2.5.6.1 **Input**. The pipe edgedrain design inputs are the following:

Longtudinal grade, S
Pipe diameter, D
Manning's roughness coefficient (= 0.012 for smooth pipes or 0.024 for rough pipes)

For permeable base discharge calculation, the following are required:

Base thickness, H
Transverse slope, S_T
Base permeability, *k*

For time-to-drain discharge calculation, the following are required:

Base thickness, H
Base width, W
Time-to-drain
Effective porosity, n_e
Percent drained, U (50 percent)

If the *Roadway Geometry* module was used to determine resultant slope and drainage path, the values from that module will automatically be copied to the appropriate input boxes in this module. Similarly, if *Sieve Analysis* module was used to determine gradation parameters, the effective porosity calculated from that module will be automatically imported to this module.

Example C-2C. Pipe Edgedrain Design

Design a pipe edgedrain for the permeable base in Example C-2B. Assume corrugated pipe drain with 6-in. diameter.

Solution

1. From the *Design and Analysis* window, ensure that the *Pipe* radio button is selected and click on the *Edgedrain* button to open the *Pipe Edgedrain* window.

2. Enter the values for the longitudinal slope, S, and the pipe diameter, D. Click the *Corrugated Pipe* checkbox to enter the appropriate Manning's roughness coefficient, n. The longitudinal slope, S, will automatically be imported into this window if the *Roadway Geometry* module was previously used in the same session.

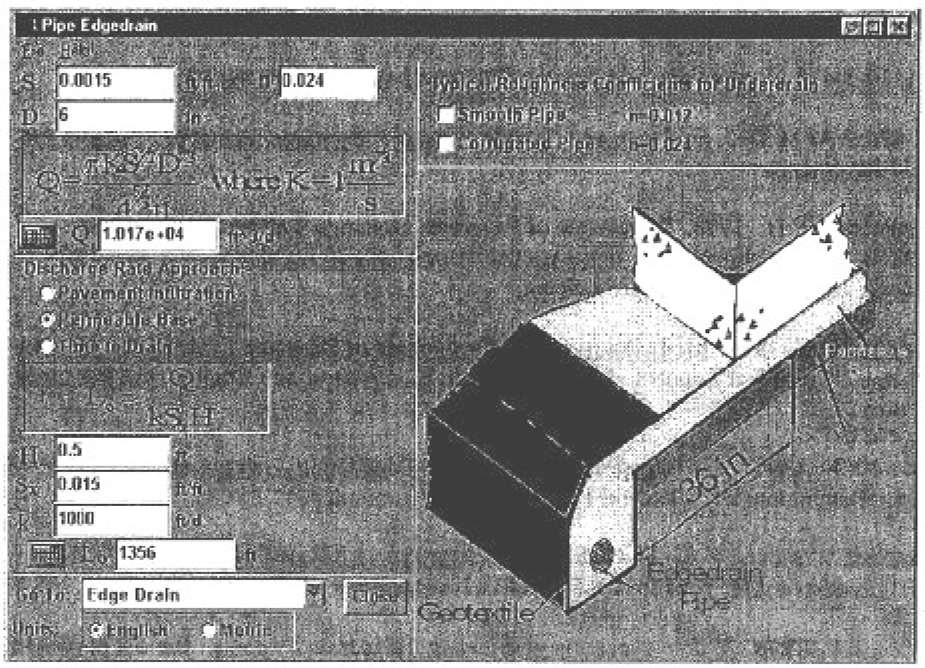
3. Click on the calculator button next to pipe capacity, *Q*, to calculate the flow capacity of the edgedrains.

4. Select the *Permeable Base* discharge rate approach and enter the base thickness (H), transverse slope (S_T), and base permeability (k). If you completed Example C-2B, the values from the *Permeable Base* module will be automatically imported into the appropriate input boxes.

5. Click on the calculator icon next to the outlet spacing, L_o, to determine the maximum outlet spacing based on hydraulic considerations.

The inputs and outputs for this example are illustrated in Figure C-9. The maximum outlet spacing determined based on hydraulic consideration for this example is 1,356 ft. However, this value far exceeds the recommended maximum outlet spacing of 250 ft (500 ft for smooth pipes), based on maintenance consideration.

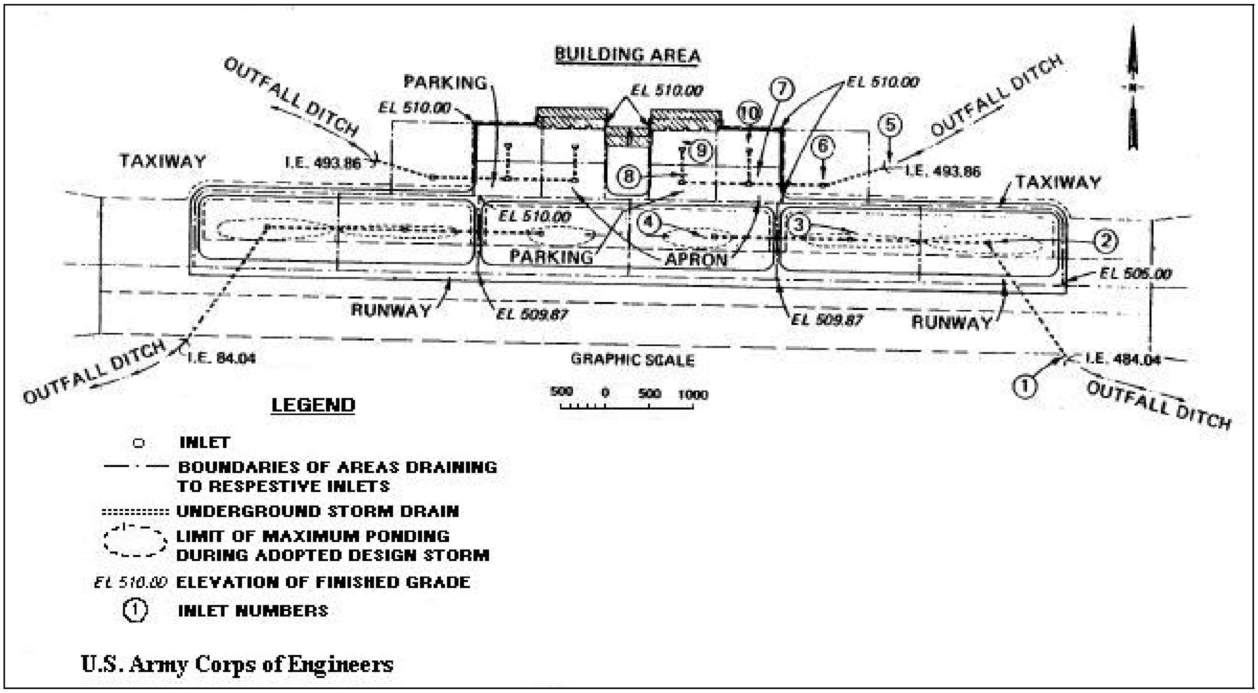
Figure C-9. Pipe Edgedrain Design Window



C-3 EFFECT OF PONDING ON PIPE SIZE REQUIREMENTS

C-3.1 The proposed layout for the primary storm drainage system for an airfield is depicted in Figure C-10. This airfield is to be located in central Mississippi where the design storm index for a 2-year 1-hour rainfall intensity, according to Figure 2-2, is 2.0 inches per hour. The duration of storm being considered is 60 minutes; thus, Figure 3-1 need not initially be used. Infiltration values for the paved and turfed area are considered to be 0.0 and 0.5 inches per hour, respectively, according to Section 3-6. The supply curves applicable to this airfield are No. 2.0 for paved areas (2.0-0.0) and No. 1.5 for turfed areas (2.0-0.5). These supply curves are provided in Figure 3-1. Coefficients of roughness have been selected for the paved and turfed areas as 0.01 and 0.40, respectively, as suggested in Table C-5.

Figure C-10. Sample Computations of Layout of Primary Storm Drainage System



C-3.2 In this example, two conditions are considered: where ponding is permissible at Inlets 4, 3, and 2, and where no ponding is allowed at these inlets. The purpose of these examples is to portray the difference in pipe size requirements under these two imposing conditions. Tables C-4, C-5, and C-6 reflect the design where ponding is permissible, and Tables C-7, C-8, and C-9 reflect the design where ponding is not acceptable.

C-4 OUTLET PROTECTION DESIGN

C-4.1 This section contains examples of recommended application to estimate the extent of scour in a cohesionless soil and alternative schemes of protection required to prevent local scour.

C-4.2 Circular and rectangular outlets with equivalent cross-sectional areas that will be subjected to a range of discharges for a duration of 1 hr are used with the following parameters:

Dimensions of rectangular outlet = W_o = 10 ft, D_o = 5 ft

Diameter of circular outlet, D_o = 8 feet

Range of discharge, Q = 362 to 1,086 cubic feet per second

Discharge parameter for rectangular culvert, $q/D_o^{3/2}$ = 3.2 to 9.7

Table C-4

Table C-4 (cont)

Table C-4 (cont)

Table C-5

Table C-5 (cont)

Table C-5 (cont)

Table C-6

Table C-6 (cont)

Table C-6 (cont)

Table C-7

Table C-7 (cont)

Table C-8

Table C-9

Discharge parameter for circular culvert, $Q/D_o^{5/2}$ = 2 to 6

Duration of runoff event, t = 60 minutes

Maximum tailwater el = 6.4 feet above outlet invert (>0.5 D_o)

Minimum tailwater el = 2.0 feet above outlet invert (<0.5 D_o)

Example C-4A. Determine maximum depth of scour for minimum and maximum flow conditions:

RECTANGULAR CULVERT (see Figure 4-15)

MINIMUM TAILWATER

$$\frac{D_{sm}}{D_o} = 0.80 \left(\frac{q}{D_o^{3/2}} \right)^{0.375} t^{0.10} \qquad \text{(eq. C-2)}$$

$$D_{sm} = 0.80\,(3.2 \text{ to } 9.7)^{0.375}\ (60)^{0.1}\ (5) = 9.3\ \mathit{ft}\ \mathit{to}\ 14.0\ \mathit{ft} \qquad \text{(eq. C-3)}$$

MAXIMUM TAILWATER

$$\frac{D_{sm}}{D_o} = 0.74 \left(\frac{q}{D_o^{3/2}} \right)^{0.375} t^{0.10} \qquad \text{(eq. C-4)}$$

$$D_{sm} = 0.74\,(3.2 \text{ to } 9.7)^{0.375}\ (60)^{0.1}\ (5) = 8.6\ \mathit{ft}\ \mathit{to}\ 13.0\ \mathit{ft} \qquad \text{(eq. C-5)}$$

CIRCULAR CULVERT (see Figure 4-15)

MINIMUM TAILWATER

$$\frac{D_{sm}}{D_o} = 0.80 \left(\frac{Q}{D_o^{5/2}} \right)^{0.375} t^{0.10} \qquad \text{(eq. C-6)}$$

$$D_{sm} = 0.80\,(2 \text{ to } 6)^{0.375}\ (60)^{0.1}\ (8) = 12.5\ \mathit{ft}\ \mathit{to}\ 18.9\ \mathit{ft} \qquad \text{(eq. C-7)}$$

MAXIMUM TAILWATER

$$\frac{D_{sm}}{D_o} = 0.74\left(\frac{q}{D_o^{5/2}}\right)^{0.375} \quad t^{0.1} \qquad \text{(eq. C-8)}$$

$$D_{sm} = 0.74\ (2 \text{ to } 6)^{0.375}\ (60)^{0.1}\ (8) = 11.6\ ft\ to\ 17.5\ ft \qquad \text{(eq. C-9)}$$

<u>Example C-4B. Determine maximum width of scour for minimum and maximum flow conditions:</u>

RECTANGULAR CULVERT (see Figure 4-16)

MINIMUM TAILWATER

$$\frac{W_{sm}}{D_o} = 1.00\left(\frac{q}{D_o^{3/2}}\right)^{0.915} \quad t^{0.15} \qquad \text{(eq. C-10)}$$

$$W_{sm} = 1.00\ (3.2 \text{ to } 9.7)^{0.915}\ (60)^{0.15}\ (5) = 27\ ft\ to\ 74\ ft \qquad \text{(eq. C-11)}$$

$$W_{smr} = W_{sm} + \frac{W_o}{2} - \frac{D_o}{2} = (27 \text{ to } 74) + \frac{10}{2} - \frac{5}{2} = 29.5\ ft\ to\ 76.5\ ft \qquad \text{(eq. C-12)}$$

MAXIMUM TAILWATER

$$\frac{W_{sm}}{D_o} = 0.72\left(\frac{q}{D_o^{3/2}}\right)^{0.915} \quad t^{0.15} \qquad \text{(eq. C-13)}$$

$$W_{sm} = 0.72\ (3.2 \text{ to } 9.7)^{0.915}\ (60)^{0.015} = 19\ ft\ to\ 53\ ft \qquad \text{(eq. C-14)}$$

$$W_{smr} = W_{sm} + \frac{W_o}{2} - \frac{D_o}{2} = (19 \text{ to } 53) + \frac{10}{2} - \frac{5}{2} = 21.5\ ft\ to\ 55.5\ ft \qquad \text{(eq. C-15)}$$

CIRCULAR CULVERT (see Figure 4-16)

MINIMUM TAILWATER

$$\frac{W_{sm}}{D_o} = 1.00\left(\frac{Q}{D_o^{5/2}}\right)^{0.915} \quad t^{0.15} \qquad \text{(eq. C-16)}$$

$$W_{sm} = 1.00\ (2 \text{ to } 6)^{0.915}\ (60)^{0.15}\ (8) = 28\ ft\ to\ 76\ ft \qquad \text{(eq. C-17)}$$

MAXIMUM TAILWATER

$$\frac{W_{sm}}{D_o} = 0.72 \left(\frac{Q}{D_o^{5/2}} \right)^{0.915} t^{0.15} \qquad \text{(eq. C-18)}$$

$$W_{sm} = 0.72\,(2 \text{ to } 6)^{0.915}\ (60)^{0.15}\ (8) = 20\ ft\ to\ 55\ ft \qquad \text{(eq. C-19)}$$

<u>Example C-4C – Determine maximum length of scour for minimum and maximum flow conditions:</u>

RECTANGULAR CULVERT (see Figure 4-17)

MINIMUM TAILWATER

$$\frac{L_{sm}}{D_o} = 2.40 \left(\frac{q}{D_o^{3/2}} \right)^{0.71} t^{0.125} \qquad \text{(eq. C-20)}$$

$$L_{sm} = 2.4\,(3.2 \text{ to } 9.7)^{0.71}\ (60)^{0.125}\ (5) = 46\ ft\ to\ 101\ ft \qquad \text{(eq. C-21)}$$

MAXIMUM TAILWATER

$$\frac{L_{sm}}{D_o} = 4.10 \left(\frac{q}{D_o^{3/2}} \right)^{0.71} t^{0.125} \qquad \text{(eq. C-22)}$$

$$L_{sm} = 4.10\,(3.2 \text{ to } 9.7)^{0.71}\ (60)^{0.125}\ (5) = 78\ ft\ to\ 171\ ft \qquad \text{(eq. C-23)}$$

CIRCULAR CULVERT (see Figure 4-17)

MINIMUM TAILWATER

$$\frac{L_{sm}}{D_o} = 2.40 \left(\frac{Q}{D_o^{5/2}} \right)^{0.71} t^{0.125} \qquad \text{(eq. C-24)}$$

$$L_{sm} = 2.4\,(2 \text{ to } 6)^{0.71}\ (60)^{0.125}\ (8) = 52\ ft\ to\ 114\ ft \qquad \text{(eq. C-25)}$$

MAXIMUM TAILWATER

$$\frac{L_{sm}}{D_o} = 4.10 \left(\frac{Q}{D_o^{5/2}} \right)^{0.71} t^{0.125} \qquad \text{(eq. C-26)}$$

$$L_{sm} = 4.10\,(2 \text{ to } 6)^{0.71}\ (60)^{0.125}\ (8) = 90\ ft\ to\ 195\ ft \qquad \text{(eq. C-27)}$$

Example C-4D. Determine profile and cross section of scour for maximum discharge and minimum tailwater conditions (see Figure 4-19):

CIRCULAR CULVERT

For L_{sm} = 114 ft and D_{sm} = 18.9 ft											
L_s/L_{sm}	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
L	0.0	11.4	22.8	34.2	45.6	57.0	68.4	79.8	91.2	102.6	114.0
D_s/D_{sm}	0.7	0.75	0.85	0.95	1.0	0.95	0.75	0.55	0.33	0.15	0.0
D_s	13.2	14.2	16.1	18.0	18.9	18.0	14.2	10.4	6.3	2.9	0.0
For W_{sm} = 76 ft and D_{sm} = 18.9 ft											
W_s/W_{sm}	0.0		0.2		0.4		0.6		0.8		1.0
W_s	0.0		15.2		30.4		45.6		60.8		76.0
D_s/D_{sm}	1.0		0.67		0.27		0.15		0.05		0.0
D_s	18.9		12.6		5.1		2.8		0.95		0.0

RECTANGULAR CULVERT

For L_{sm} = 101 ft and D_{sm} = 14.0 ft											
L_s/L_{sm}	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
L	0.0	10.1	20.2	30.3	40.4	50.5	60.6	70.7	80.8	90.9	101.0
D_s/D_{sm}	0.7	0.75	0.85	0.95	1.0	0.95	0.75	0.55	0.33	0.15	0.0
D_s	9.8	10.5	11.9	13.3	14.0	13.3	10.5	7.7	4.6	2.1	0.0
For W_{sm} = 74 ft and D_{sm} = 14.0 ft											
W_s/W_{sm}	0.0		0.2		0.4		0.6		0.8		1.0
W_s	0.0		14.8		29.6		44.4		59.2		74.0
D_s/D_{sm}	1.0		0.67		0.27		0.15		0.05		0.0
D_s	14.0		9.38		3.78		2.10		0.70		0.0
$W_{sr} = W_s$ $W_s + \frac{W_o}{2} - \frac{D_o}{2}$	0-2.5		17.3		32.1		46.9		61.7		76.5

Example C-4E. Determine depth and width of cutoff wall:

RECTANGULAR CULVERT, Maximum depth and width of scour = 14 ft and 76.5 ft

From Figure 4-19, depth of cutoff wall = 0.7 (D_{sm}) = 0.7 (14) = 9.8 ft

From Figure 4-19, width of cutoff wall = 2 (W_{smr}) = 2 (76.5) = 153 ft

CIRCULAR CULVERT, Maximum depth and width of scour = 18.9 ft and 76.0 ft

From Figure 4-19, depth of cutoff wall = 0.7 (D_{sm}) = 0.7 (18.9) = 13.2 ft

From Figure 4-19, width of cutoff wall = 2 (W_{sm}) = 2 (76) = 152 ft

Note: The depth of cutoff wall may be varied with width in accordance with the cross section of the scour hole at the location of the maximum depth of scour. See Figures 4-19 and 4-20.

Example C-4F. Determine size and extent of horizontal blanket of riprap:

RECTANGULAR CULVERT

MINIMUM TAILWATER

$$\text{From Figure 4-21, } \frac{d_{50}}{D_o} = 0.020\ \frac{D_o}{TW}\left(\frac{q}{D_o^{3/2}}\right)^{4/3} \quad \text{(eq. C-28)}$$

$$d_{50} = 0.020\,(5/2)\,(3.2\ \ to\ \ 9.7)^{4/3}\ \ (5) = 1.2\ ft\ to\ 5.2\ ft \quad \text{(eq. C-29)}$$

$$\text{From Figure 4-22, } \frac{L_{sp}}{D_o} = 1.8\left(\frac{q}{D_o^{3/2}}\right) + 7 \quad \text{(eq. C-30)}$$

$$L_{sp} = [1.8\,(3.2\ \text{ to }\ 9.7) + 7]\ \ 5 = 64\ ft\ to\ 122\ ft \quad \text{(eq. C-31)}$$

MAXIMUM TAILWATER

$$\frac{d_{50}}{D_o} = 0.020\ \frac{D_o}{TW}\left(\frac{q}{D_o^{3/2}}\right)^{4/3} \quad \text{(eq. C-32)}$$

$$d_{50} = 0.020\ \ (5/6.4)\,(3.2\ \ to\ \ 9.7)^{4/3}\,(5) = 0.37\ ft\ to\ 0.76\ ft \quad \text{(eq. C-33)}$$

$$\frac{L_{sp}}{D_o} = 3 \left(\frac{q}{D_o^{3/2}} \right) \qquad \text{(eq. C-34)}$$

$$L_{sp} = 3\,(3.2 \text{ to } 9.7)\;\; 5 = 48 \textit{ ft to } 145 \textit{ ft} \qquad \text{(eq. C-35)}$$

CIRCULAR CULVERT

MINIMUM TAILWATER

$$\frac{d_{50}}{D_o} = 0.020 \;\frac{D_o}{TW} \left(\frac{Q}{D_o^{5/2}} \right)^{4/3} \qquad \text{(eq. C-36)}$$

$$d_{50} = 0.020 \;\; (8/2)\,(2 \textit{ to } 6)^{4/3} \;\; (8) = 1.6 \textit{ ft to } 7.0 \textit{ ft} \qquad \text{(eq. C-37)}$$

$$\frac{L_{sp}}{D_o} = 1.8 \left(\frac{Q}{D_o^{5/2}} \right) + 7 \qquad \text{(eq. C-38)}$$

$$L_{sp} = 1.8\,(2 \text{ to } 6) + 7 \quad\; 8 = 85 \textit{ ft to } 142 \textit{ ft} \qquad \text{(eq. C-39)}$$

MAXIMUM TAILWATER

$$\frac{d_{50}}{D_o} = 0.020 \;\frac{D_o}{TW} \left(\frac{Q}{D_o^{5/2}} \right)^{4/3} \qquad \text{(eq. C-40)}$$

$$d_{50} = 0.020 \;\; (8/6.4)\,(2 \textit{ to } 6)^{4/3}\,(8) = 0.50 \textit{ ft to } 2.18 \textit{ ft} \qquad \text{(eq. C-41)}$$

$$\frac{L_{sp}}{D_o} = 3 \left(\frac{Q}{D_o^{5/2}} \right) \qquad \text{(eq. C-42)}$$

$$L_{sp} = 3\,(2 \text{ to } 6)\;\; 8 = 48 \textit{ ft to } 144 \textit{ ft} \qquad \text{(eq. C-43)}$$

Use Figure 4-23 to determine recommended configuration of horizontal blanket of riprap subject to minimum and maximum tailwaters.

Example C-4G – Determine size and geometry of riprap-lined preformed scour holes 0.5- and 1.0-D_o deep for minimum tailwater conditions:

RECTANGULAR CULVERT (see Figure 4-21)

0.5-D_o-DEEP RIPRAP-LINED PREFORMED SCOUR HOLE

$$\frac{d_{50}}{D_o} = 0.0125 \ \frac{D_o}{TW} \left(\frac{q}{D_o^{3/2}} \right)^{4/3} \quad \text{(eq. C-44)}$$

$$d_{50} = 0.0125 \ (5/2)(3.2 \ \ to \ \ 9.7)^{4/3} (5) = 0.73 \ ft \ to \ 3.2 \ ft \quad \text{(eq. C-45)}$$

1.0-D_o-DEEP RIPRAP-LINED PREFORMED SCOUR HOLE

$$\frac{d_{50}}{D_o} = 0.0082 \ \frac{D_o}{TW} \left(\frac{q}{D_o^{3/2}} \right)^{4/3} \quad \text{(eq. C-46)}$$

$$d_{50} = 0.0082 \ (5/2)(3.2 \ \ to \ \ 9.7)^{4/3} \ (5) = 0.48 \ ft \ to \ 2.1 \ ft \quad \text{(eq. C-47)}$$

CIRCULAR CULVERT

0.5-D_o-DEEP RIPRAP-LINED PREFORMED SCOUR HOLE

$$\frac{d_{50}}{D_o} = 0.0125 \ \frac{D_o}{TW} \left(\frac{Q}{D_o^{5/2}} \right)^{4/3} \quad \text{(eq. C-48)}$$

$$d_{50} = 0.0125 \ (8/2)(2 \ \ to \ \ 6)^{4/3} \ (8) = 1.0 \ ft \ to \ 4.4 \ ft \quad \text{(eq. C-49)}$$

1.0-D_o-DEEP RIPRAP-LINED PREFORMED SCOUR HOLE

$$\frac{d_{50}}{D_o} = 0.0082 \ \frac{D_o}{TW} \left(\frac{Q}{D_o^{5/2}} \right)^{4/3} \quad \text{(eq. C-50)}$$

$$d_{50} = 0.0082 \ (8/2)(2 \ \ to \ \ 6)^{4/3} \ (8) = 0.66 \ ft \ to \ 2.9 \ ft \quad \text{(eq. C-51)}$$

See Figure 4-24 for geometry.

<u>Example 4-CH. Determine size and geometry of riprap-lined-channel expansion for minimum tailwaters (see Figure 4-26):</u>

RECTANGULAR CULVERT

$$\frac{d_{50}}{D_o} = 0.016 \ \frac{D_o}{TW} \left(\frac{q}{D_o^{3/2}} \right)^{4/3} \quad \text{(eq. C-52)}$$

$$d_{50} = 0.016 \ (5/2)(3.2 \ \ to \ \ 9.7)^{4/3} \ (5) = 0.94 \ ft \ to \ 4.1 \ ft \quad \text{(eq. C-53)}$$

CIRCULAR CULVERT

$$\frac{d_{50}}{D_o} = 0.016 \ \frac{D_o}{TW} \ \left(\frac{Q}{D_o^{5/2}}\right)^{4/3} \qquad \text{(eq. C-54)}$$

$$d_{50} = 0.016 \ \ (8/2)\,(2 \ \ to \ \ 6)^{4/3} \ \ (8) = 1.29 \ ft \ to \ 5.6 \ ft \qquad \text{(eq. C-55)}$$

See Figure 4-25 for geometry.

Example 4-CI. Determine length and geometry of a flared outlet transition for minimum tailwaters:

RECTANGULAR CULVERT

$$\frac{L}{D_o} = 0.30 \ \left(\frac{D_o}{TW}\right)^2 \ \left(\frac{q}{D_o^{3/2}}\right)^{2.5(TW/D_o)1/3} \qquad \text{(eq. C-56)}$$

$$L = 0.3\,(5/2)^2 \ (3.2 \ \ to \ \ 9.7)^{2.5(2/5)^{1/3}} \ \ 5 = 80 \ ft \ to \ 616 \ ft \qquad \text{(eq. C-57)}$$

CIRCULAR CULVERT

$$\frac{L}{D_o} = \left[0.30\left(\frac{D_o}{TW}\right)^2 \left(\frac{Q}{D_o^{5/2}}\right)^{2.5(TW/D_o)^{1/3}}\right] \qquad \text{(eq. C-58)}$$

$$L = \left[0.3\,(8/2)^2 \ (2 \ \ to \ \ 6)^{2.5(2/8)^{1/3}}\right] 8 = 114 \ ft \ to \ 645 \ ft \qquad \text{(eq. C-59)}$$

See Figure 4-27 for geometric details; above equations developed for H = 0 or horizontal apron at outlet invert elevation without an end sill.

Example 4-CJ. Determine diameter of stilling well required downstream of the 8-ft-diam outlet:

From Figure 4-28

$$\frac{D_W}{D_o} = 0.53 \ \left(\frac{Q}{D_o^{5/2}}\right)^{1.0} \qquad \text{(eq. C-60)}$$

$$D_W = 0.53\,(2 \;\; to \;\; 6)\;\; 8 = 8.5\; ft\; to\; 25.4\; ft \qquad \text{(eq. C-61)}$$

See Figure 4-28 for additional dimensions.

<u>Example 4-CK. Determine width of U.S. Bureau of Reclamation type VI basin required downstream of the 8-ft-diam outlet:</u>

From Figure 4-29

$$\frac{W_{VI}}{D_o} = 1.30 \; \left(\frac{Q}{D_o^{5/2}}\right)^{0.55} \qquad \text{(eq. C-62)}$$

$$W_{VI} = \left[1.3\,(2 \;\; to \;\; 6)^{0.55}\right]\; 8 = 15.2\; ft\; to\; 27.9\; ft \qquad \text{(eq. C-63)}$$

See Figure 4-29 for additional dimensions.

<u>Example 4-CL. Determine width of SAF basin required downstream of the 8-ft-diam outlet:</u>

From Figure 4-30

$$\frac{W_{SAF}}{D_o} = 0.30 \; \left(\frac{Q}{D_o^{5/2}}\right)^{1.0} \qquad \text{(eq. C-64)}$$

$$W_{SAF} = 0.30\,(2 \;\; to \;\; 6)\;\; 8 = 4.8\; ft\; to\; 14.4\; ft \qquad \text{(eq. C-65)}$$

See Figure 4-30 for additional dimensions.

<u>Example 4-CM. Determine size of riprap required downstream of 8-ft-diam culvert and 14.4-ft-wide SAF basin with discharge of 1,086 cfs:</u>

$$q = \frac{Q}{W_{SAF}} = \frac{1086}{14.4} = 75\; cfs/ft \qquad \text{(eq. C-66)}$$

$$V_1 = \frac{Q}{A} = \frac{1086}{0.785(8)^2} = 21.6\; fps \qquad \text{(eq. C-67)}$$

$$d_1 = \frac{q}{V_1} = \frac{75}{21.6} = 3.5\; ft \qquad \text{(eq. C-68)}$$

d_2 = 8.4 ft (from conjugate depth relations)

MINIMUM TAILWATER REQUIRED FOR A HYDRAULIC JUMP = 0.90 (8.4) = 7.6 ft

$$d_{50} = D\left(\frac{V}{\sqrt{gD}}\right)^3 \qquad \text{(eq. C-69)}$$

$$V = \frac{q}{D} = \frac{75}{7.6} = 9.9\ fps \qquad \text{(eq. C-70)}$$

$$d_{50} = 1.0\left[\frac{9.9}{\sqrt{32.2\,(7.6)}}\right]^3\ 7.6 \qquad \text{(eq. C-71)}$$

$$d_{50} = 1.9\ ft \qquad \text{(eq. C-72)}$$

C-5 CHANNEL DESIGN

C-5.1 **Design Procedure**. The following steps will permit the design of a channel that will satisfy the conditions desired for the design discharge and one that will ensure no deposition or erosion under these conditions.

C-5.1.1 Determine gradation of material common to drainage basin from representative samples and sieve analyses.

C-5.1.2 Determine maximum discharges to be experienced annually and during the design storm.

C-5.1.3 Assume maximum desirable depth of flow, D, to be experienced with the design discharge.

C-5.1.4 Determine the sizes of material to be transported by examining the gradation of the local material (sizes and percentages of the total by weight). Particular attention should be given to the possibility of the transport of material from upper portions of the basin or drainage system and the need to prevent deposition of this material within the channel of interest.

C-5.1.5 Compute ratios of the diameter of the materials that should and should not be transported at the maximum depth of flow, (d_{50}/D).

C-5.1.6 Compute the Froude numbers of flow required to initiate transport of the selected sizes of cohesionless materials based on the equation, $F = 1.88\ (d_{50}/D)^{1/3}$, to determine the range of F desired in the channel.

C-5.2 **Channel Design**.

C-5.2.1 Design the desired channel as indicated in the following steps.

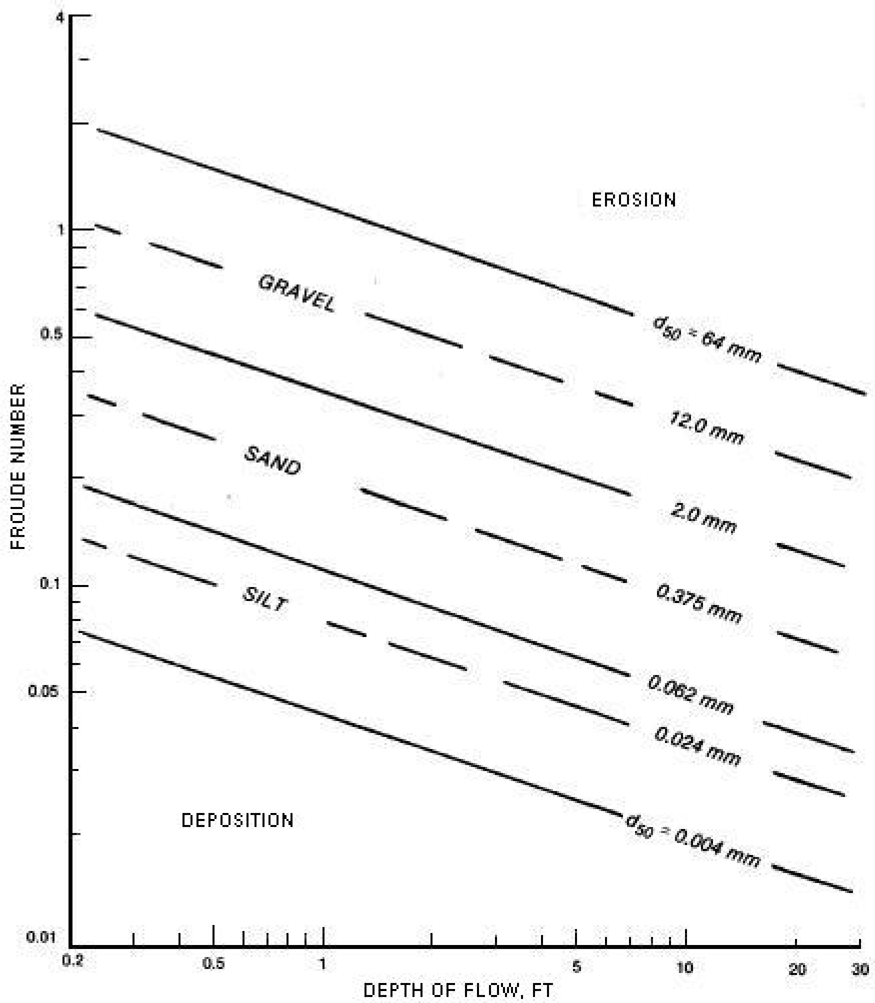
C-5.2.1.1 Assume that a channel is to be provided within and for drainage of an area composed of medium sand (grain diameter of 0.375 mm) for conveyance of a maximum rate of runoff of 400 cubic feet per second. Also assume that a channel depth of 6 feet is the maximum that can be tolerated from the standpoint of the existing groundwater level, minimum freeboard of 1 foot, and other considerations such as ease of excavation, maintenance, and aesthetics.

C-5.2.1.2 From Figure C-11 or the equation

$$F = 1.88(d_{50} / D)^{1/3} \quad \text{(eq. C-73)}$$

the Froude number of flow required for incipient transport and prevention of deposition of medium sand in a channel with a 5-foot depth of flow can be estimated to be about

Figure C-11. Froude Number and Depth of Flow Required for Incipient Transport of Cohesionless Material



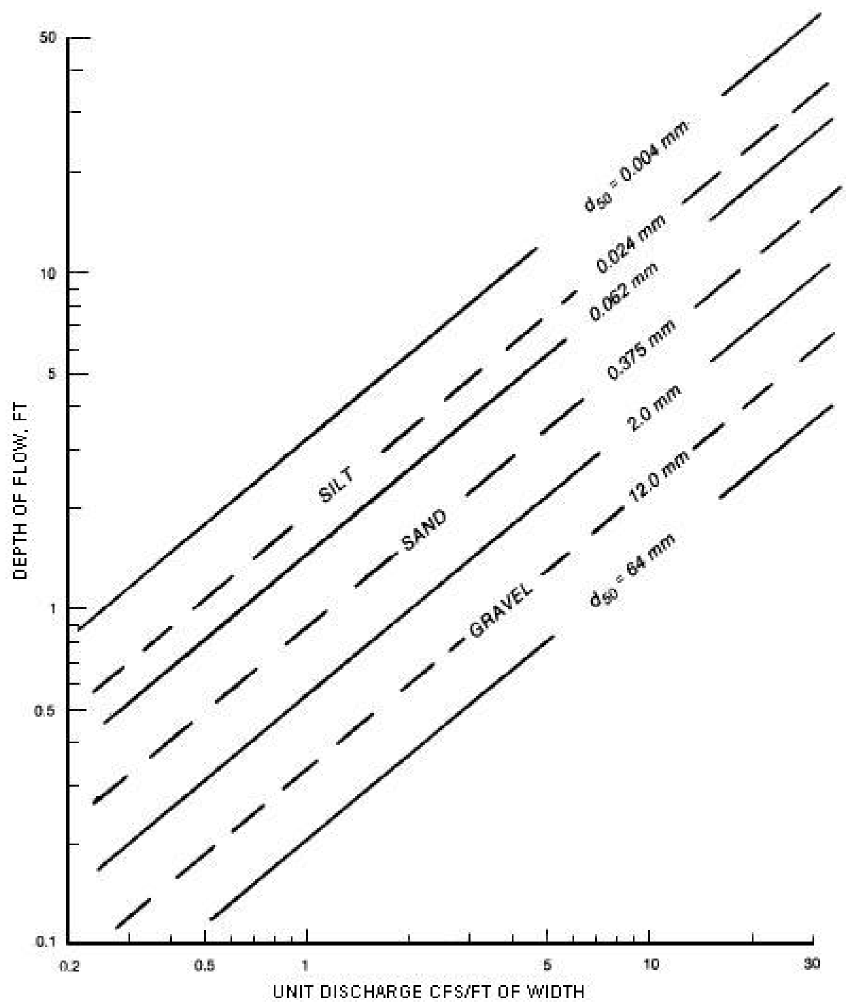
0.12. Further, it is indicated that a Froude number of about 0.20 would be required to prevent deposition of very coarse sand or very fine gravel. Therefore, an average Froude number of about 0.16 should not cause severe erosion or deposition of the medium sand common to the basin with a flow depth of 5 feet in the desired channel.

C-5.2.1.3 The unit discharge required for incipient transport and prevention of deposition of medium sand in a channel with a 5-foot depth of flow can be estimated to be about 7.4 cubic feet per second per foot of width from the equation

$$q = 10.66\, {d_{50}}^{1/3} D^{7/6} \qquad \text{(eq. C-74)}$$

or Figure C-12. In addition, it is indicated that a unit discharge of about 13 cubic feet per second per foot of width would be required to prevent deposition of very coarse sand or very fine gravel. Thus, an average unit discharge of about 10 cubic feet per

Figure C-12. Depth of Flow and Unit Discharge for Incipient Transport of Cohesionless Material



second per foot of width should not cause severe erosion or deposition of the medium sand common to the basin and a 5-foot depth of flow in the desired channel.

C-5.2.1.4 The width of a rectangular channel and the average width of a trapezoidal channel required to convey the maximum rate of runoff of 400 cubic feet per second can be determined by dividing the discharge by the permissible unit discharge. For the example problem an average channel width of 40 feet is required. The base width of a trapezoidal channel can be determined by subtracting the product of the horizontal component of the side slope corresponding to a vertical displacement of 1 foot and the depth of flow from the previously estimated average width. The base width of a trapezoidal channel with side slopes of 1V on 3H required to convey the design discharge with a 5-foot depth of flow would be 25 feet.

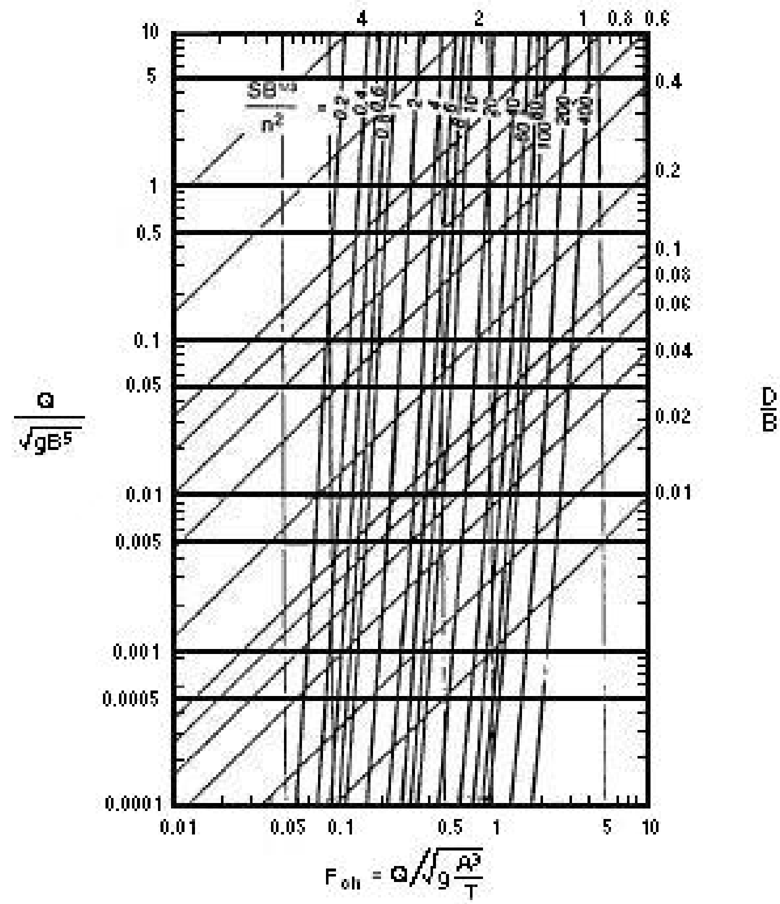
C-5.2.1.5 The values of the parameters D/B and $Q/\sqrt{gB^5}$ can now be calculated as 0.2 and 0.0225, respectively. Entering Figure C-13 with these values, it is apparent that corresponding values of 0.95 and 0.185 are required for the parameters of $SB^{1/3}/n^2$ and F, respectively. Assuming a Manning's n of 0.025, a slope of 0.000203 foot per foot would be required to satisfy the $SB^{1/3}/n^2$ relation for the 5-foot deep trapezoidal channel with base width of 25 feet and 1V-on-3H side slopes.

C-5.2.1.6 The Froude number of flow in the channel slightly in excess of the value of 0.16 previously estimated to be satisfactory with a depth of flow of 5 feet, but it is within the range of 0.12 and 0.20 considered to be satisfactory for preventing either severe erosion or deposition of medium to very coarse sand. However, should it be desired to convey the design discharge of 400 cubic feet per second with a Froude number of 0.16 in a trapezoidal channel of 25-foot base width and 1V-on-3H side slopes, the values of 0.0225 and 0.16 for $Q/\sqrt{gB^5}$ and F, respectively, can be used in conjunction with the Figure C-13 to determine corresponding values of $SB^{1/3}/n^2$ (0.72) and D/B (0.21) required for such a channel. Thus, a depth of flow equal to 5.25 feet, and a slope of 0.000154 foot per foot would be required for the channel to convey the flow with a Froude number of 0.16.

C-5.2.1.7 The slopes required for either the rectangular or the trapezoidal channels are extremely moderate. If a steeper slope of channel is desired for correlation with the local topography, the feasibility of a lined channel should be investigated as well as the alternative of check dams or drop structures in conjunction with the channel previously considered. For the latter case, the difference between the total drop in elevation desired due to the local topography and that permissible with the slope of an alluvial channel most adaptable to the terrain would have to be accomplished by means of one or more check dams and/or drop structures.

C-5.2.1.8 Assume that there is a source of stone for supply of riprap with an average dimension of 3 inches. The feasibility of a riprap-lined trapezoidal channel with 1V-on-3H side slopes that will convey the design discharge of 400 cubic feet per second with

Figure C-13. Flow Characteristics of Trapezoidal Channels with 1V-on-3H Side Slopes

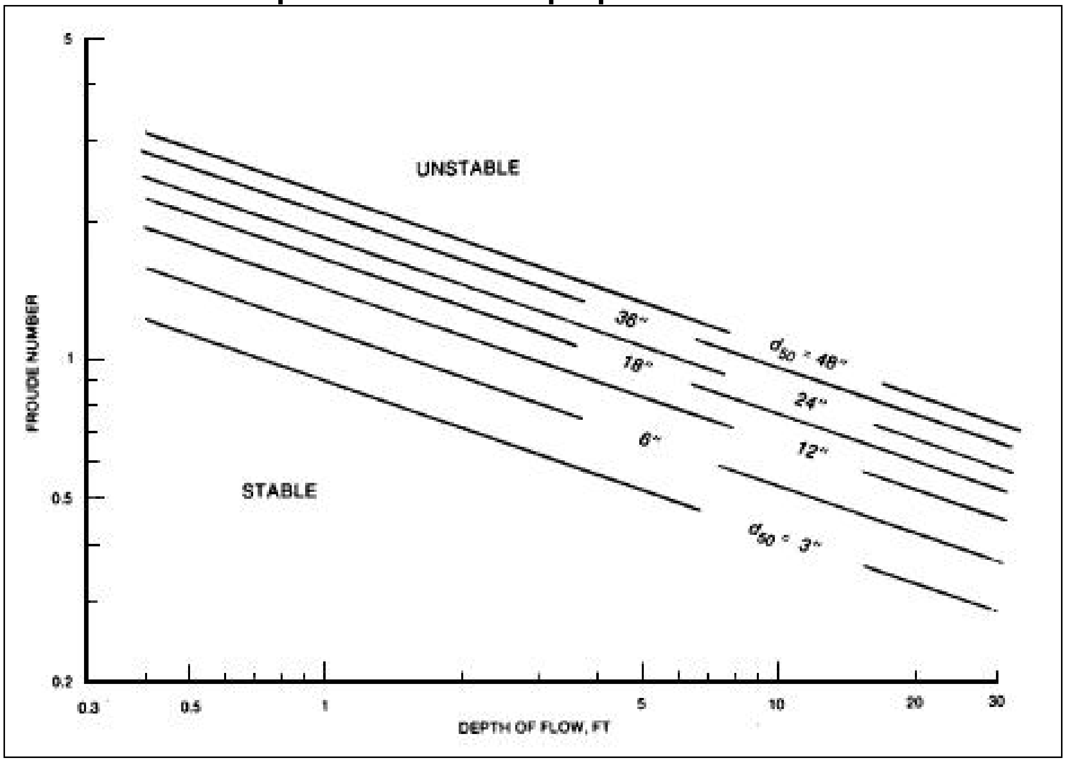


depths of flow up to 5 feet can be investigated as follows. The equation, F = $1.42(d_{50}/D)^{1/3}$, or Figure C-14 can be used to estimate the Froude number of flow that will result in failure of various sizes of natural or crushed stone riprap with various depths of flow. The maximum Froude number of flow that can be permitted with average size stone of 0.25-foot-diameter and a flow depth of 5 feet is 0.52. Similarly, the maximum unit discharge permissible (33 cubic feet per second per foot of width) can be determined by the equation,

$$q = 8.05\, d_{50}^{\ 1/3}\, D^{7/6} \qquad \text{(eq. C-75)}$$

or Figure C-15. For conservative design, it is recommended that the maximum unit discharge be limited to about two thirds of this value or say 22 cubic feet per second per foot of width for this example. Thus, an average channel width of about 18.2 feet is required to convey the design discharge of 400 cubic feet per second with a depth of 5 feet. The base width required of the riprap-lined trapezoidal channel with side slopes of 1V on 3H would be about 3 feet.

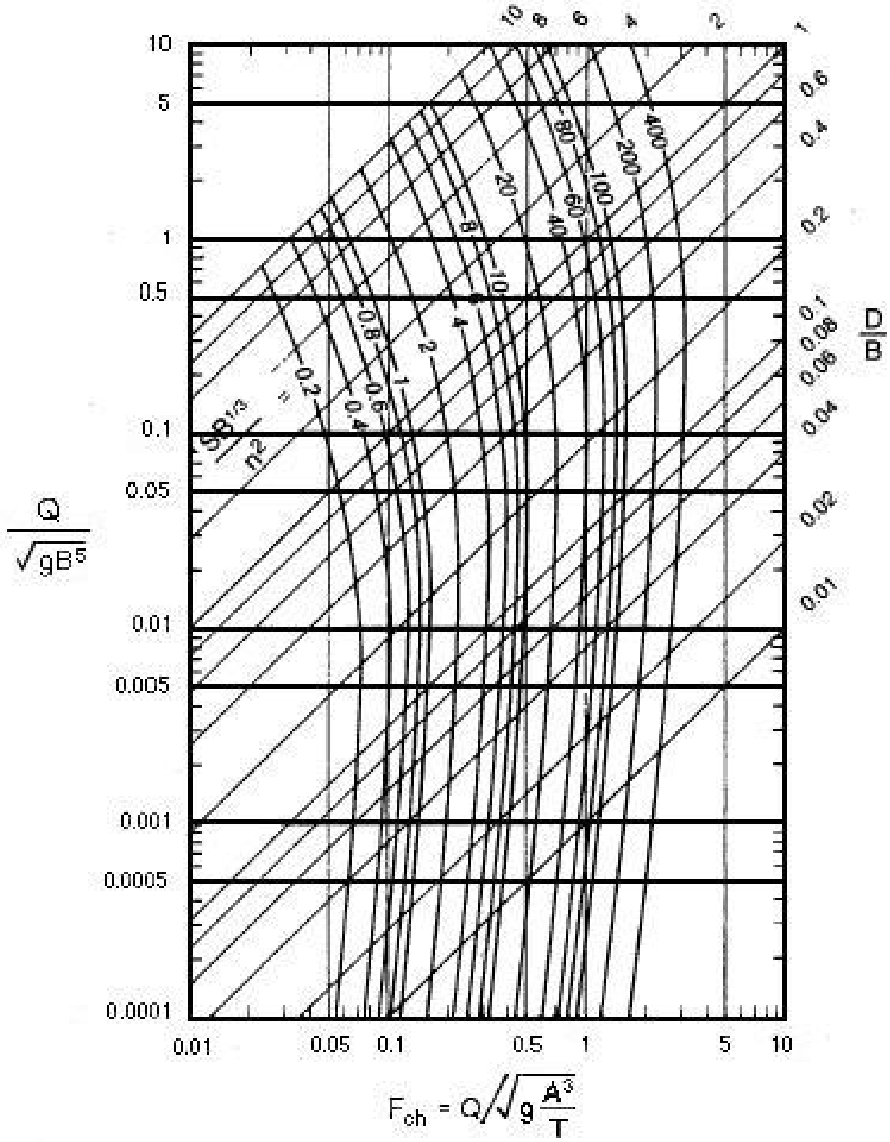
Figure C-14. Froude Number and Depth of Flow for Incipient Failure of Riprap-Lines Channel



C-5.2.1.9 The values of D/B and $Q/\sqrt{gB^5}$ can be calculated as 1.67 and 4.52, respectively. Entering Figure C-13 with these values, it is apparent that corresponding values of 4.5 and 0.52 are required for the parameters of $SB^{1/3}/n^2$ and F, respectively. Assume n = 0.035 $(d_{50})^{1/6}$ and calculate Manning's roughness coefficient of 0.25-foot-stone to be 0.028. A slope of 0.00245 foot per foot would be required for the 5-foot-deep riprap-lined trapezoidal channel with base width of 3 feet and 1V-on-3H side slopes. The Froude number of flow in the channel would meet the 3-inch-diameter average size requirement for riprap as well as the maximum recommended value of 0.8 needed to prevent instabilities of flow and excessive wave heights in subcritical open channel flow.

C-5.2.1.10 Similar analyses could be made for design of stable channels with different sizes of riprap protection should other sizes be available and steeper slopes be desired. This could reduce the number of drop structures required to provide the necessary grade change equal to the difference in elevation between that of the local terrain and the drop provided by the slope and length of the selected channel design.

Figure C-15. Depth of Flow and Unit Discharge of Incipient Failure of Riprap-Lined Channel



C-5.2.1.11 The feasibility of a paved rectangular channel on a slope commensurate with that of the local terrain for conveyance of the design discharge at either subcritical or supercritical velocities should also be investigated. Such a channel should be designed to convey the flow with a Froude number less than 0.8 if subcritical, or greater than 1.2 and less than 2.0 if supercritical to prevent flow instabilities and excessive wave heights. It should also be designed to have a depth-to-width ratio as near 0.5 (the most efficient hydraulic rectangular cross section) as practical depending upon the local conditions of design discharge, maximum depth of flow permissible, and commensuration of a slope with that of the local terrain.

C-5.2.1.12 For example, assume that a paved rectangular channel is to be provided with a Manning's n = 0.015 and a slope of 0.01 foot per foot (average slope of local terrain) for conveyance of a design discharge of 400 cubic feet per second at supercritical conditions. A depth-to-width ratio of 0.5 is desired for hydraulic efficiency and a Froude number of flow between 1.2 and 2.0 is desired for stable supercritical flow. The range of values of the parameter $SB^{1/3}/n^2$ (70-180) required to satisfy the desired D/B and range of Froude number of supercritical flow can be determined from Figure C-16. Corresponding values of the parameter $\sqrt{gB^5}$ (0.44-0.68) can also be determined from Figure C-16 for calculation of the discharge capacities of channels that will satisfy the desired conditions. The calculated values of discharge and channel widths can be plotted on log-log paper as shown in Figure C-17 to determine the respective relations for supercritical rectangular channels with a depth-to-width ratio of 0.5, a slope of 0.01 foot per foot, and a Manning's n of 0.015. Figure C-17 may then be used to select a channel width of 7.5 feet for conveyance of the design discharge of 400 cubic feet per second. The exact value of the constraining parameter $SB^{1/3}/n^2$ can be calculated to be 87 and used in conjunction with a D/B ratio of 0.5 and Figure C-16 to obtain corresponding values of the remaining constraining parameters, $Q\sqrt{gB^5}$ = 0.48 and F = 1.4, required to satisfy all of the dimensionless relations shown in Figure C-16. The actual discharge capacity of the selected 7.5-foot-wide channel with a depth of flow equal to 3.75 feet can be calculated based on these relations to ensure the adequacy of the selected design. For example, based on the magnitude of a discharge parameter equal to 0.48, the channel should convey 419 cubic feet per second:

$$Q = 0.48\sqrt{g(7.5)^{5/2}} = 419 \text{ cubic feet per second} \qquad \text{(eq. C-76)}$$

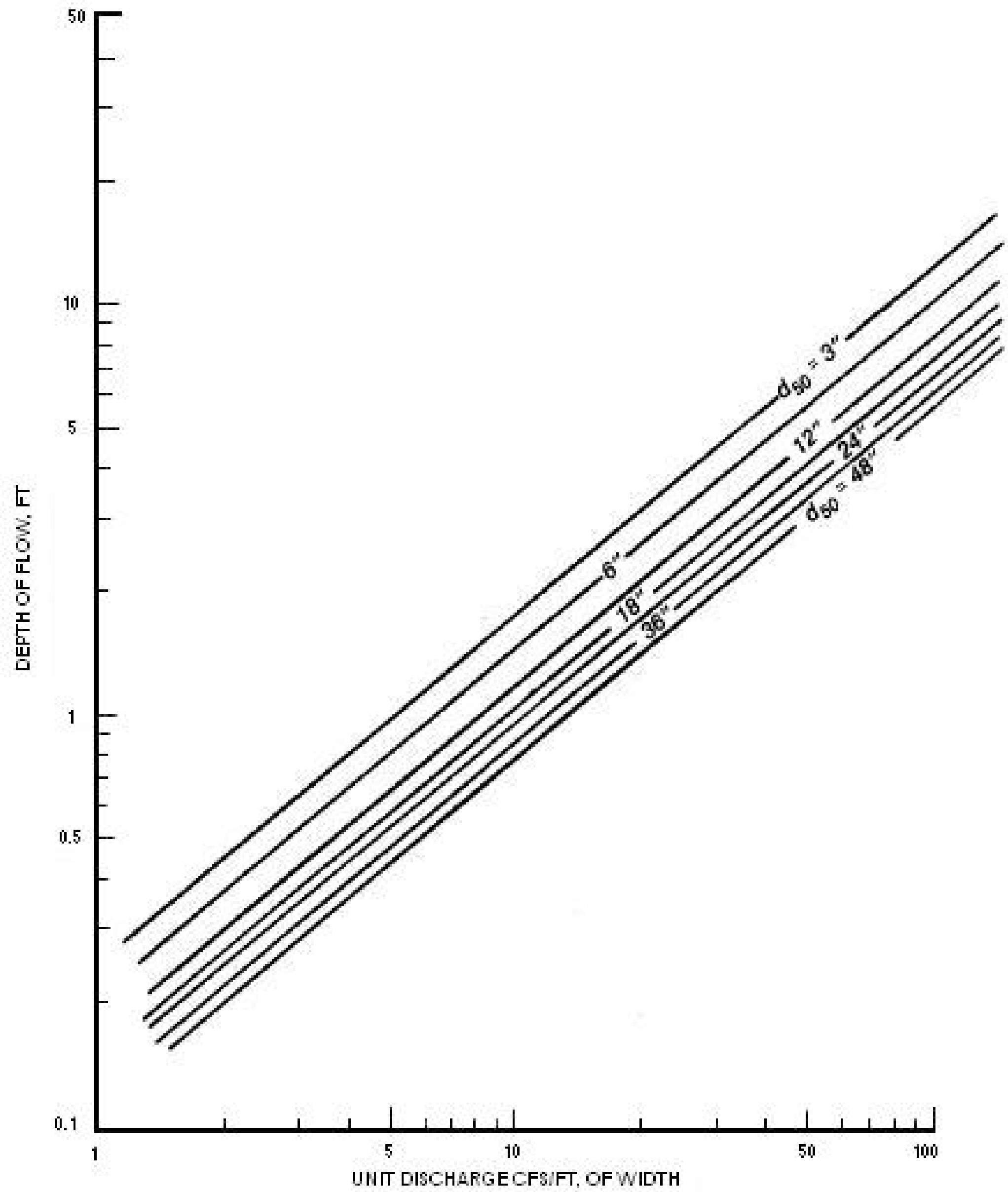
Similarly, based on the magnitude of a Froude number of flow equal to 1.4, the channel should convey a discharge of 432 cubic feet per second:

$$Q = 1.4\frac{\sqrt{g(7.5 \times 3.75)^3}}{7.5} = 432 \text{ cubic feet per second} \qquad \text{(eq. C-77)}$$

Obviously, the capacity of the 7.5-foot-wide channel is adequate for the design discharge of 400 cubic feet per second.

C-5.2.1.13 The feasibility of a paved channel with a slope compatible with that of the local for conveyance of the design discharge at subcritical conditions should be investigated. However, it may not be feasible with slopes of 1 percent or greater. Paved channels for subcritical conveyance of flows should be designed to provide Froude numbers of flow ranging from about 0.25 to 0.8 to prevent excessive deposition and flow instabilities, respectively. If rectangular, paved channels should be designed to have a depth of width radio as near 0.5 as practical for hydraulic efficiency; if

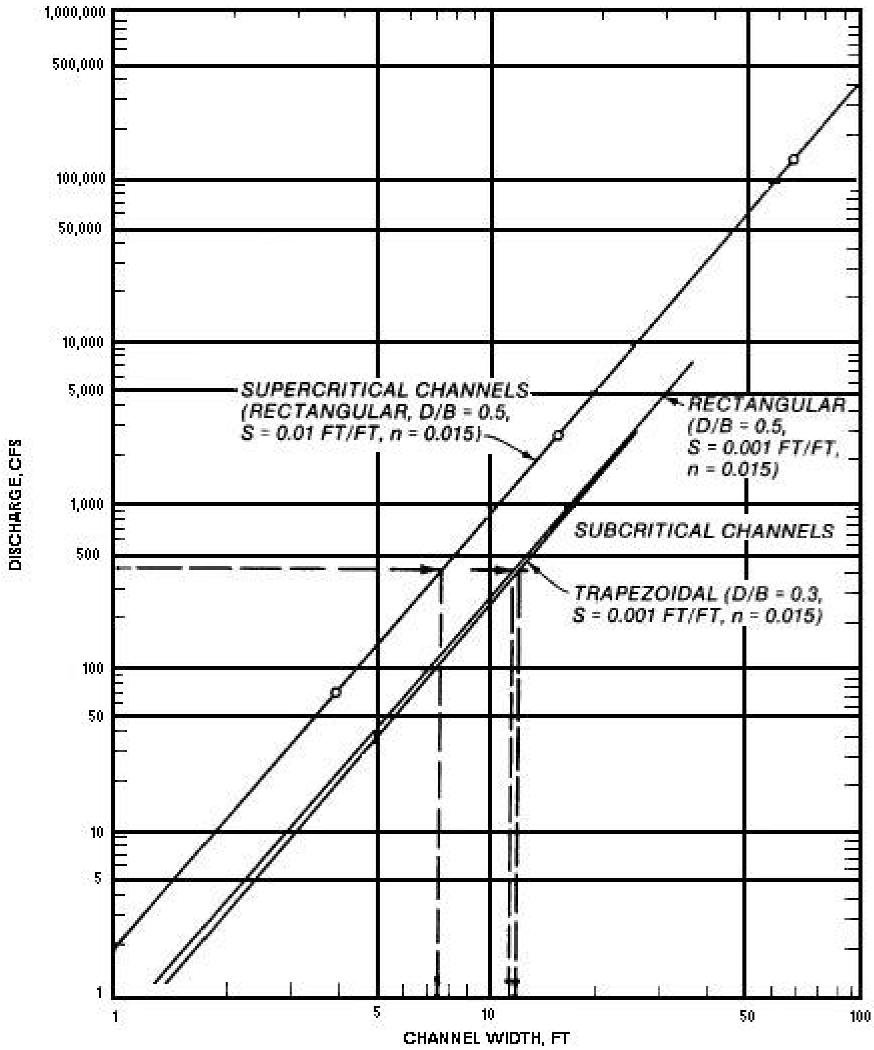
Figure C-16. Flow Characteristics of Rectangular Channels



trapezoidal, they should be designed to have side slopes of 1V on 3H and a depth-to-width ratio of 0.3.

C-5.2.1.14 For example, assume a subcritical paved channel with a Manning's n of 0.015 and slope of 0.01 foot per foot is to be provided for a design discharge of 400 cubic feet per second. The maximum slope and discharge permissible for conveying flow with a Froude number less than 0.8 in a hydraulically efficient rectangular channel with a minimum practical width of 1.0 foot can be determined from Figure C-16. For a D/B = 0.5 and Froude number of flow of 0.8, the corresponding

Figure C-17. Discharge Characteristics of Various Channels



values of $SB^{1/3}/n^2$ and $Q\sqrt{gB^5}$ are determined as 30 and 0.275, respectively. Solving these regulations for S and Q based on n = 0.015 and B = 1 foot yields

$$S = 30\, n^2 / B^{1/3} = 0.00675 \text{ foot per foot} \qquad \text{(eq. C-78)}$$

$$Q = 0.275\sqrt{gB^{5/2}} = 1.56 \text{ cubic feet per second} \qquad \text{(eq. C-79)}$$

Greater widths of hydraulically efficient rectangular channels would convey greater discharges, but slopes flatter than 0.00675 foot per foot would be required to prevent the Froude number of flow from exceeding 0.8. Therefore, a rectangular channel of the most efficient cross section and a slope as steep as 0.01 foot per foot are not practical for subcritical conveyance of the design discharge and the example problem. A similar analysis for any shape of channel would result in the same conclusion; stable subcritical conveyance of the design discharge on a slope of 0.01 foot per foot is not feasible.

C-5.2.1.15 Assuming that the average slope of the local terrain was about 0.001 foot per foot for the example problem, practical subcritical paved channels could be designed as discussed in paragraphs (16) through (19) below.

C-5.2.1.16 Based on the desired range of Froude numbers of flow (0.25 to 0.8) in a rectangular channel of efficient cross section (D/B = 0.5), Figure C-16 indicates the corresponding range of values of the restraining parameters $SB^{1/3}/n^2$ and $Q\sqrt{gB^5}$ to be from 3 to 30 and 0.085 to 0.275, respectively. The relations between discharge and channel width for subcritical rectangular channels with a depth-to-width ratio of 0.5, a slope of 0.001 foot per foot, and a Manning's n of 0.015 can be plotted as shown in Figure C-17 to select the 11.5-foot-width of channel required to convey the design discharge of 400 cubic feet per second.

C-5.2.1.17 As a check, the exact value of $SB^{1/3}/n^2$ can be calculated to be 10.1 and used in conjunction with a D/B ratio of 0.5 and Figure C-16 to obtain corresponding values of the remaining constraining parameters, $Q\sqrt{gB^5}$ = 0.16 and F = 0.47, required to satisfy all of the dimensionless relations for rectangular channels. The actual discharge capacity of the selected 11.5-foot-wide channel with a depth of 5.75 feet can be calculated based on these relations to ensure the adequacy of the selected design. For example, based on the magnitude of the discharge parameter (0.16), the channel should convey 407 cubit feet per second:

$$Q = 0.16\sqrt{g(11.5)^{5/2}} = 407 \text{ cubic feet per second} \qquad \text{(eq. C-80)}$$

Similarly, based on the Froude number of flow to 0.47, the channel should convey a discharge of 422 cubic feet per second:

$$Q = 0.47 \quad \frac{\sqrt{g(11.5\times 5.75)^3}}{11.5} = 422 \text{ cubic feet per second} \qquad \text{(eq. C-81)}$$

Therefore, the 11.5-foot-wide channel is sufficient for subcritical conveyance of the design discharge of 400 cubic feet per second and, based on Figure C-11, is sufficient for transporting materials as large as average size gravel.

C-5.2.1.18 A similar procedure would be followed to design a trapezoidal channel with a depth-to-width ratio of 0.3, a slope of 0.001 foot per foot, and a Manning's n of 0.015 utilizing Figure C-13. For example, in order to maintain a Froude number of flow between 0.25 and 0.75 in a trapezoidal channel with side slopes 1V on 3H and a depth-to-width ratio of 0.3, the constraining parameter of $SB^{1/3}/n^2$ would have to have a value between 2 and 15 (Figure C-13). The relations between discharge and base width for these subcritical trapezoidal channels were plotted as shown in Figure C-17 to select the 12-foot-base width required to convey the design discharge of 400 cubic feet per second.

C-5.2.1.19 As a check, the exact value of $SB^{1/3}/n^2$ was calculated to be 10.2 and used in conjunction with D/B of 0.3 and Figure C-13 to obtain corresponding values of the remaining constraining parameters, $Q/\sqrt{gB^5}$ = 0.15 and F = 0.63, required to satisfy the dimensionless relations of trapezoidal channels. The actual discharge capacity of the selected trapezoidal channel with a base width of 12 feet and a flow depth of 3.6 feet based on these relations would be 425 and 458 cubic feet per second, respectively.

$$Q = 0.15\sqrt{g(12)^{5/2}} = 425 \text{ cubic feet per second} \qquad \text{(eq. C-82)}$$

$$Q = 0.63\sqrt{\frac{\dfrac{g\ 45.6 \times 3.6^3}{2}}{33.6}} = 458 \text{ cubic feet per second} \qquad \text{(eq. C-83)}$$

Therefore, the selected trapezoidal channel is sufficient for subcritical conveyance of the design discharge of 400 cubic feet per second and based on Figure C-11 is sufficient for transporting materials as large as coarse gravel.

C-5.2.2 Having determined a channel that will satisfy the conditions desired for the design discharge, determine the relations that will occur with the anticipated maximum annual discharge and ensure that deposition and/or erosion will not occur under these conditions. It may be necessary to compromise and permit some erosion during design discharge conditions in order to prevent deposition under annual discharge conditions. Lime stabilization can be effectively used to confine clay soils, and soil-cement stabilization may be effective in areas subject to sparse vegetative cover. Sand-cement and rubble protection of channels may be extremely valuable in areas where rock protection is unavailable or costly. Appropriate filters should be provided to prevent leaching of the natural soil through the protective material. Facilities for subsurface drainage or relief of hydrostatic pressures beneath channel linings should be provided to prevent structural failure.

C-6 CONCRETE CHUTE DESIGN

C-6.1 Design a concrete chute to carry 25 cubic feet per second down a slope with a 25 percent grade. The allowable head is 1 foot and Manning's n is 0.014.

C-6.2 Solution one. Using equation 4-21 with no drop at the entrance, $Q=3.1W(H)^{1.5}$, with Q=25 cubic feet per second and H = 1 foot.

$$25 = 3.1W\ (1)^{1.5} \text{ or } W = 8.06\ \textit{feet} \qquad \text{(eq. C-84)}$$

Use W = 8 feet

Now

$$A = Wd = 8d \qquad \text{(eq. C-85)}$$

and

$$R = \frac{\text{area}}{\text{wetted perimeter}} = \frac{8d}{W + 2d} = \frac{8d}{8 + 2d} \qquad \text{(eq. C-86)}$$

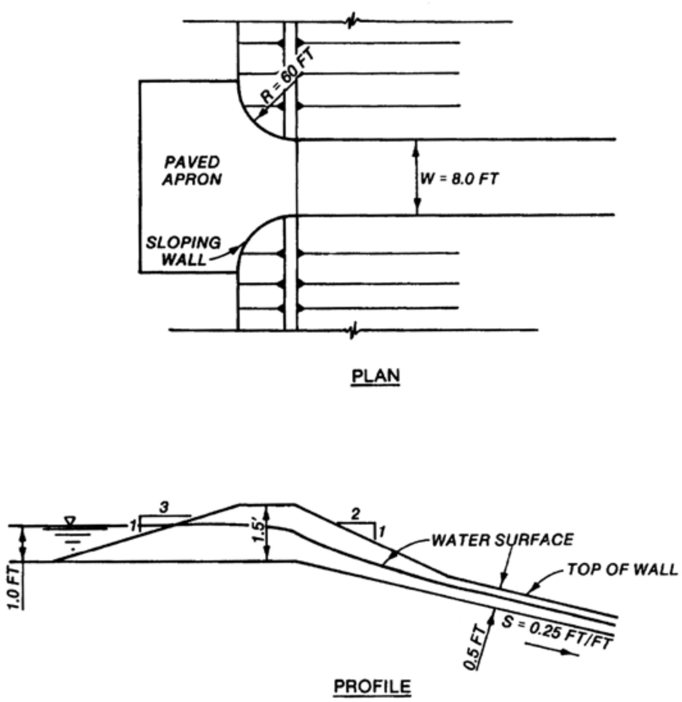
Use Manning's equation (4-22) to determine depth of water:

$$Q = \frac{1.486}{n} A\, S^{1/2} R^{2/3} = \frac{1.486}{0.014} A (0.25)^{1/2} R^{2/3} = 25 \qquad \text{(eq. C-87)}$$

$$25 = \frac{1.486}{0.014} \times 8d \times (0.25)^{1/2} \times = \left(\frac{8d}{8 + 2d} \right)^{2/3} \qquad \text{(eq. C-88)}$$

Solving for d by trial and error, the depth of water is d=0.186 foot. For use in Figure 4-39, the size of the angle of the chute is equal to 0.243 and q=Q/W=25/8=3.125. Thus, $S/q^{1/5}$ equals 0.1935, which corresponds to a design air concentration $T = d_{air}/ (d_{air} + d) = 0.471$. Solving for d_{air} gives 0.166 foot. Then, the total depth of flow is depth of water plus depth of air, 0.352 foot. Wall height should be 1.5 times the total depth of flow or 0.528 foot. One should use 0.5 foot. This design is shown in Figure C-18.

Figure C-18. Design Problem – Solution One



C-6.3 A drop will be provided at the entrance. Therefore, a width of chute can be selected and the appropriate length and depth of drop determined from the curves in Figure 4-38. For this design select a width of 2 feet. Then H/W = 1/2 = 0.5 and $Q/W^{5/2} = 25/(2)^{5/2} = 4.42$. From Figure 4-38, find a curve that matches these values. This is found on the curve for D/w 1.0, on the chart for B/W = 4. Therefore, B = 8 feet and D =2.0 feet. Using Manning's equation (4-22) to determine depth of water as in the first solution, find d_w = 0.493 foot. From Figure 4-39, with q equals 12.5, sine of angle of slope equals 0.243 and d_w equals 0.493 foot, determine the depth of air to be 0.311 foot. Thus, total depth is 0.804 foot. Use 0.80 foot. Wall height is 1.5 times 0.80 foot, or 1.20 feet. This design is shown in Figure C-19.

Figure C-19. Design Problem – Solution Two