APPENDIX D

CHANNEL DESIGN PROBLEM

D-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.

a. Determine gradation of material common to drainage basin from representative samples and sieve analyses.

b. Determine maximum discharges to be experienced annually and during the design storm.

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

d. 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.

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

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

D-2. Channel design.

a. Design the desired channel as indicated in the following steps.

(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.

(2) From Figure D-1 or the equation

$$F = 1.88\,(d_{50}/D)^{1/3}, \qquad \text{(eq D-1)}$$

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 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.

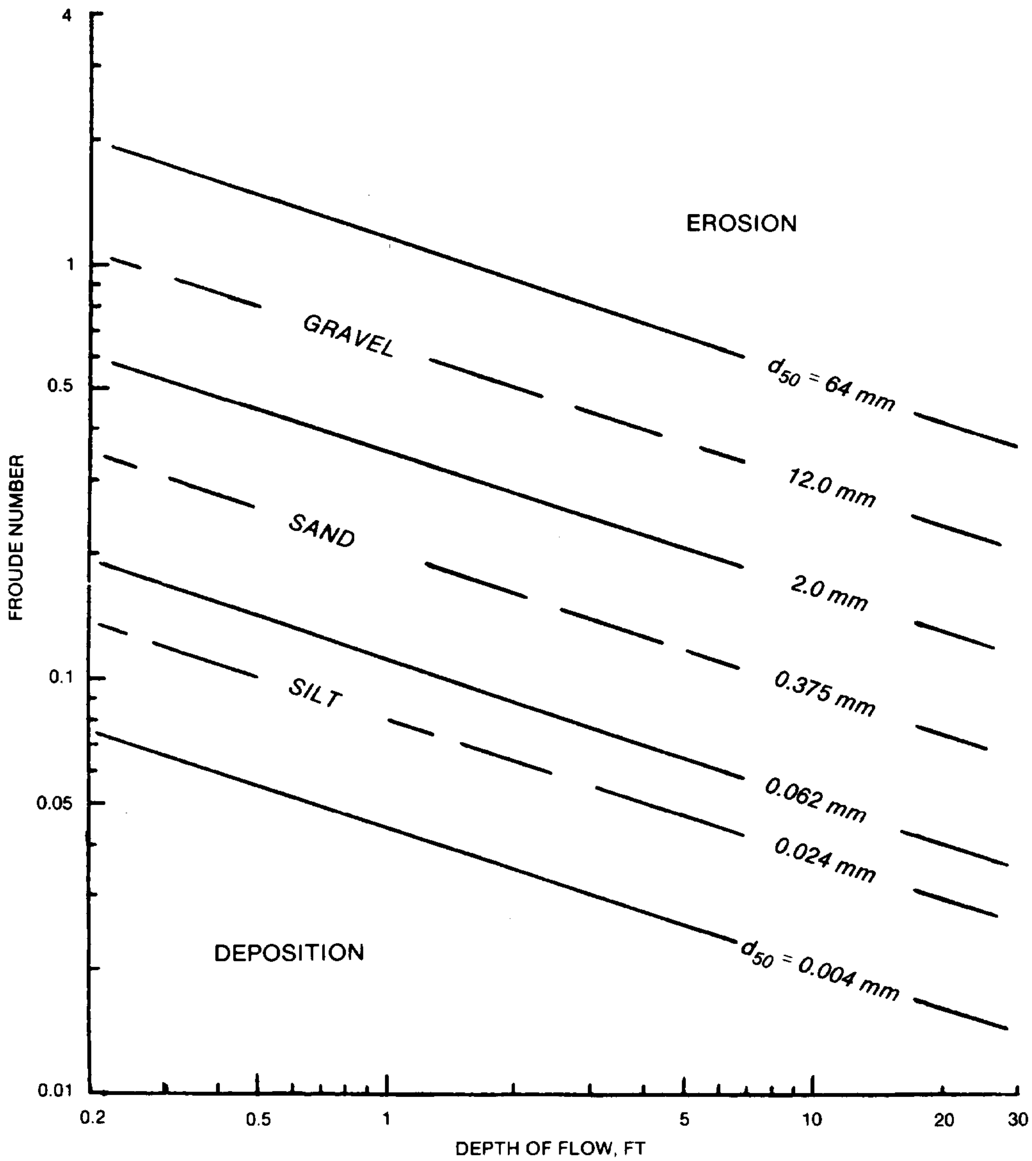

Figure D-1. Froude number and depth of flow required for incipient transport of cohesionless material.

(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

$$q = 10.66\, d_{50}^{1/3} D^{7/6} \qquad \text{(eq D-2)}$$

or figure D-2. 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 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.

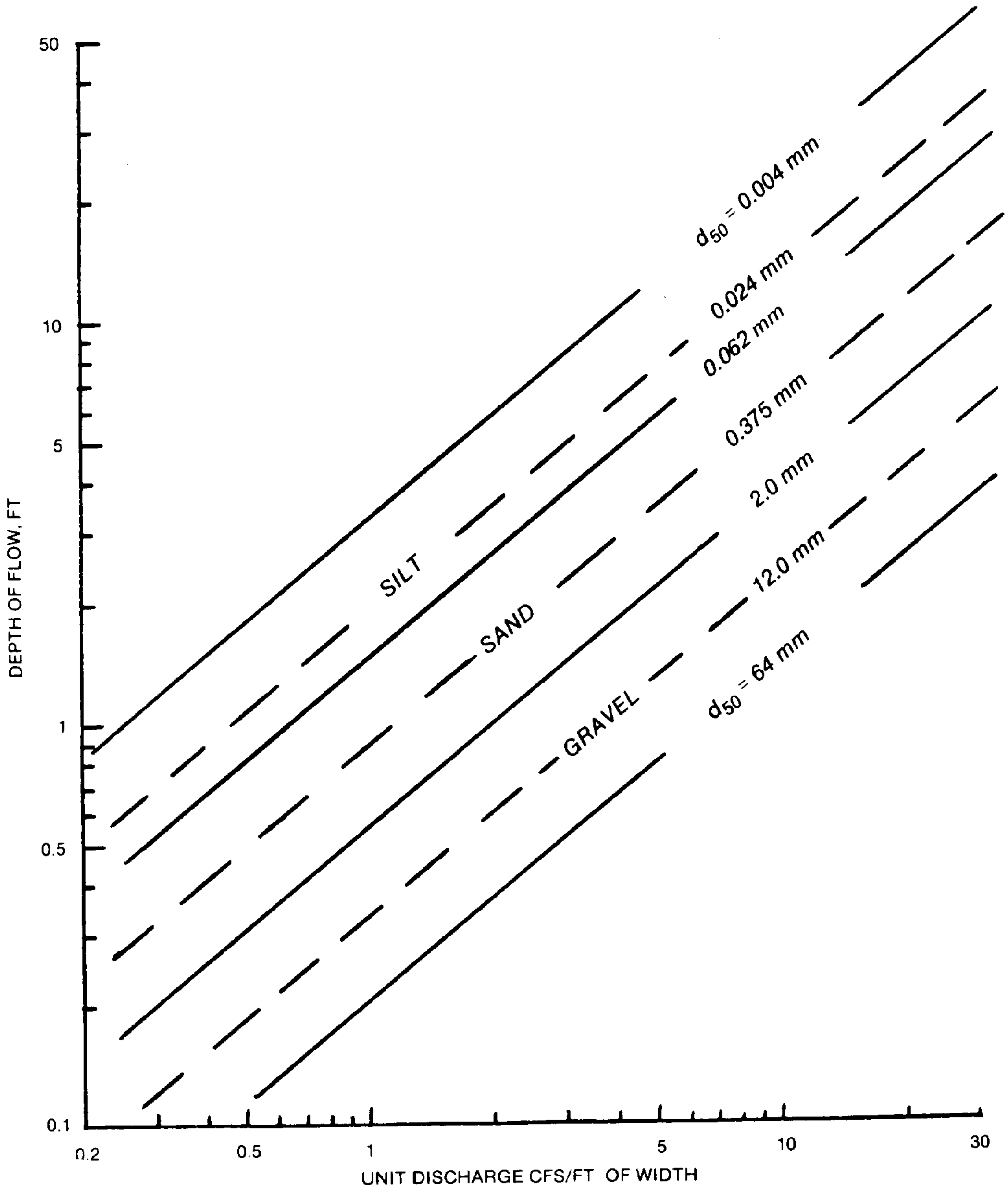

Figure D-2. Depth of flow and unit discharge for incipient transport of cohesionless material.

(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 design 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 IV on 3H required to convey the design discharge with a 5-foot depth of flow would be 25 feet.

(5) The values of the parameters D/B and $Q/\sqrt{g}B^5$ can now be calculated as 0.2 and 0.0225, respectively. Entering figure D-3 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 IV-on-3H side slopes.

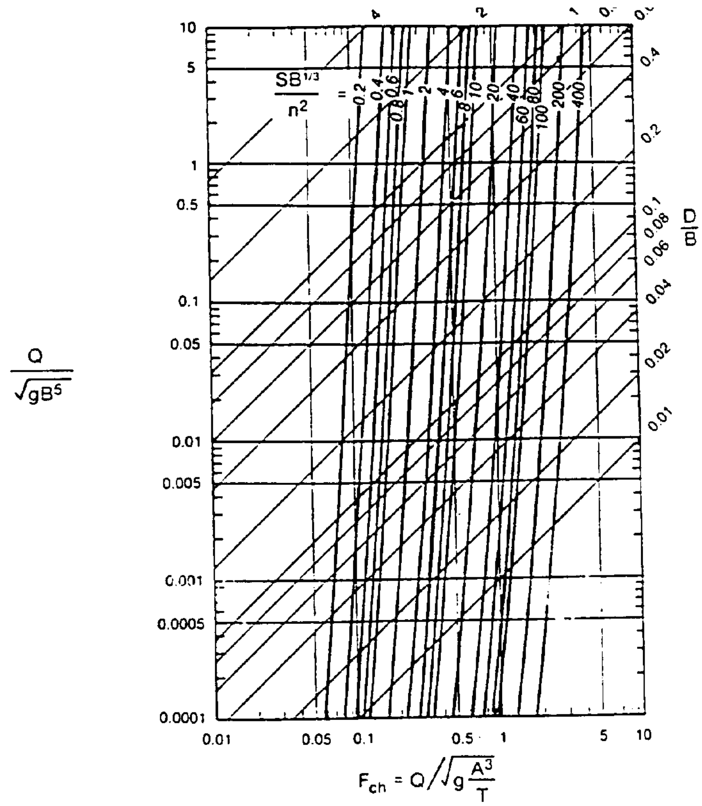

Figure D-3. Flow characteristics of trapezoidal channels with 1V-on-3H side slopes.

(6) The Froude number of flow in the channel is 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 D-3 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.

(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.

(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 depths of flow up to 5 feet can be investigated as follows. The equation, $F = 1.42(d_{50}/D)^{1/3}$, or figure D-4 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,

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

or figure D-5. 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 lV on 3H would be about 3 feet.

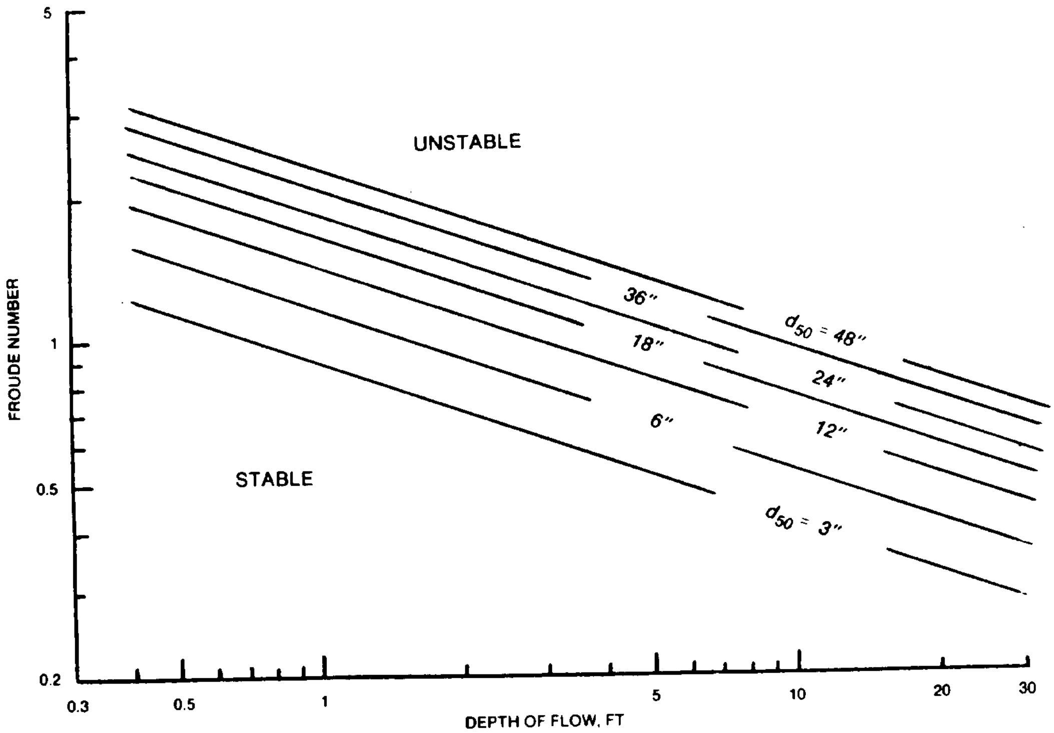

Figure D-4. Froude number and depth of flow for incipient failure of riprap-lined channel.

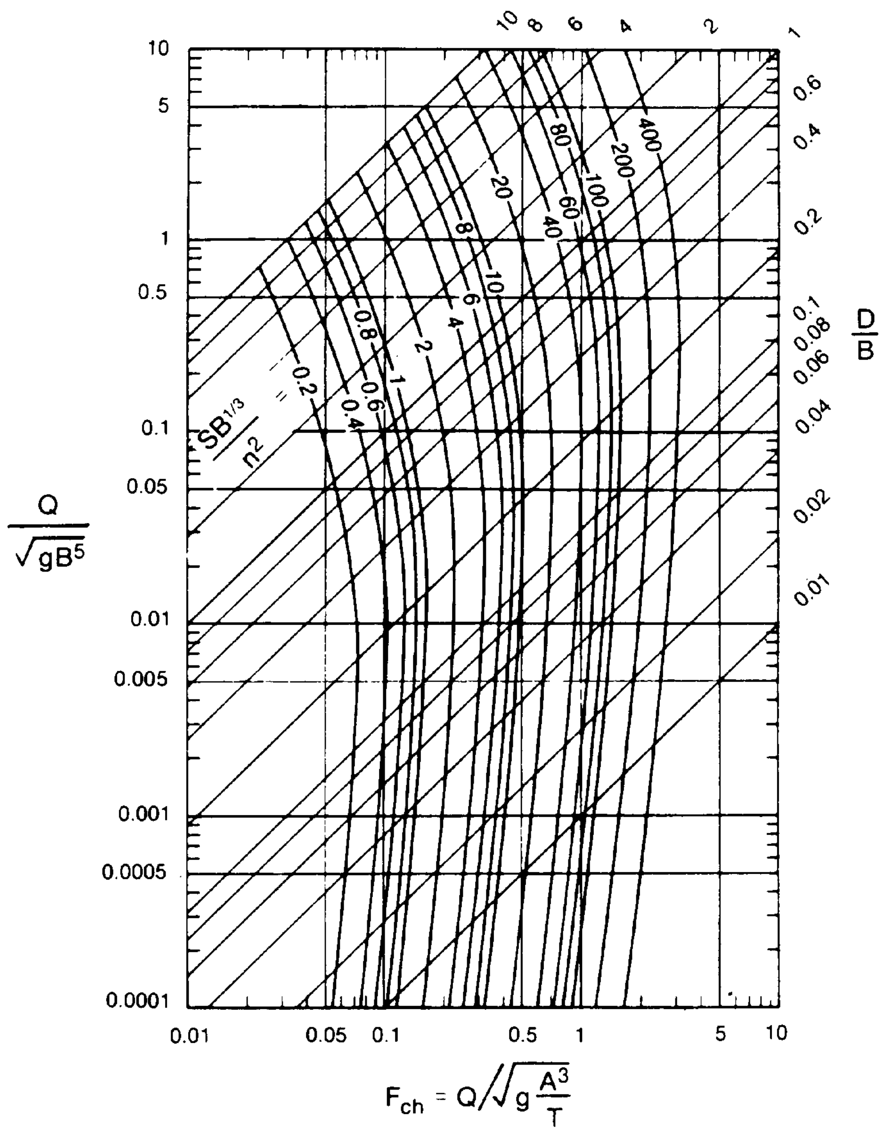

Figure D-5. Depth of flow and unit discharge for incipient failure of riprap-lined channel.

(9) The values of D/B and $Q/\sqrt{gB^5}$ can be calculated as 1.67 and 4.52, respectively. Entering figure D-3 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-311 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.

(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.

(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.

(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 $SB^{1/3}]/n^2(70\text{-}180)$ required to satisfy the desired D/B and range of Froude number of supercritical flow can be determined from figure D-6. Corresponding values of the parameter $\sqrt{gB^5}$ (0.44-0.68) can also be determined from figure D-6 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 D-7 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 D-7 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 D-6 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 D-6. 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:

$$Q = 0.48\sqrt{g}(7.5)^{5/2} = 419 \text{ cubic feet per second} \qquad \text{ed D-4)}$$

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:

$$Q = 1.4 \frac{\sqrt{g(7.5x3.75)^3}}{7.5} = 432 \text{ cubic feet per second} \qquad \text{(ed D-5)}$$

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

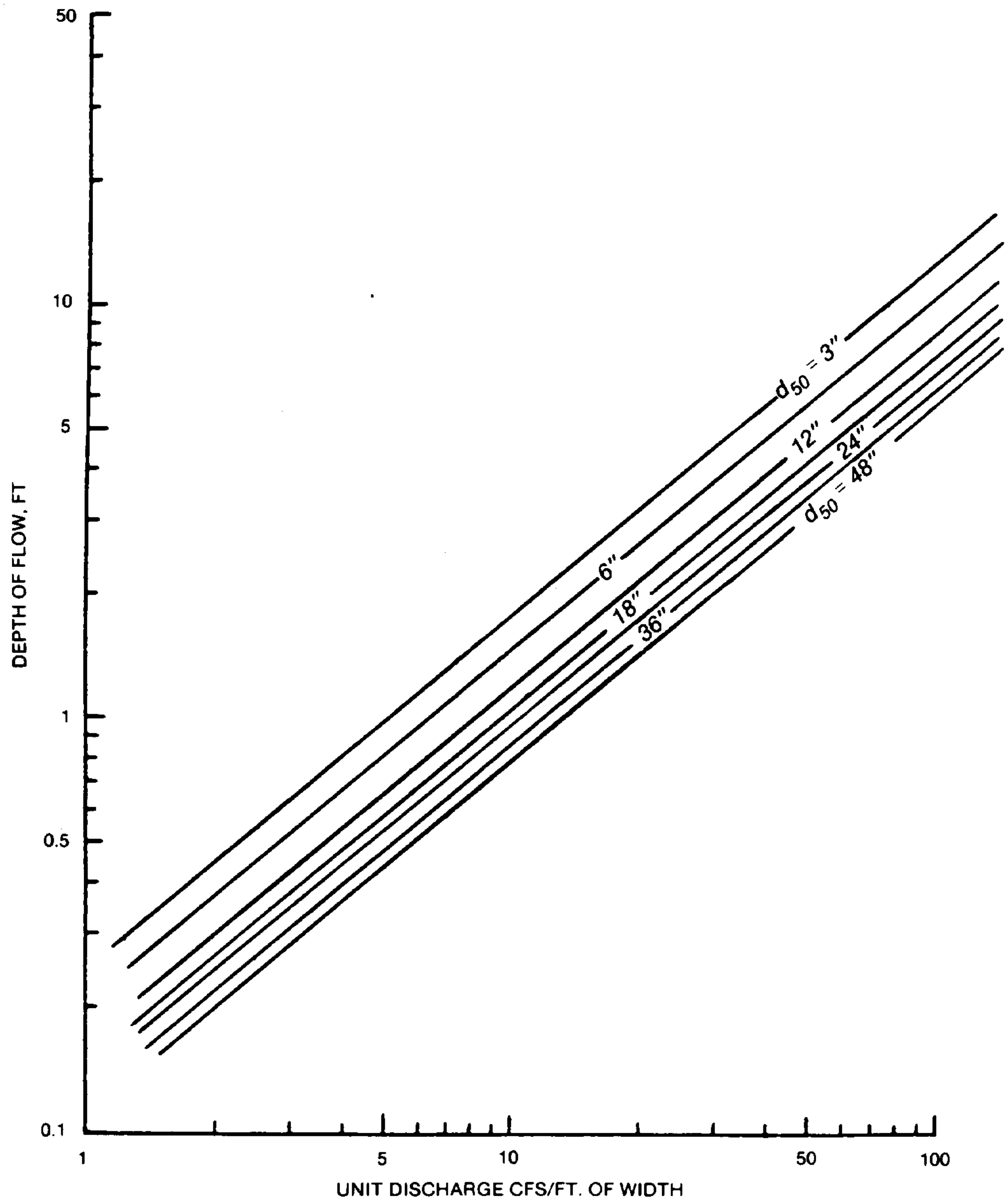

Figure D-6. Flow characteristics of rectangular channels.

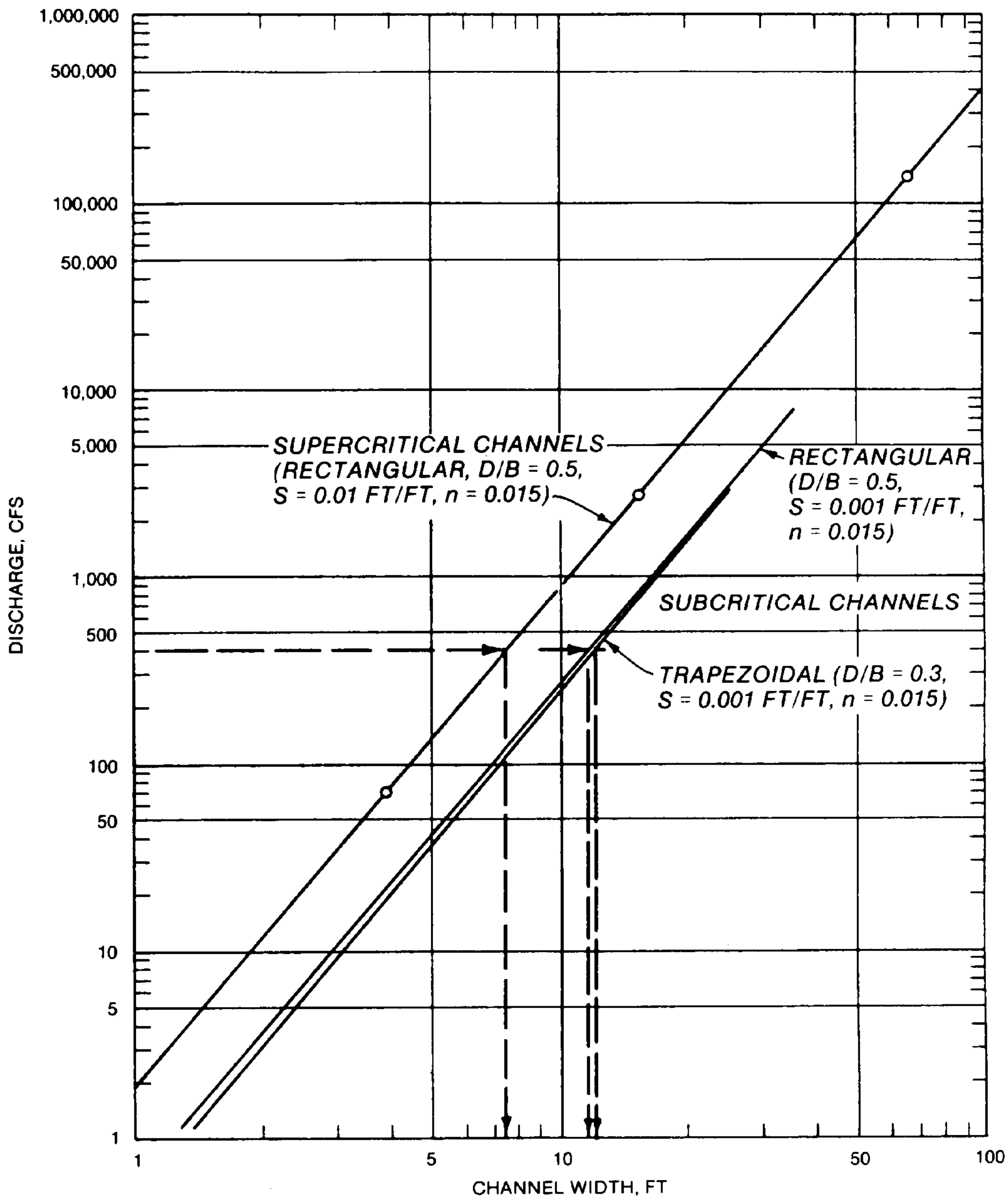

Figure D-7. Discharge characteristics of various channels.

(13) The feasibility of a paved channel with a slope compatible with that of the local terrain 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 trapezoidal, they should be designed to have side slopes of lV on 3H and a depth-to-width ratio of 0.3.

(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 D-6. For a D/B = 0.5 and

Froude number of flow of 0.8, the corresponding 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

$$S = 30\, n^2/B^{1/3} = 0.00675 \text{ foot per foot} \quad \text{(eq D-6)}$$

$$Q = 0.275\sqrt{g}B^{5/2} = 1.56 \text{ cubic feet per second} \quad \text{(eq D-7)}$$

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.

(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.

(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 D-6 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 D-7 to select the 11.5-foot-width of channel required to convey the design discharge of 400 cubic feet per second.

(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 D-6 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:

$$Q = 0.16\sqrt{g}(11.5)^{5/2} = 407 \text{ cubic feet per second} \quad \text{(eq D-8)}$$

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

$$Q = 0.47 \sqrt{\frac{g(11.5 \times 5.75)^3}{11.5}} = 422 \text{ cubic feet per second} \quad \text{(eq D-9)}$$

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 D-1, is sufficient for transporting materials as large as average size gravel.

(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 D-3. For example, in order to maintain a Froude number

of flow between 0.25 and 0.75 in a trapezoidal channel with side slopes lV 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 (fig. D-3). The relations between discharge and base width for these subcritical trapezoidal channels were plotted as shown in figure D-7 to select the 12-foot-base width required to convey the design discharge of 400 cubic feet per second.

(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 D-3 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.

$$Q = 0.15 \sqrt{g}\, (12)^{5/2} = 425 \text{ cubic feet per second} \quad \text{(eq D-10)}$$

$$Q = 0.63 \sqrt{\frac{\frac{g\, 45.6 \times 3.6^3}{2}}{33.6}} = 458 \text{ cubic feet per second} \quad \text{(eq D-11)}$$

Therefore, the selected trapezoidal channel is sufficient for subcritical conveyance of the design discharge of 400 cubic feet per second and based on figure D-1 is sufficient for transporting materials as large as coarse gravel.

b. 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.