CHAPTER 10

OPEN CHANNELS

10-1. General. Maximum use will be made of open channels for drainage consistent with safety and operational requirements since greater flexibility and a higher safety factor can be obtained at lower cost.

10-2. Channel design. The following items merit special consideration in designing channels.

a. Hydraulics. The hydraulic characteristics of the channel may be studied by use of an open channel formula such as the Manning equation:

$$V = \frac{1.49}{n} R^{2/3} S^{1/2}$$

where:

V = velocity of flow in feet per second
n = a coefficient of roughness
R = hydraulic radius in feet
S = slope of the energy gradient

Suggested retardance coefficients and maximum permissible velocities for non-vegetated channels are given in table 10-1. Retardance coefficients for turf-lined channels are a function of both the turf characteristics and the depth and velocity of flow and can be estimated by the graphical relations shown in figure 10-1. It is suggested that maximum velocity in turf-lined channels not exceed 6 fps. In regions where runoff has appreciable silt load, particular care will be given to securing generally nonsilting velocities.

b. Cross section. The selection of the channel cross section is predicted on several factors other than hydraulic elements. Within operational areas the adopted section will conform with the grading criteria. Figure 10-2 indicates typical airfield slope and clearance criteria. Proposed maintenance methods affect the selection of side slopes for turfed channels since gang mowers cannot be used on slopes steeper than 1 to 3, and hand cutting is normally required on steeper slopes. In addition, other factors that might affect the stability of the side slopes, such as soil characteristics, excessive ground water inflow, and bank erosion from local surface-water inflow should be addressed.

c. Linings. Earth channels normally require some type of lining such as that obtained by developing a strong turf of a species not susceptible to rank growth. Several grass species are discussed in

Table 10-1.

Suggested Coefficients of Roughness and Maximum Permissible Mean Velocities for Open Channels

Material	n	Maximum Permissible Mean Velocity Feet per Second
Concrete, with surfaces as indicated:		
Formed, no finish	0.014	---
Trowel finish	0.012	---
Float finish	0.012	---
Gunite, good section	0.016	30
Concrete, bottom float finish, sides as indicated:		
Cement rubble masonry	0.020	20
Cement rubble masonry, plastered	0.018	25
Rubble lined, uniform section	0.030-0.045	7-13
Asphalt:		
Smooth	0.012	15
Rough	0.016	12
Earth, uniform section:		
Sandy silt, weathered	0.020	2.0
Silty clay	0.020	3.5
Soft shale	0.020	3.5
Clay	0.020	6.0
Soft sandstone	0.020	8.0
Gravelly soil, clean	0.025	6.0
Natural earth, with vegetation	0.03-0.150	6.0
Grass swales and ditches[1]		6.0

1 See figure 10-1

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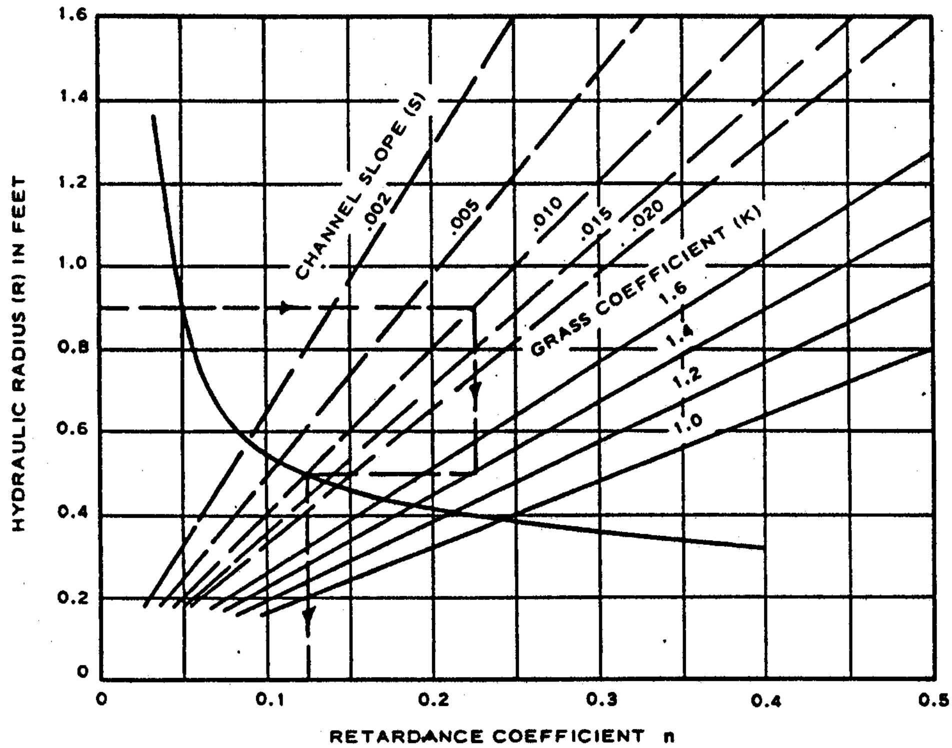

GRASS COEFFICIENTS (K) FOR DENSE AIRFIELD TURF

GRASS SPECIES	AVG LENGTH OF GRASS IN INCHES		
	<6	6-12	>12
BUFFALO	1.6	--	--
BLUE GRAMMA	1.5	1.4	1.3
BLUE GRASS	1.4	1.3	1.2
BERMUDA	1.4	1.3	1.2
LESPEDEZA SERICEA	1.3	1.2	1.1

EXAMPLE:

DETERMINE n FOR 4-INCH BERMUDA GRASS CHANNEL WITH R = 0.9 AND S = .010.

FROM TABLE K = 1.4 AND FROM GRAPH, FOLLOWING DASHED LINE, n IS EQUAL TO 0.125.

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FIGURE 10-1. RETARDANCE COEFFICIENTS FOR FLOW IN TURFED CHANNELS

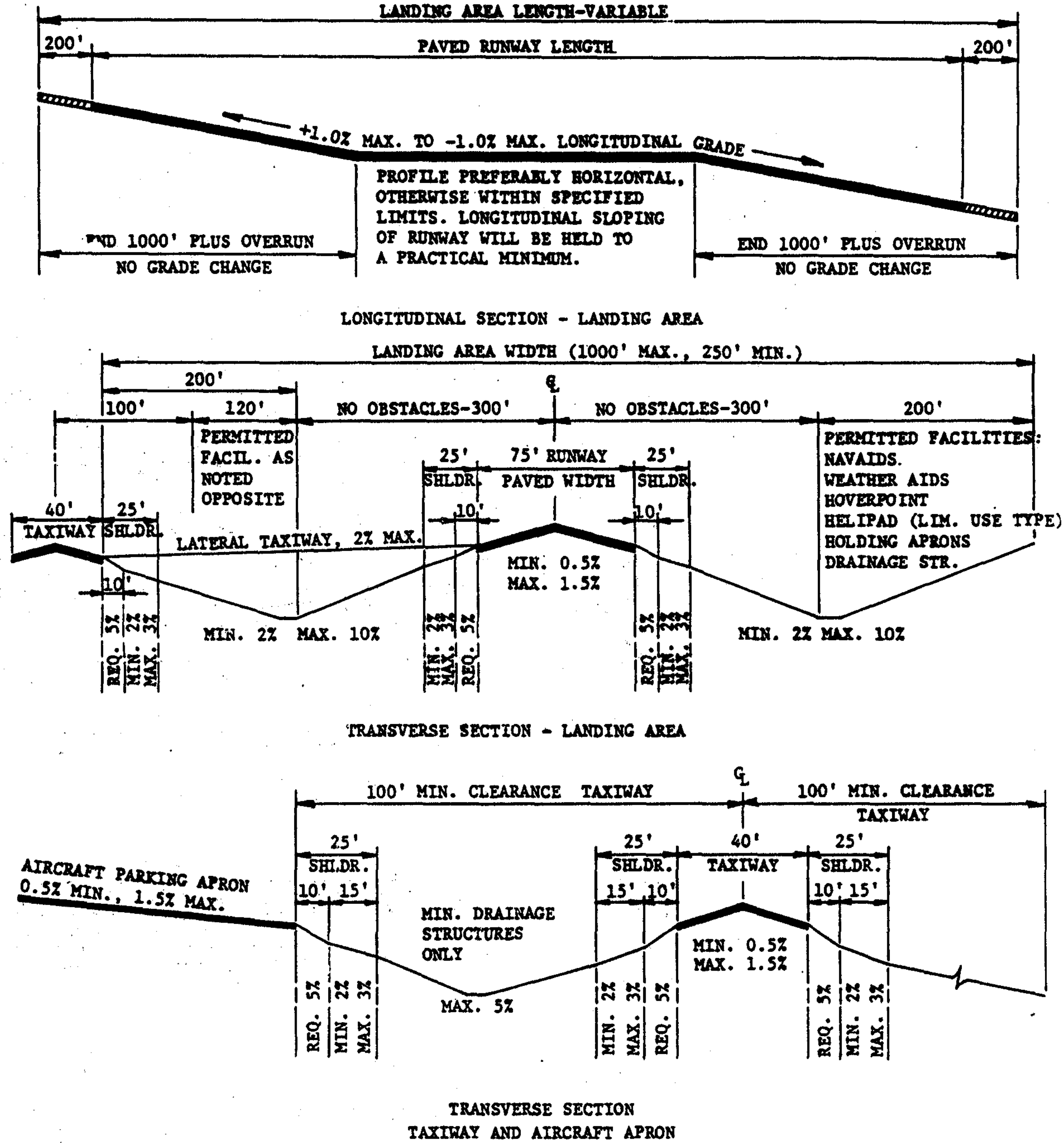

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FIGURE 10-2. AIRFIELD RUNWAY, TAXIWAY, APRON, AND OVERRUN GRADES paragraph 15-2. In particularly erosive soils, special methods will be necessary to establish the turf quickly or to provide supplemental protection by mulching or similar means. Where excessive velocities are to be encountered or where satisfactory turf cannot be established and maintained, it may be necessary to provide a paved channel.

d. Turbulence. An abrupt change in the normal flow pattern induces turbulence and results in excessive loss of head, erosion, or deposition of silt. Such a condition may result at channel transitions, junctions, storm-drain outlets, and reaches of excessive curvature, and special attention will be given to the design of structures at these locations.

e. Inflow conditions. Uncontrolled inflow from drainage areas adjacent to open channels has been a source of numerous failures and requires special consideration in the design of a surface drainage system. This local inflow is particularly detrimental where, due to the normal irregularities experienced in grading operations, runoff becomes concentrated and results in excessive erosion as it flows over the sides of the channel. Experience indicates the desirability of constructing a berm at the top edge of the channel to prevent inflow except at designated points where an inlet properly protected against erosion is provided. The inlet may vary from a sodded or paved chute to a standard field inlet with a storm-drain connection to the channel. Erosion resulting from inflow into shallow drainage ditches or swales with flat side slopes can be controlled by a vigorous turfing program supplemented by mulching where required. See part four chapter 15 for more details on turfs.

f. Froude number of flow. Stable channels relatively free of deposition and/or erosion can be obtained provided the Froude number of flow in the channel is limited to a certain range depending upon the type of soil. An analysis of experimental data indicates that the Froude number of flow (based on average velocity and depth of flow) required to initiate transport of various diameters of cohesionless material, d_{50}, in a relatively wide channel can be predicted by the empirical equation 10-1:

$$F = 1.88 \, (d_{50}/D)^{1/3} \qquad \text{(eq 10-1)}$$

where:

F = Froude number of flow
d_{50} = diameter of average size stone, feet
D = maximum desired depth of flow, feet

10-3. Design problem.

a. Design procedure. This design procedure is based on the premise that the above empirical relation can be used to determine the Froude number of flow in the channel required to initiate or prevent movement of various sizes of material. Relations based on the Manning formula can then be applied to determine the geometry and slope of a channel of practical proportion that will convey flows with Froude numbers within a desired range such that finer material will be transported to prevent deposition, but larger material will not be transported to prevent erosion. The following steps will permit the design of a channel that will satisfy the conditions desired for the design discharge and one that will insure no deposition or erosion under these conditions.

(1) Determine gradation of material common to drainage basin from representative samples and sieve analyses.

(2) Determine maximum discharges to be experienced annually and during the design storm.

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

(4) Based on the gradation of the local material (sizes and percentages of the total by weight) exercise judgment as to the sizes of material that should and should not be transported. 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. Compute ratios of the diameter of the materials that should and should not be transported at the maximum depth of flow, d_{50}/D.

(5) Compute the Froude numbers of flow required to initiate transport of the selected sizes of cohesionless materials based on equation 10-1 to determine the range of F desired in the channel.

b. Channel design. 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 cfs. Also assume that a channel depth of 6 feet is the maximum that can be tolerated from the standpoint of the existing ground water level, minimum freeboard of 1 foot, and other considerations such as ease of excavation, maintenance, and aesthetics.

(2) From figure 10-3 or equation 10-1, 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

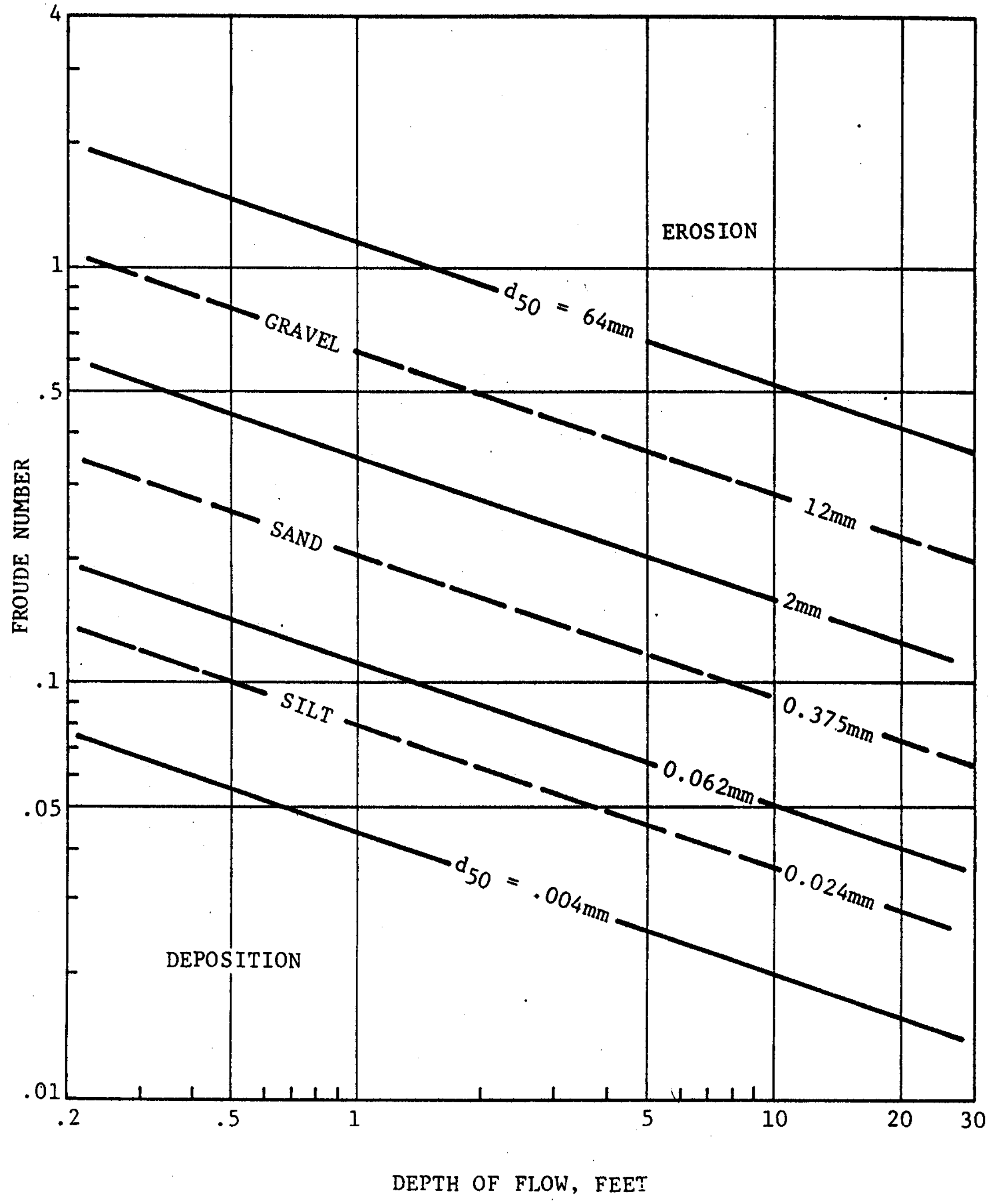

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FIGURE 10-3. FROUDE NUMBER AND DEPTH OF FLOW REQUIRED FOR INCIPIENT TRANSPORT OF COHESIONLESS MATERIAL should not cause severe erosion or deposition of the medium sand common to the basin with a flow depth of 5-foot in the desired channel.

(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 cfs/foot of width from the following equation:

$$q = 10.66\ d_{50}^{1/3} D^{7/6}$$

where:

q = discharge per foot of width, cfs/foot
d_{50} = diameter of average size stove, feet
D = depth of flow in channel, feet

or figure 10-4. In addition, it is indicated that a unit discharge of about 13 cfs/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 cfs/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.

(4) The width of a rectangular channel (B) and the average width of a trapezoidal channel required to convey the maximum rate of runoff of 400 cfs 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 (B) with side slopes of 1V-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 $Q/(gB^5)^{1/2}$ can now be calculated as 0.2 and 0.0225, respectively. Entering figure 10-5 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_{ch}, respectively. Assuming a Manning's n of 0.025, a slope of 0.000203 ft/ft 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.

(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

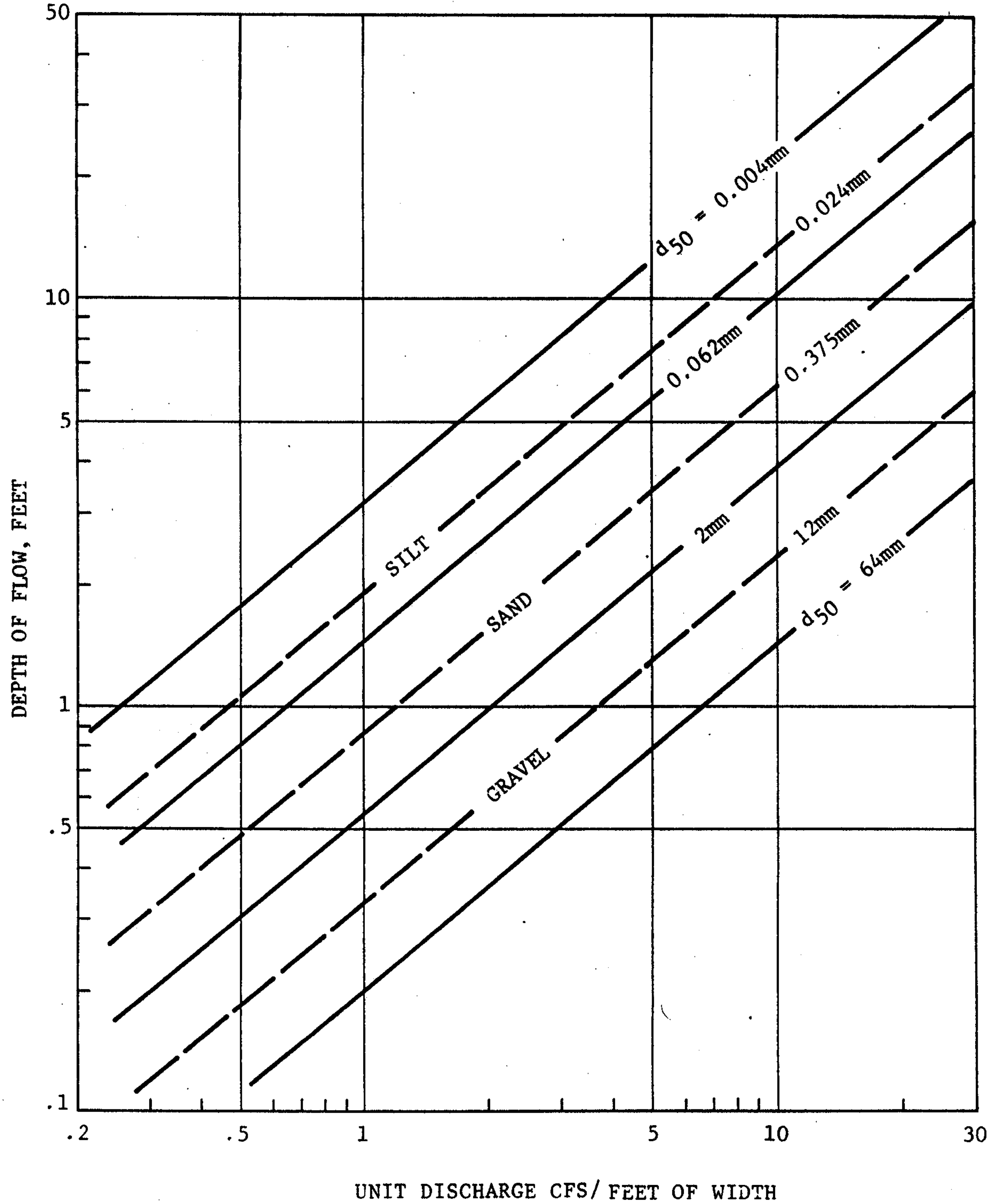

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FIGURE 10-4. DEPTH OF FLOW AND UNIT DISCHARGE FOR INCIPIENT TRANSPORT OF COHESIONLESS MATERIAL

DEFINITION OF TERMS:

D = DEPTH OF FLOW IN CHANNEL, FEET
B = BASE WIDTH OF CHANNEL, FEET
Q = DISCHARGE, CFS
G = ACCELERATION DUE TO GRAVITY, FEET/SECOND
S = SLOPE OF CHANNEL BOTTOM
N = MANNING'S COEFFICIENT OF ROUGHNESS

F_{ch} = FROUDE NUMBER OF FLOW IN CHANNEL

$$F_{ch} = \frac{Q}{\sqrt{g\frac{A^3}{T}}}$$

WHERE:

A = CROSS SECTIONAL AREA OF FLOW IN CHANNEL, SQ. FT.

T = TOP WIDTH OF FLOW IN CHANNEL, FEET

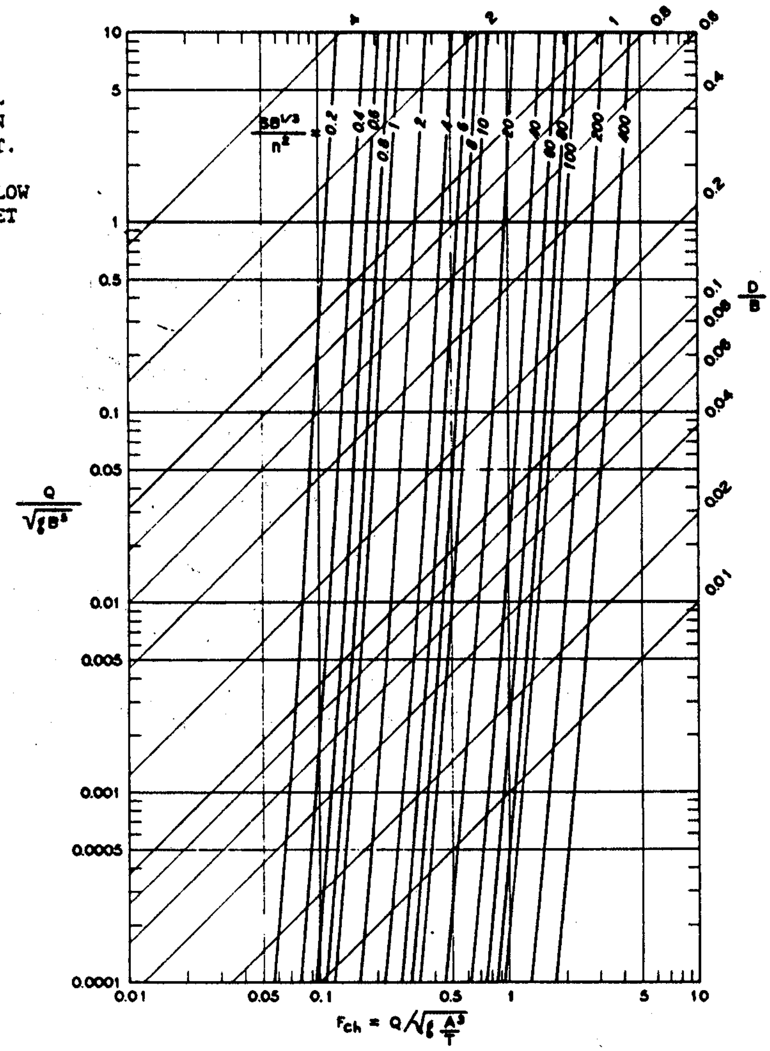

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FIGURE 10-5. FLOW CHARACTERISTICS OF TRAPEZOIDAL CHANNELS WITH 1-ON-3 SIDE SLOPES desired to convey the design discharge of 400 cfs with a Froude number of 0.16 in a trapezoidal channel of 25-foot base width and 1V-on-3H side slopes, the values of 0.0225 and 0.16 for $Q/(gB^5)^{1/2}$ and F_{ch}, respectively, can be used in conjunction with figure 10-5 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/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 mild. In the event that 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 a source of stone exists 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 cfs 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 10-6 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. Similarily, the maximum unit discharge permissible (33 cfs/foot of width) can be determined by the following equation:

$$q = 8.05\ d_{50}{}^{1/3} D^{7/6}$$

or figure 10-7. For conservative design, it is recommended that the maximum unit discharge be limited to about 2/3 of this value or say 22 cfs/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 cfs 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.

(9) The values of D/B and $Q/(gB^5)^{1/2}$ can be calculated as 1.67 and 4.52, respectively. Entering figure 10-5 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_{ch}, respectively. Assuming 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/foot would be required for the 5-foot-deep riprap lined trapezoidal channel with base

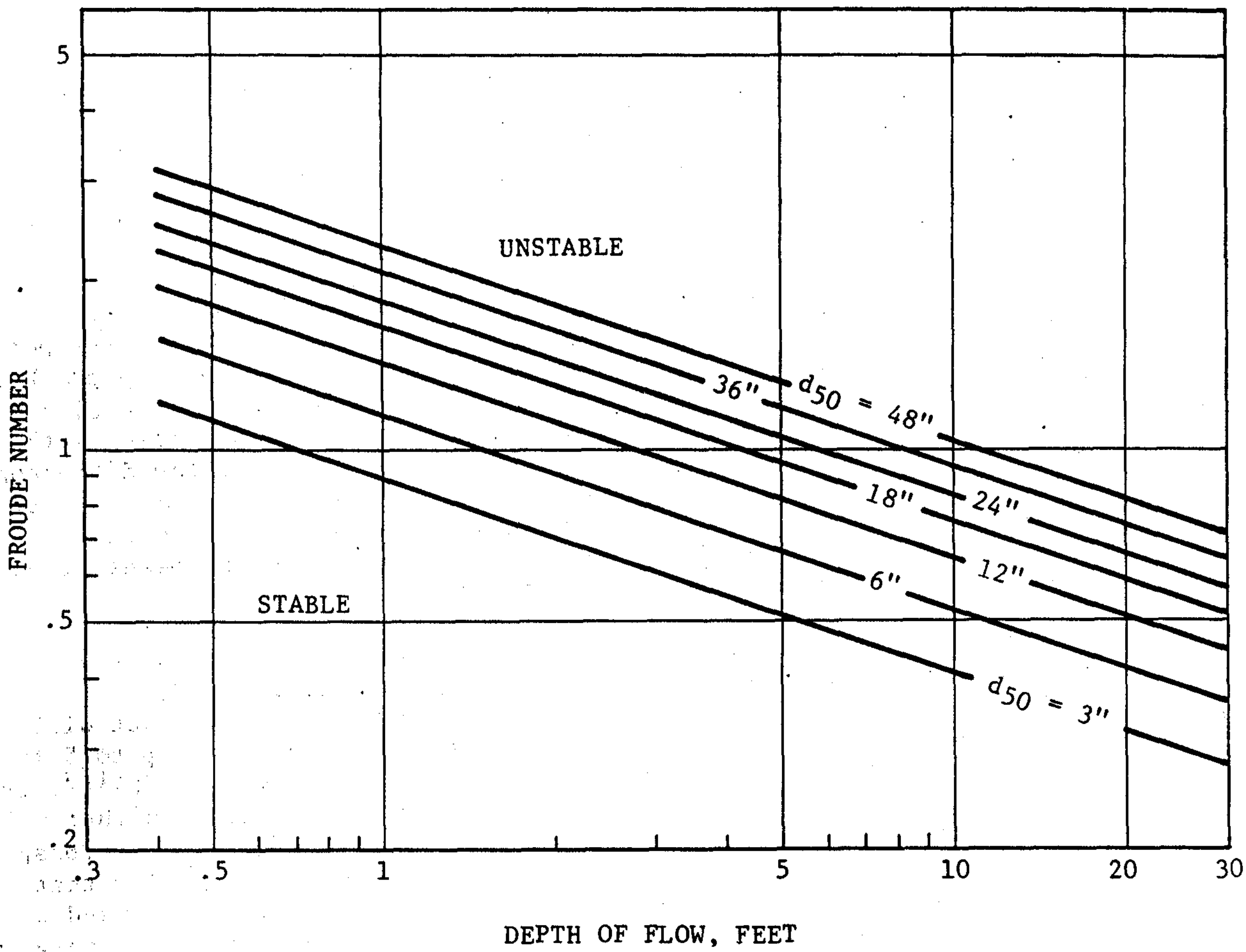

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FIGURE 10-6. FROUDE NUMBER AND DEPTH OF FLOW FOR INCIPIENT FAILURE OF RIPRAP LINED CHANNEL

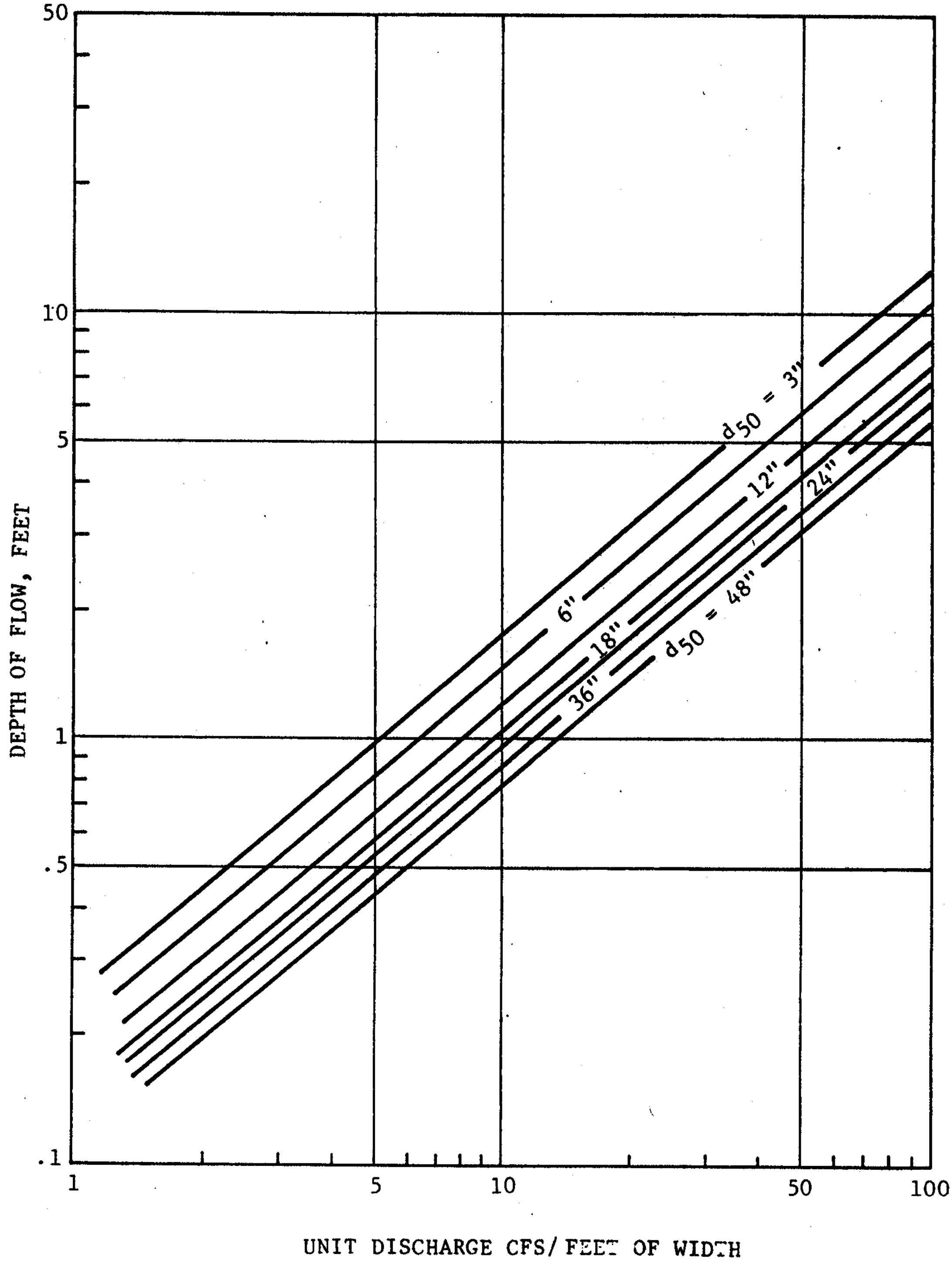

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FIGURE 10-7. DEPTH OF FLOW AND UNIT DISCHARGE FOR INCIPIENT FAILURE OF RIPRAP LINED CHANNEL width of 3 feet and 1V-on-3H side slopes. The Froude number of flow in the channel would be satisfactory relative to the stability of the 3-inch-diameter average size of riprap as well as the maximum recommended value of 0.8 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 a slope commensurate 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/foot (average slope of local terrain) for conveyance of a design discharge of 400 cfs 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 10-8. Corresponding values of the parameter $Q/(gB^5)^{1/2}$ (0.44-0.68) can also be determined from figure 10-8 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 10-9 to determine the respective relations for supercritical rectangular channels with a depth-to-width ratio of 0.5, a slope of 0.01 foot/foot, and a Manning's n of 0.015. Figure 10-9 may then be used to select a channel width of 7.5 feet for conveyance of the design discharge of 400 cfs. 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 10-8 to obtain corresponding values of the remaining constraining parameters, $Q/(gB^5)^{1/2} = 0.48$ and $F = 1.4$, required to satisfy all of the dimensionless relations shown in figure 10-8. 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

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- S = SLOPE OF CHANNEL BOTTOM
- N = MANNING'S COEFFICIENT OF ROUGHNESS

$$F_{ch} = \frac{Q}{\sqrt{g \frac{A^3}{T}}}$$

WHERE:
- A = CROSS SECTIONAL AREA OF FIGW IN CHANNEL, SQ. FT.
- T = TOP WIDTH OF FLOW IN CHANNEL, FEET

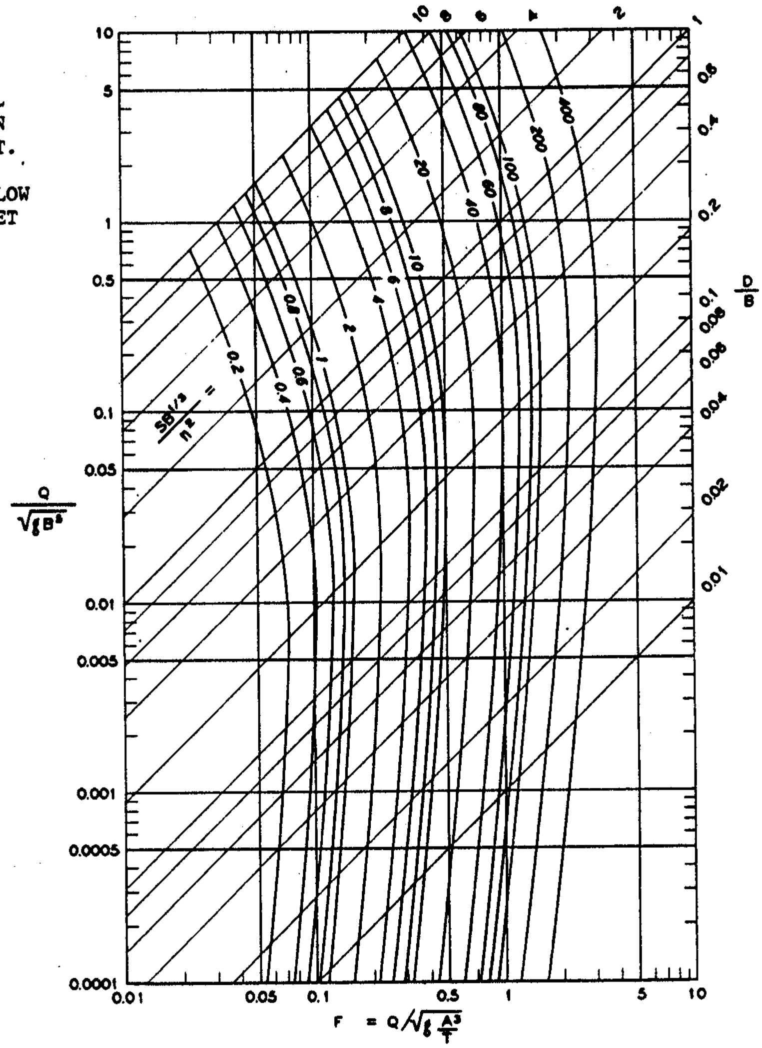

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FIGURE 10-8. FLOW CHARACTERISTICS OF RECTANGULAR CHANNELS

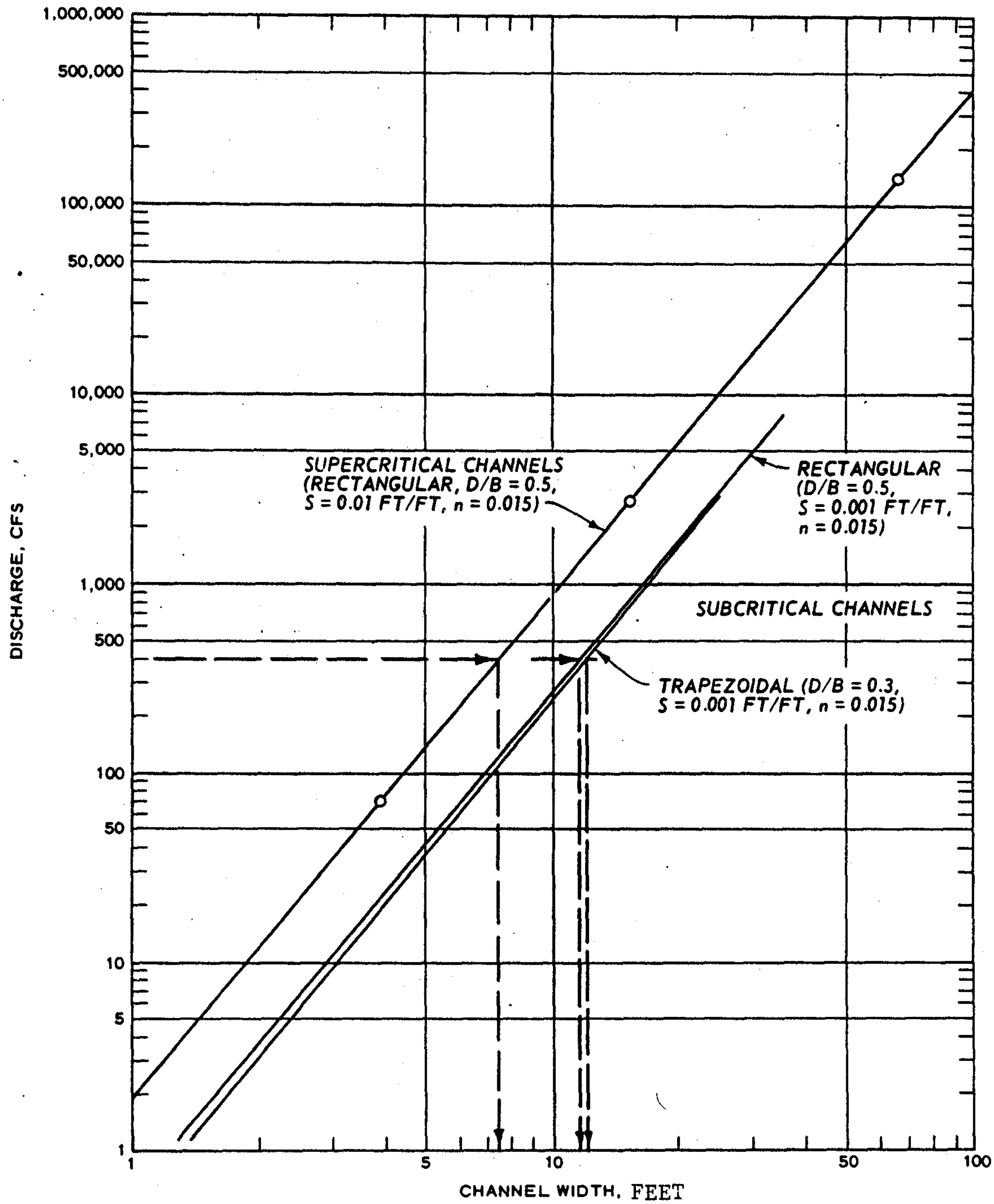

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FIGURE 10-9. DISCHARGE CHARACTERISTICS OF VARIOUS CHANNELS relations to insure the adequacy of the selected design. For example, based on the magnitude of a discharge parameter equal to 0.84, the channel should convey 419 cfs:

$$Q = 0.48\ (g(7.5)^5)^{1/2} = 419\ \text{cfs}$$

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

$$Q = 1.4\left(\frac{g(7.5 \times 3.75)^3}{7.5}\right)^{1/2} = 432\ \text{cfs}$$

Obviously, the capacity of the 7.5-foot-wide channel is adequate for the design discharge of 400 cfs.

(13) The feasibility of 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 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 ratio as near 0.5 as practical for hydraulic efficiency; if trapezoidal, they should be designed to have side slopes of 1V-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/foot is to be provided for a design discharge of 400 cfs. 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 10-8. For a D/B = 0.5 and Froude number of flow of 0.8, the corresponding values of $SB^{1/3}/n^2$ and $Q/\ gB^5$ are determined as 30 and 0.275, respectively. Solving these relations for S and Q based on n = 0.015 and B = 1 foot yields.

$$S = 30\ n^2/B^{1/3} = 0.00675\ \text{ft/ft}$$
$$Q = 0.275\ g^{1/2}\ B^{5/2} = 1.56\ \text{cfs}$$

Greater widths of hydraulically efficient rectangular channels would convey greater discharges, but slopes flatter than 0.00675 foot/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/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/foot is not feasible.

(15) Assuming that the average slope of the local terrain was about 0.001 foot/foot for the example problem, practical subcritical paved channels could be designed as discussed in (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 10-8 indicates the corresponding range of values of the restraining parameters $SB^{1/3}/n^2$ and $Q/\ gB^5$ 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 0.01 foot/foot, and a Manning's n of 0.015 can be plotted as shown in figure 10-9 to select the 11.5-foot-width of channel required to convey the design discharge of 400 cfs.

(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 10-8 to obtain corresponding values of the remaining constraining parameters, $Q/(gB^5)^{1/2} = 0.16$ 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 insure the adequacy of the selected design. For example, based on the magnitude of the discharge parameter (0.16), the channel should convey 407 cfs;

$$Q = 0.16\ (g(11.5)^5)^{1/2} = 407\ \text{cfs}$$

Similarly, based on the Froude number of flow equal to 0.47, the channel should convey a discharge of 422 cfs:

$$Q = 0.47 \left(\frac{g\ (11.5 \times 5.75)^3}{11.5} \right)^{1/2} = 422\ \text{cfs}$$

Therefore, the 11.5-foot-wide channel is sufficient for subcritical conveyance of the design discharge of 400 cfs and, based on figure 10-3 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/foot, and a Manning's n of 0.015 utilizing figure 10-5. 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 (fig 10-5). The relations

between discharge and base width for these subcritical trapezoidal channels were plotted as shown in figure 10-4 to select the 12-foot-base width required to convey the design discharge of 400 cfs.

(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 10-6 to obtain corresponding values of the remaining constraining parameters, $Q/(gB^5)^{1/2} = 0.15$ 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 cfs, respectively.

$$Q = 0.15\,(g(12)^5)^{1/2} = 425 \text{ cfs}$$

$$Q = 0.63\left(\frac{g\,(45.6/2 \times 3.6)^3}{33.6}\right)^{1/2} = 458 \text{ cfs}$$

Therefore, the selected trapezoidal channel is sufficient for subcritical conveyance of the design discharge of 400 cfs and based on figure 10-3 is sufficient for transporting materials as large as coarse gravel.

c. Channel analysis. 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 insure that deposition and/or erosion will not be experienced 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 have considerable merit 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.