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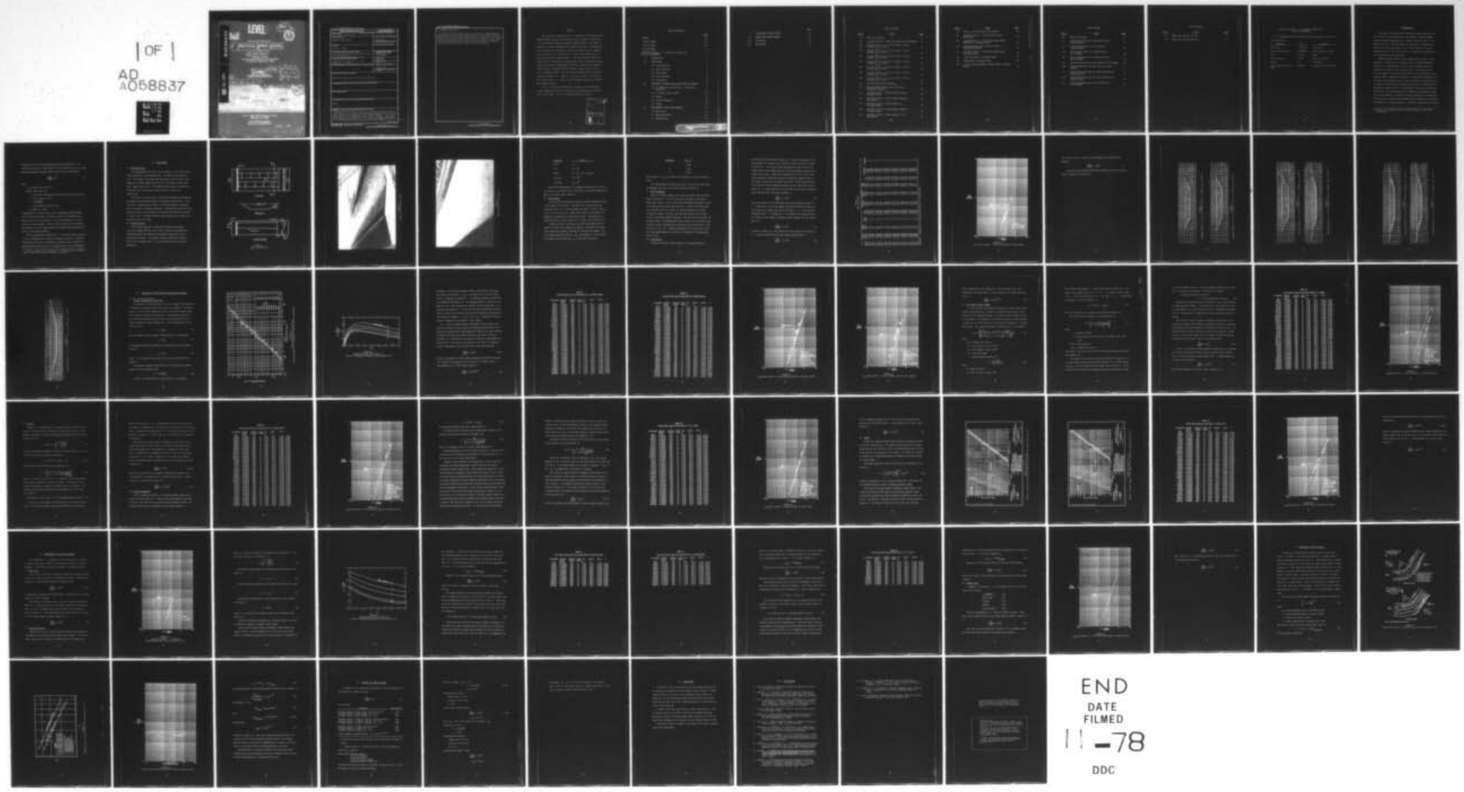

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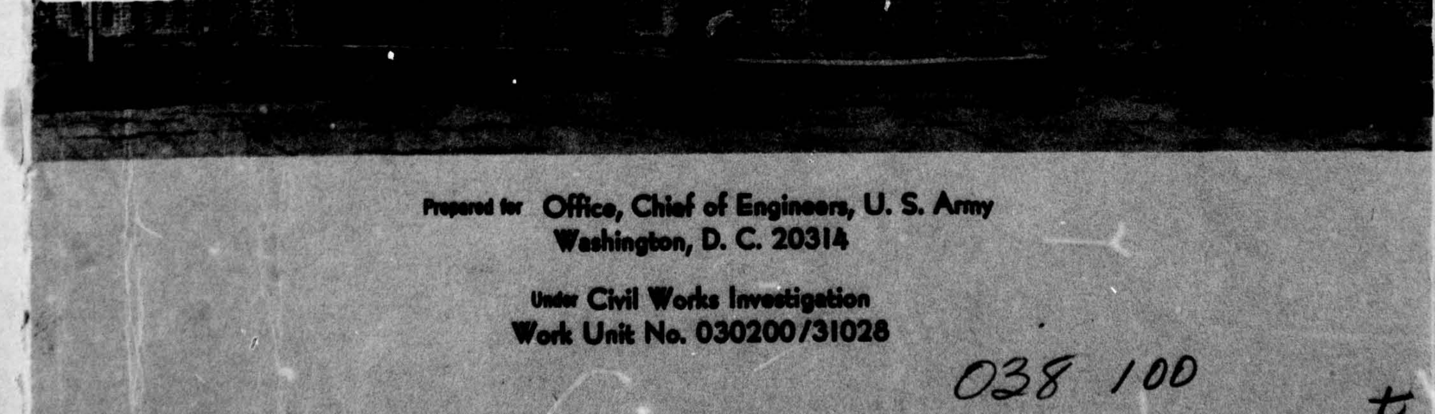

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Determination of stable riprap size is a problem that has been studied extensively but not yet solved. Existing design methods are based on the shear stress exerted by the flowing water on the channel boundaries. The various methods available for computing the shear stress do not agree. Determination of the amount of shear stress a given size riprap can withstand depends upon which investigator's coefficient is used in the Shields' equation.

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The objective of this investigation was to develop a riprap design procedure based on known or easily calculated variables that properly describes riprap stability. Model tests of riprap stability were used in this investigation to insure that the proposed design procedure is applicable to the higher turbulence levels found in decelerating flow in open channels. Design curves for bottom riprap and side slope riprap in straight channels are presented. Tentative criteria for riprap in channel bends are discussed.

PREFACE

This report was prepared by Mr. S. T. Maynord of the Spillways and Channels Branch, Hydraulic Structures Division, Hydraulics Laboratory, U. S. Army Engineer Waterways Experiment Station (WES). This report is essentially a thesis submitted by Mr. Maynord in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering to the faculty of the University of Texas at Arlington, and is a study concerned with riprap stability. The study described herein was conducted by the Hydraulics Laboratory, WES, under Civil Works Investigation, work unit No. 030200/31028, "Effects of Water Flow on Riprap in Flood Channels," Waterways Research Program, sponsored by the Office, Chief of Engineers (OCE). The study was accomplished under the general direction of Messrs. J. L. Grace, Jr., and N. R. Oswalt. This report was reviewed by Mr. S. B. Powell of OCE, Technical Monitor of the Waterways Research Program.

COL G. H. Hilt, CE, and COL John L. Cannon, CE, were Directors of WES during the period of this study and the preparation and publication of this report. Mr. F. R. Brown was Technical Director.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
cubic feet per second	0.02831685	cubic metres per second
feet	0.3048	metres
feet per second	0.3048	metres per second
inches	25.4	millimetres
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre

I. INTRODUCTION

The subject investigation was conducted to develop practical design criteria for sizing riprap in open channels. Existing design criteria consider parameters such as shear or tractive force at the boundaries (1-5)*. Several methods are available for computing the shear stress in an open channel (1,2). These methods do not yield comparable results (3,6), and can lead to confusion in using the tractive force method to design riprap.

Gradually varied flow in an open channel can be in one of three conditions: uniform flow, accelerating flow, or decelerating flow. Equations for computing shear stress in an open channel have been formulated for uniform flow conditions (2,4). These equations are routinely applied to all three flow conditions for the purpose of designing riprap. According to Stevens at Colorado State University (7), the shear stress equations can be used in uniform or accelerating flow. For these two conditions the turbulence in the flow is created at the boundary and shear stress is a good measure of the level of turbulence in the flow. For decelerating flow the shear stress equations should not be used because of intensified vorticity generated in an expansion. This vorticity is intense and irregular and can resemble the turbulence downstream of an energy dissipator. The subject investigation involved

---

* Numbers in parentheses refer to reference numbers listed under Bibliography.

determination of the design parameters which are applicable to all three flow conditions. Model studies (8,9) conducted at the U. S. Army Engineer Waterways Experiment Station show that the relationship

$$\frac{D_{50}}{\text{depth}} = CF^3 \qquad (1)$$

where

D_{50} = mean stone size, ft*

depth = water depth, ft

C = coefficient determined from laboratory and field testing

F = Froude number of flow

= $V/\sqrt{g \text{ depth}}$

V = mean channel velocity, ft/sec

g = gravity, ft/sec^2

is applicable for sizing riprap. This investigation includes model tests of riprap stability in straight reaches for decelerating flow. From those tests the coefficient C will be determined for bottom riprap in an open channel. Curves for safe design will be presented and comparisons will be made between the relations developed and five existing riprap design methods.

After determining the coefficient C for bottom riprap, values of C will be determined for riprap on a channel side slope. Using the limited information that is available on channel bends, tentative design curves for stable rock size in channel bends will be determined.

---

* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page xi.

II. MODEL TESTS

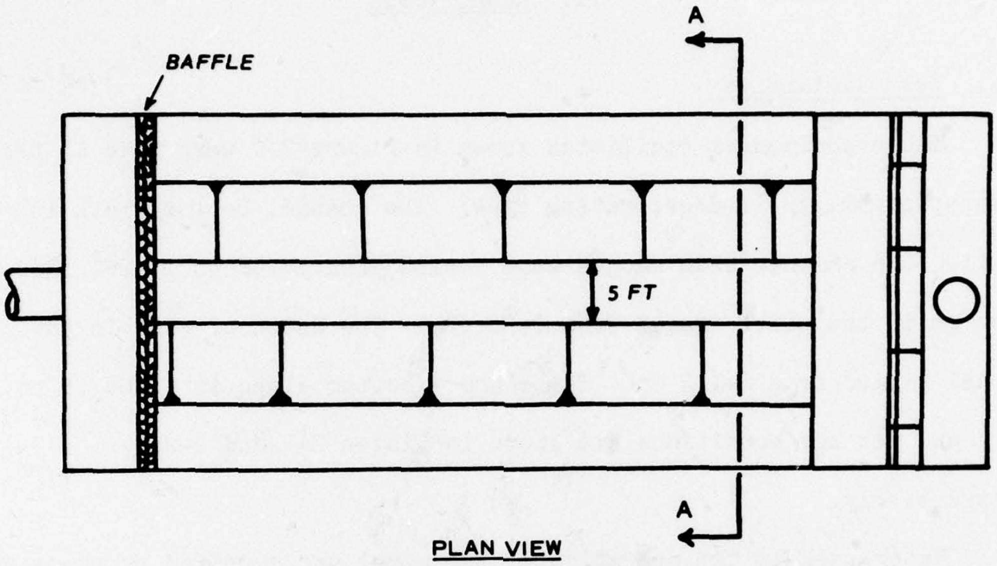
2-1 Test Facilities

The experimental facilities shown in Figure 2-1 were used to test riprap stability in decelerating flow. The channel bottom width is 5 ft. The channel side slopes were varied from 1V:4H to 1V:2H. Discharge in the model ranged from 0-35 cfs. The depth of flow in the model ranged from 0-1.3 ft. The channel bottom slope is 0.008 ft/ft. Dry and wet bed conditions are shown in Plates 2-1 and 2-2, respectively.

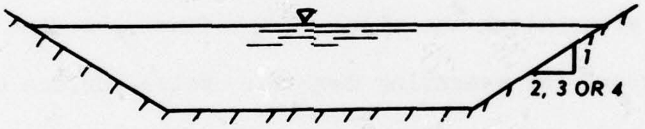
Water used in the operation of the model was supplied by pumps and discharges were measured by means of calibrated venturi meters. Steel rails set to grade along the sides of the flume provided a reference plane and support for measuring devices. Water-surface elevations were measured by means of point gages and velocities were measured by means of a pitot tube. Tailwater elevations were regulated by a gate at the downstream end of the flume.

2-2 Scale Relations

The accepted equations of hydraulic similitude, based upon the Froude number equality, can be used to express the mathematical relations between the dimensions and hydraulic quantities of the models and prototypes. The general relations expressed in terms of model scale or length ratio, L_r , are presented in the following tabulation:



PLAN VIEW



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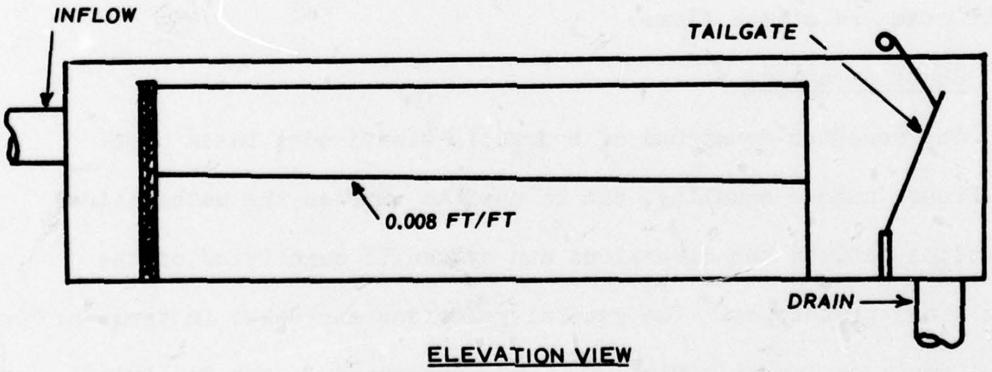


ELEVATION VIEW

FIGURE 2-1
Model Test Facility

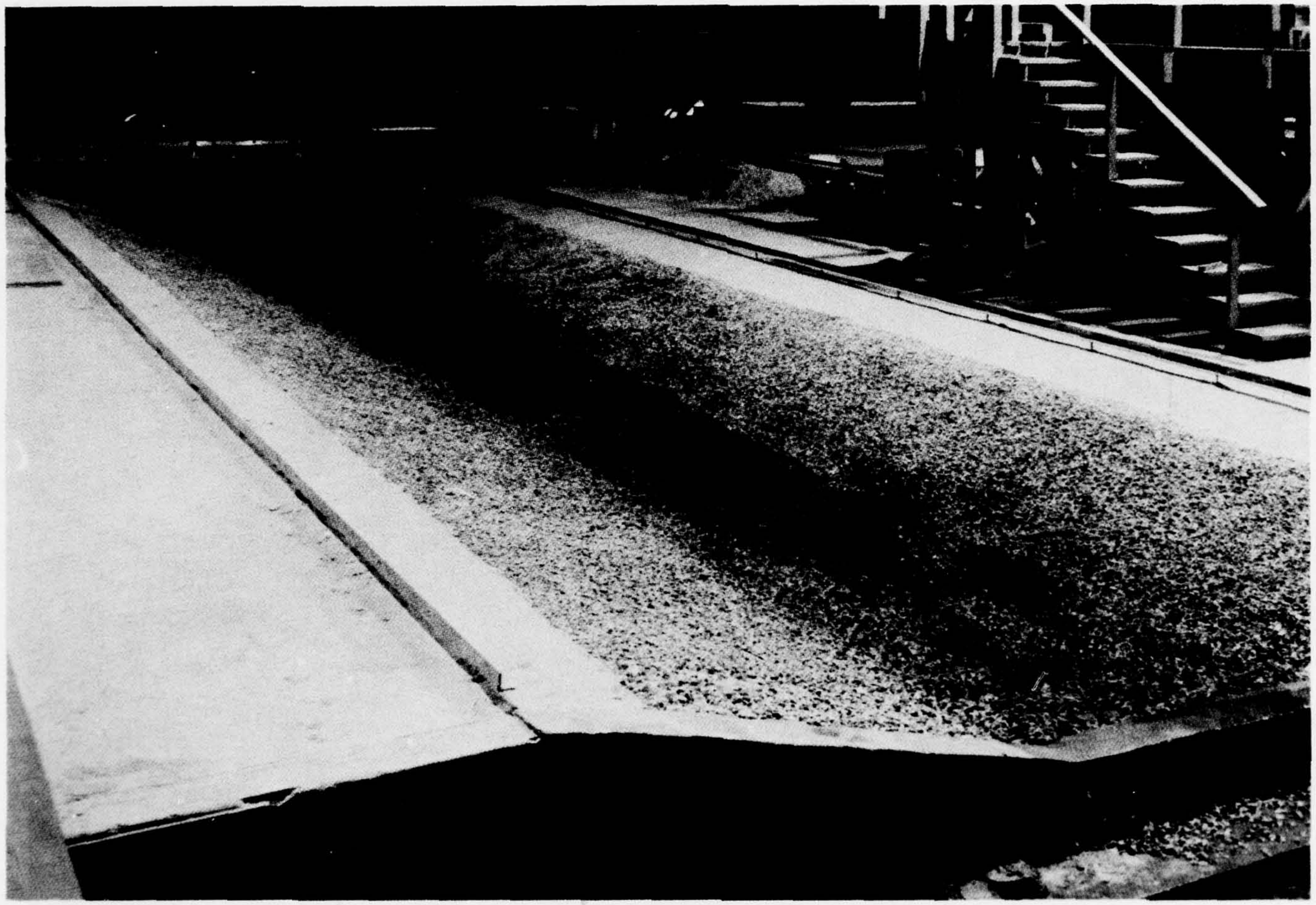


PLATE 2-1
Model Test Facility, Dry Bed

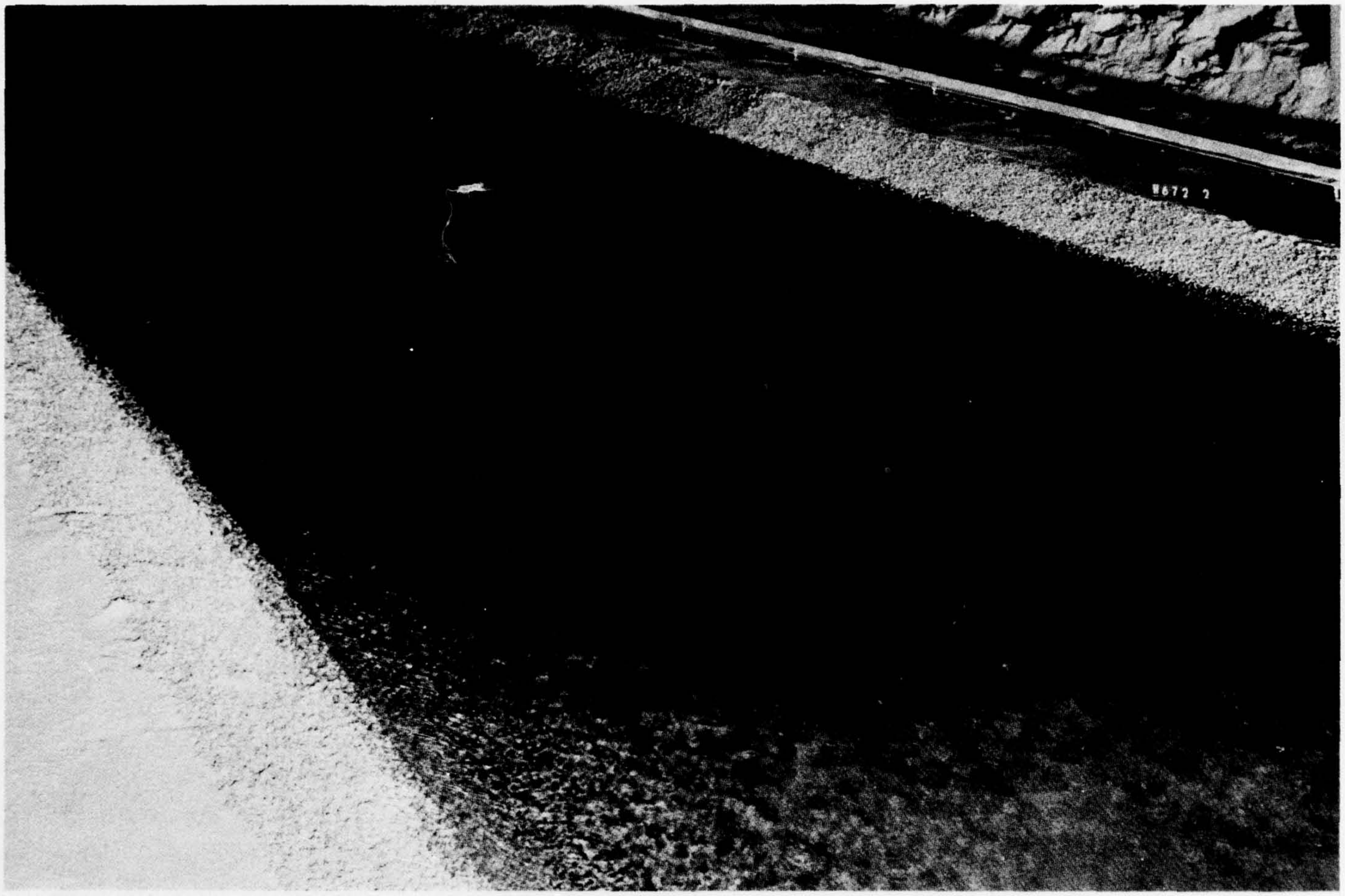


PLATE 2-2
Model Test Facility, Wet Bed

Dimension	Ratio
Length	L_r
Area	$A_r = L_r^2$
Weight	$W_r = L_r^3$, for constant g
Velocity	$V_v = L_r^{1/2}$
Discharge	$Q_r = L_r^{5/2}$

Quantitative measurements of discharge, water-surface elevation, and velocity in the model can be converted to prototype dimensions by means of the above scale relations.

2-3 Model Riprap

The rock used for the model riprap was crushed limestone having a unit weight of 167 lb/ft^3. The model rock is sieved into the following sizes: No. 4 (four openings per inch) to 3/8 in., 3/8 to 1/2 in., and 1/2 to 3/4 in. These three sizes are then mixed into gradations representative of prototype riprap. The gradation requirements used for these tests are set forth in ETL 1110-2-120 (1).

A sample of each of the three rock sizes was weighed and the number of stones in the sample was counted. From this the average stone weight was computed. Knowing the average stone weight, W_{50} , the average spherical diameter, D_{50} , was computed. For the three rock gradations the spherical D_{50} sizes were as follows:

Gradation	D_{50} , ft
1	0.026
2	0.032
3	0.037

These values of D_{50} were used in the analysis of the data from the tests.

The riprap blanket thickness was equal to one and one-half times the maximum stone size as set forth in ETL 1110-2-120 (1).

2-4 Test Procedures

Each of the three channel side slopes was tested with three different stone sizes. For each stone size a minimum of three water depths were tested. Prior to each test the channel was molded in sand to the proper bottom width and side slope. A nylon cloth was placed over the sand to act as a filter to prevent leaching of the sand through the riprap. The model rock was then placed over the nylon cloth to the proper blanket thickness. Each test was started with the tailwater high. The discharge was held constant and the tailwater was lowered in small increments until failure of the rock occurred. Each test was run for 2 hr. Failure was assumed to be the point at which the rocks began movement and resulted in exposure of the underlying filter cloth.

2-5 Test Results

Results of the model tests conducted on riprap stability in decelerating flow are shown in Table 2-1. A plot of D_{50}/depth versus Froude number for channels with 1V:3H and 1V:4H side slopes is shown in Figure 2-2. The values plotted represent the tests in which the riprap failed on the channel bottom or both the channel bottom and the channel side slopes. Model tests conducted with 1V:3H or 1V:4H side slopes generally experienced failure on either the channel bottom or the channel bottom and the channel side slope. Model tests conducted with 1V:2H side slopes experienced failure on the side slopes only in every test. A least squares fit of the model test results on channels with 1V:3H and 1V:4H side slopes results in

$$\frac{D_{50}}{\text{depth}} = 0.14F^{2.3} \qquad (2)$$

Previous studies (8) have shown that the relation should be cubic in F . Comparison of the Froude number concept with existing design criteria (Part III) supports the use of the cubic in F . This requires determination of C in Equation 1. The relation for incipient motion for channel bottom riprap in straight reaches adopted for this investigation is

$$\frac{D_{50}}{\text{depth}} = 0.22F^{3} \qquad (3)$$

as shown in Figure 2-2. The relation for safe design with a factor of 1.5 × incipient motion based on the average stone weight is

$$\frac{D_{50}}{\text{depth}} = 0.25F^{3} \qquad (4)$$

Table 2-1

Model test results

Q (cfs)	Bottom Slope (ft/ft)	Bottom Width (ft)	Side Slope	D_{50} (ft)	Upstream Depth (ft)	Downstream Depth (ft)	Avg Depth (ft)	F	D_{50}/depth	Failtype
20.0	0.008	5.0	4	0.026	0.81	0.89	0.85	0.54	0.031	1
25.0	0.008	5.0	4	0.026	0.96	1.04	1.00	0.49	0.026	1
30.0	0.008	5.0	4	0.026	1.09	1.17	1.13	0.46	0.023	2
35.0	0.008	5.0	4	0.026	1.20	1.28	1.24	0.45	0.021	2
20.0	0.008	5.0	4	0.032	0.77	0.85	0.81	0.59	0.040	2
25.0	0.008	5.0	4	0.032	0.92	1.0	0.96	0.53	0.033	2
30.0	0.008	5.0	4	0.032	1.04	1.12	1.08	0.51	0.030	3
35.0	0.008	5.0	4	0.032	1.15	1.23	1.19	0.49	0.027	3
20.0	0.008	5.0	4	0.037	0.75	0.83	0.79	0.62	0.047	1
25.0	0.008	5.0	4	0.037	0.87	0.95	0.91	0.59	0.041	1
30.0	0.008	5.0	4	0.037	1.00	1.08	1.04	0.54	0.036	2
35.0	0.008	5.0	4	0.037	1.13	1.21	1.17	0.50	0.032	2
20.0	0.008	5.0	3	0.026	0.88	0.96	0.92	0.52	0.028	1
25.0	0.008	5.0	3	0.026	1.04	1.12	1.08	0.48	0.024	2
30.0	0.008	5.0	3	0.026	1.18	1.26	1.22	0.45	0.021	2
20.0	0.008	5.0	3	0.032	0.82	0.90	0.86	0.58	0.037	2
25.0	0.008	5.0	3	0.032	0.97	1.05	1.01	0.54	0.032	2
30.0	0.008	5.0	3	0.032	1.14	1.22	1.18	0.48	0.027	2
20.0	0.008	5.0	3	0.037	0.81	0.89	0.85	0.60	0.044	3
25.0	0.008	5.0	3	0.037	0.95	1.03	0.99	0.56	0.037	3
30.0	0.008	5.0	3	0.037	1.10	1.18	1.14	0.52	0.032	3
15.0	0.008	5.0	2	0.026	0.80	0.88	0.84	0.51	0.031	3
20.0	0.008	5.0	2	0.026	1.00	1.08	1.04	0.47	0.025	3
25.0	0.008	5.0	2	0.026	1.18	1.26	1.22	0.44	0.021	3
15.0	0.008	5.0	2	0.032	0.76	0.84	0.80	0.56	0.040	3
20.0	0.008	5.0	2	0.032	0.96	1.04	1.00	0.50	0.032	3
25.0	0.008	5.0	2	0.032	1.13	1.21	1.17	0.47	0.027	3
15.0	0.008	5.0	2	0.037	0.72	0.80	0.76	0.61	0.049	3
20.0	0.008	5.0	2	0.037	0.93	1.01	0.97	0.53	0.038	3
25.0	0.008	5.0	2	0.037	1.10	1.18	1.14	0.50	0.032	3
30.0	0.008	5.0	2	0.037	1.27	1.35	1.31	0.46	0.028	3

Failtype: 1 = bottom only; 2 = bottom and side slopes; 3 = side slopes only.

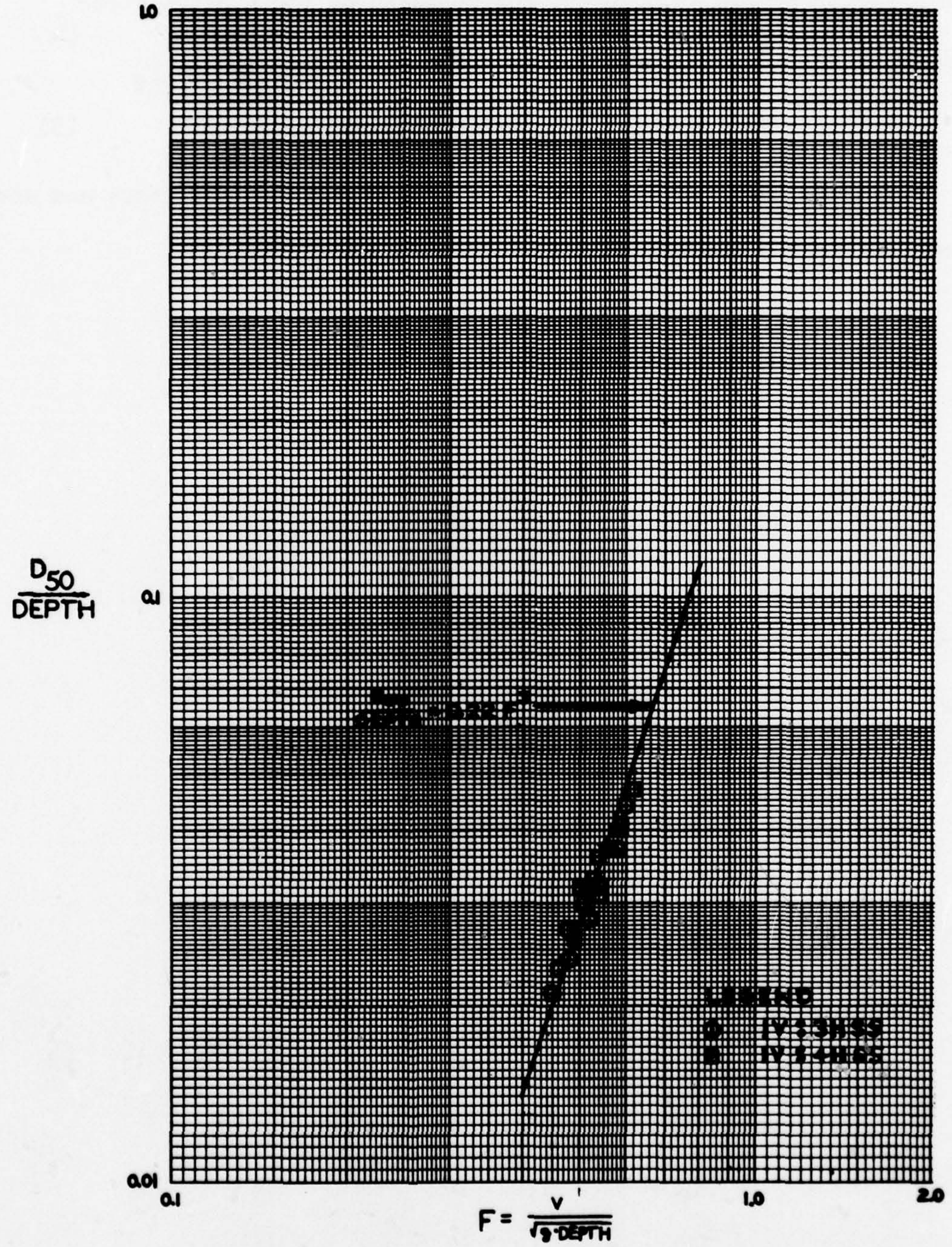


FIGURE 2-2
D_{50}/Depth Versus F - Model Test Results, Bottom Riprap

and a factor of 2.0 × incipient motion based on the average stone weight is

$$\frac{D_{50}}{\text{depth}} = 0.28F^3 \qquad (5)$$

Velocity profiles were determined for several of the tests and are shown in Figures 2-3 through 2-9.

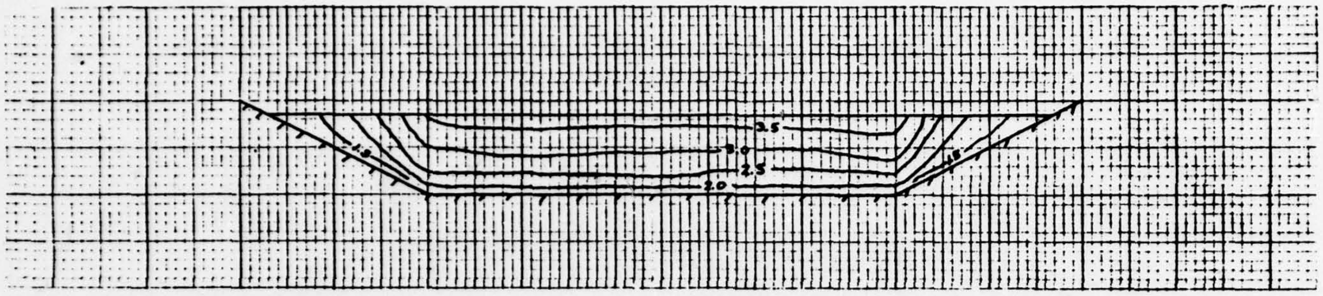


FIGURE 2-3
Velocity Profile - Q = 15 cfs, Depth = 0.84 ft, 1V:2HSS, D_{50} = 0.026 ft

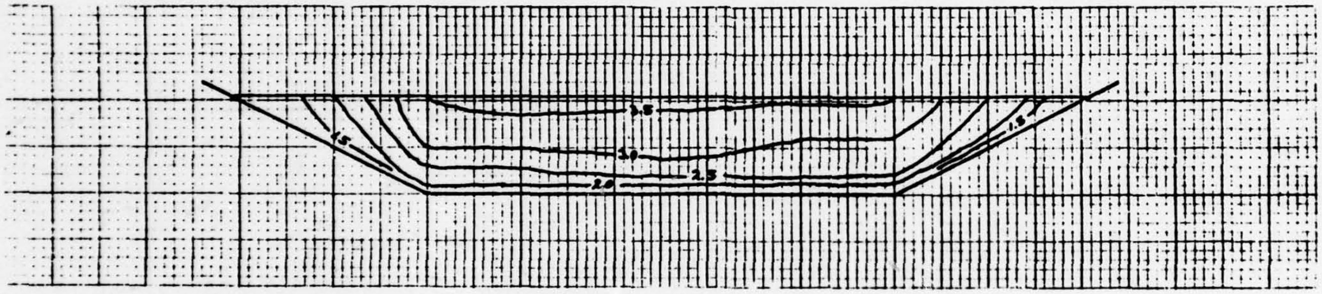


FIGURE 2-4
Velocity Profile - Q - 20 cfs, Depth = 1.04 ft, 1V:2HSS, D_{50} = 0.026 ft

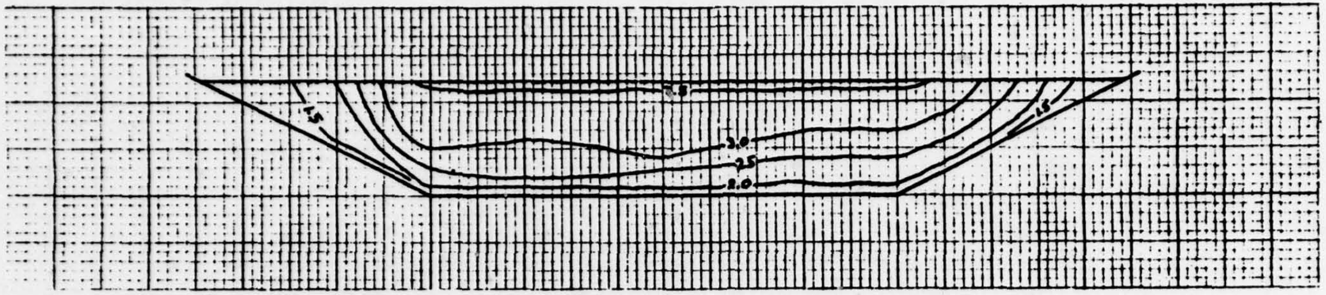


FIGURE 2-5

Velocity Profile - Q = 25 cfs, Depth = 1.22 ft, 1V:2HSS, D_{50} = 0.026 ft

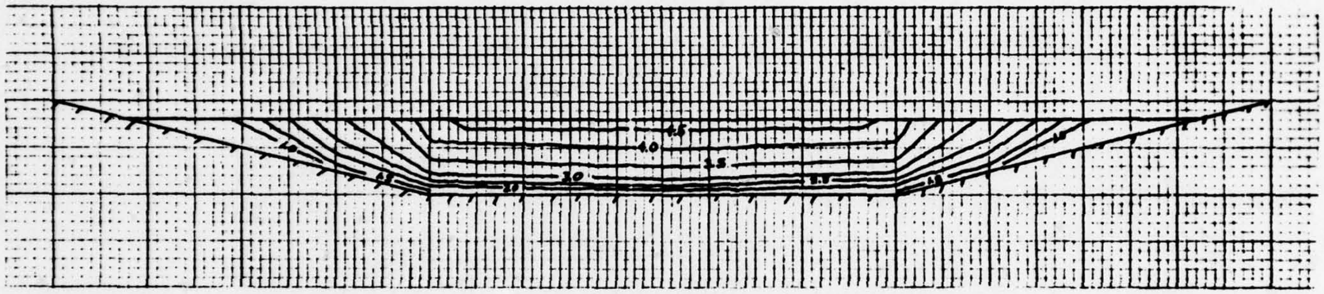


FIGURE 2-6

Velocity Profile - Q = 20 cfs, Depth = 0.81 ft, 1V:4HSS, D_{50} = 0.037 ft

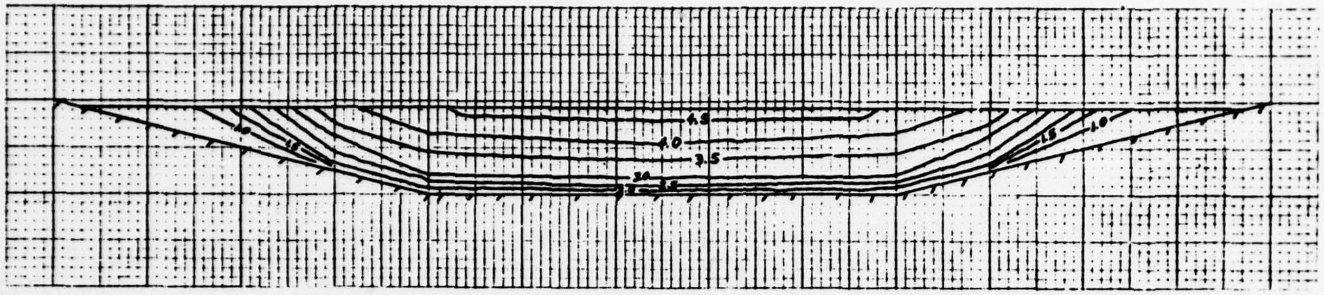


FIGURE 2-7
Velocity Profile - Q = 25 cfs, Depth = 0.93 ft, 1V:4HSS, D_{50} = 0.037 ft

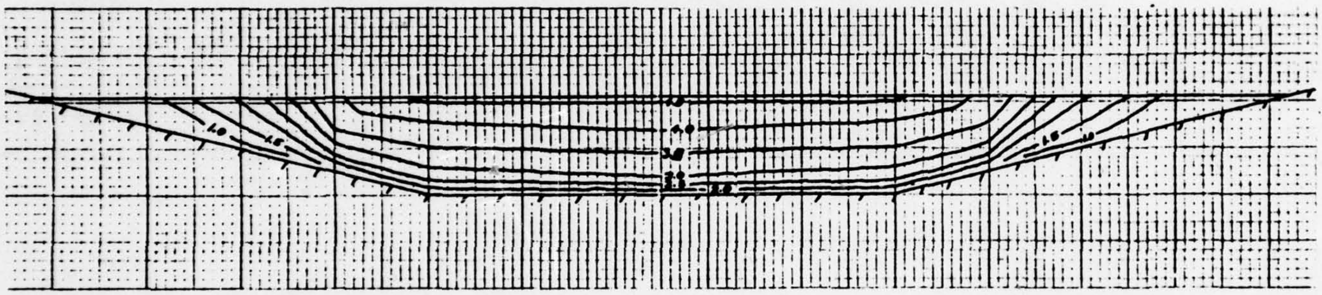


FIGURE 2-8
Velocity Profile - Q = 30 cfs, Depth = 1.06 ft, 1V:4HSS, D_{50} = 0.037 ft

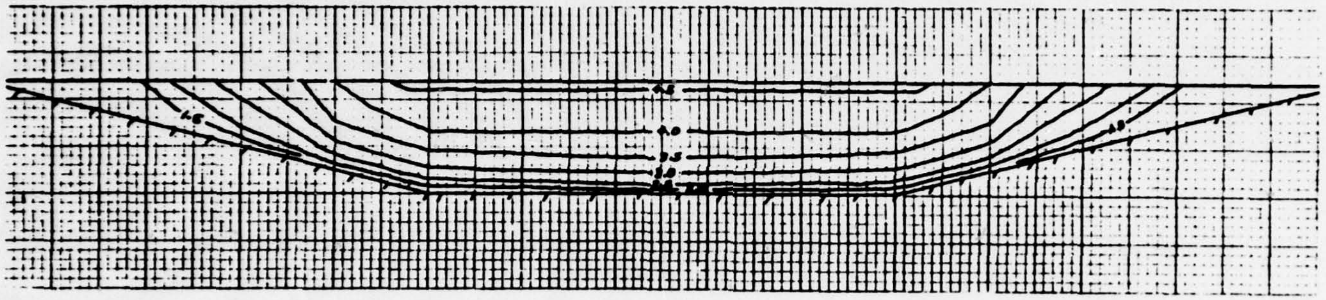


FIGURE 2-9

Velocity Profile - Q = 35 cfs, Depth = 1.19 ft, 1V:4HSS, D_{50} = 0.037 ft

III. COMPARISON OF MODEL RESULTS WITH EXISTING CRITERIA

3-1 St. Anthony Falls Laboratory - University of Minnesota

Al Anderson (2) conducted tests at the St. Anthony Falls Laboratory to determine a design procedure for riprap lined channels. The shear stress or tractive force approach is used. The critical shear stress is the amount of shear stress required to initiate particle motion. The relationship between critical shear stress and particle size as used by Anderson is shown in Figure 3-1. The relationship for incipient motion is

$$\tau_c = 5D_{50} \tag{6}$$

For the design of stable channels, Anderson used the relationship

$$\tau_c = 4D_{50} \tag{7}$$

The maximum shear stress exerted by the flowing water on the channel bottom is

$$\tau_b = C\gamma RS \tag{8}$$

where C is a function of the aspect ratio and is determined from Figure 3-2.

The Manning roughness coefficient "n" as a function of the mean particle size is determined from

$$n = 0.0395D_{50}^{1/6} \tag{9}$$

Solution of this approach to riprap design is an iterative

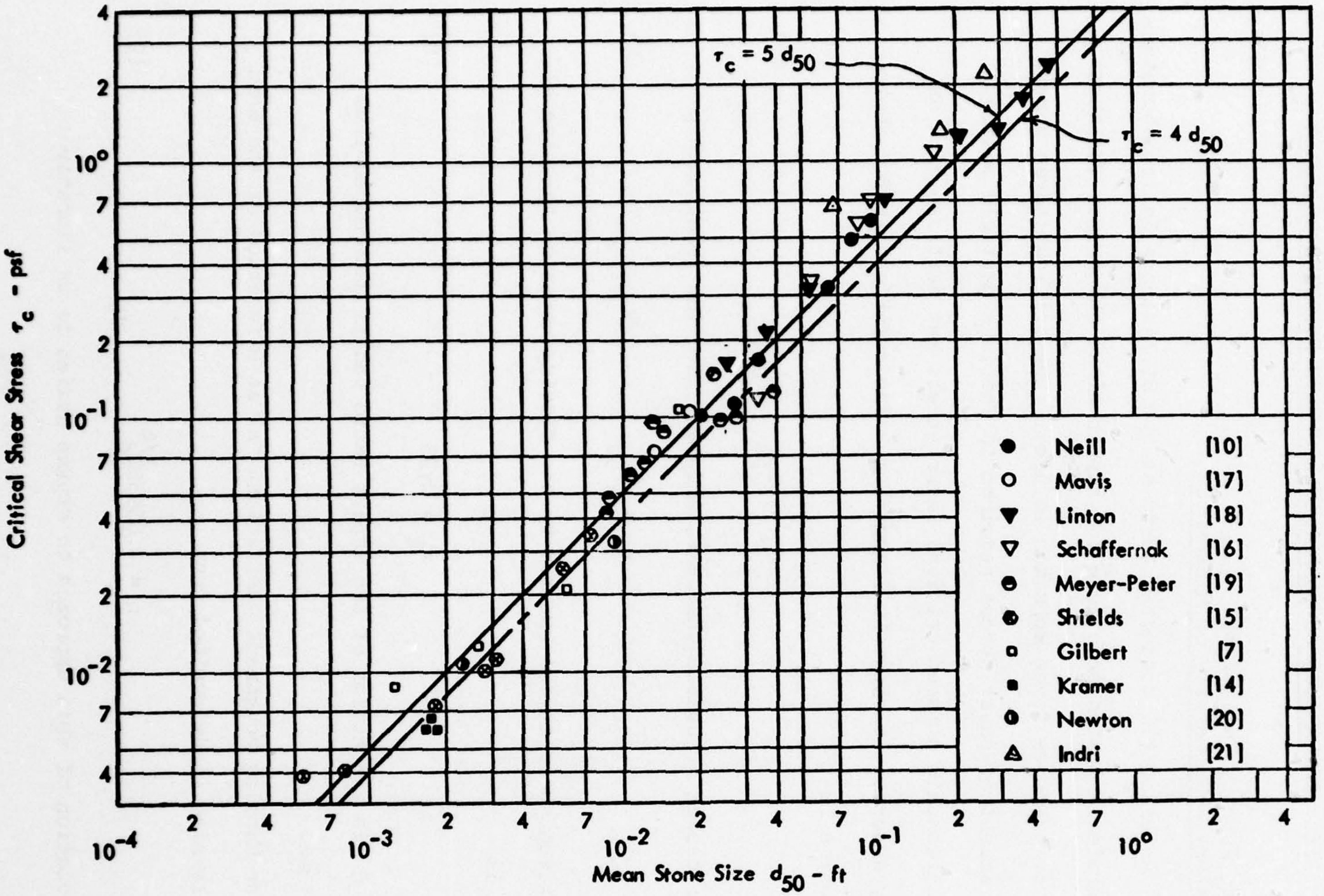


FIGURE 3-1
Critical Shear Stress Versus D_{50}
(After Anderson (2)) (References Cited are Those of Anderson)

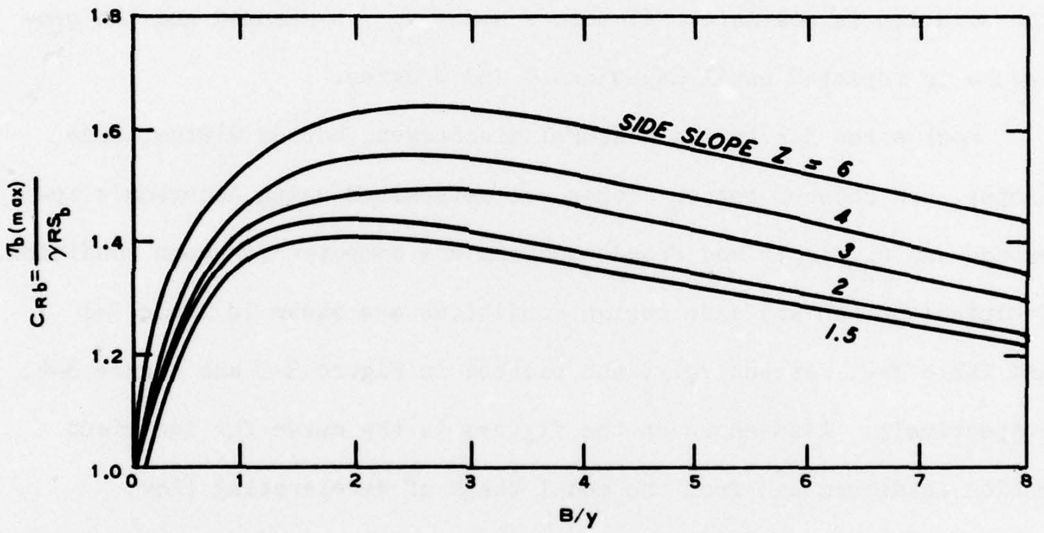


FIGURE 3-2
Maximum Boundary Shear Stress on
Bottom of Trapezoidal Channels (After Anderson (2))

procedure. For a given discharge, channel bottom width, side slope, and channel bottom slope, a D_{50} is assumed and the critical shear stress is computed from Equation 7. The Manning roughness coefficient is determined from Equation 9. The Manning equation is solved for the depth of flow. The tractive force exerted by the flowing water is determined from Equation 8. If the tractive force determined from Equation 8 is equal to the critical shear stress determined from Equation 7 the solution is complete. If not, a new D_{50} is assumed and the procedure is repeated until Equations 7 and 8 agree.

Rock sizes for typical channel discharges, bottom widths, side slopes, and channel bottom slopes are determined using Anderson's approach and D_{50}/depth and Froude numbers are computed for each condition. Incipient motion and safe design conditions are shown in Table 3-1 and Table 3-2, respectively, and plotted in Figure 3-3 and Figure 3-4, respectively. Also shown on the figures is the curve for incipient motion as determined from the model tests of decelerating flow.

$$\frac{D_{50}}{\text{depth}} = 0.22F^{3} \qquad \text{(3 bis)}$$

Values of D_{50}/depth and Froude number computed by Anderson's approach for incipient motion agree with the results of the model tests. A least-squares fit of these values results in

$$\frac{D_{50}}{\text{depth}} = 0.234F^{2.87} \qquad (10)$$

TABLE 3-1

BOTTOM RIPRAP SIZES FOR INCIPIENT MOTION BY ANDERSON METHOD

DISCHARGE CFS	BOTTOM SLOPE FT/FT	BOTTOM WIDTH FT	SIDE SLOPE	D50 FT	DEPTH FT	D50/D	F
15795.	0.00501	100.	4.	0.60	10.0	0.060	0.629
21904.	0.01337	100.	4.	1.60	10.0	0.160	0.872
25751.	0.02172	100.	4.	2.60	10.0	0.260	1.026
40919.	0.00237	100.	4.	0.60	20.0	0.030	0.448
56744.	0.00633	100.	4.	1.60	20.0	0.080	0.622
66712.	0.01029	100.	4.	2.60	20.0	0.130	0.731
70917.	0.00251	200.	4.	0.60	20.0	0.030	0.499
98343.	0.00668	200.	4.	1.60	20.0	0.080	0.692
115619.	0.01086	200.	4.	2.60	20.0	0.130	0.814
121045.	0.00159	200.	4.	0.60	30.0	0.020	0.406
167857.	0.00424	200.	4.	1.60	30.0	0.053	0.563
197345.	0.00689	200.	4.	2.60	30.0	0.087	0.662
170719.	0.00167	300.	4.	0.60	30.0	0.020	0.436
236742.	0.00446	300.	4.	1.60	30.0	0.053	0.605
278331.	0.00724	300.	4.	2.60	30.0	0.087	0.711
14116.	0.00416	100.	3.	0.50	10.0	0.050	0.605
20358.	0.01247	100.	3.	1.50	10.0	0.150	0.873
24137.	0.02079	100.	3.	2.50	10.0	0.250	1.035
35166.	0.00198	100.	3.	0.50	20.0	0.025	0.433
50719.	0.00595	100.	3.	1.50	20.0	0.075	0.625
60134.	0.00991	100.	3.	2.50	20.0	0.125	0.741
63376.	0.00208	200.	3.	0.50	20.0	0.025	0.481
91405.	0.00624	200.	3.	1.50	20.0	0.075	0.693
108373.	0.01039	200.	3.	2.50	20.0	0.125	0.822
105934.	0.00132	200.	3.	0.50	30.0	0.017	0.392
152784.	0.00397	200.	3.	1.50	30.0	0.050	0.565
181146.	0.00661	200.	3.	2.50	30.0	0.083	0.670
152566.	0.00139	300.	3.	0.50	30.0	0.017	0.420
220039.	0.00416	300.	3.	1.50	30.0	0.050	0.605
260887.	0.00693	300.	3.	2.50	30.0	0.083	0.718
12384.	0.00330	100.	2.	0.40	10.0	0.040	0.575
18802.	0.01156	100.	2.	1.40	10.0	0.140	0.874
22503.	0.01982	100.	2.	2.40	10.0	0.240	1.046
29621.	0.00161	100.	2.	0.40	20.0	0.020	0.417
44973.	0.00562	100.	2.	1.40	20.0	0.070	0.633
53825.	0.00964	100.	2.	2.40	20.0	0.120	0.758
55601.	0.00165	200.	2.	0.40	20.0	0.020	0.457
84420.	0.00578	200.	2.	1.40	20.0	0.070	0.693
101035.	0.00991	200.	2.	2.40	20.0	0.120	0.830
91092.	0.00106	200.	2.	0.40	30.0	0.013	0.376
138305.	0.00373	200.	2.	1.40	30.0	0.047	0.571
165526.	0.00639	200.	2.	2.40	30.0	0.080	0.683
133849.	0.00110	300.	2.	0.40	30.0	0.013	0.399
203224.	0.00385	300.	2.	1.40	30.0	0.047	0.606
243223.	0.00661	300.	2.	2.40	30.0	0.080	0.725

TABLE 3-2

BOTTOM RIPRAP SIZES FOR SAFE DESIGN BY ANDERSON METHOD

DISCHARGE	BOTTOM SLOPE	BOTTOM WIDTH	SIDE SLOPE	D50	DEPTH	D50/D	F
CFS	FT/FT	FT		FT	FT		
14128.	0.00401	100.	4.	0.60	10.0	0.060	0.563
19591.	0.01069	100.	4.	1.60	10.0	0.160	0.780
23033.	0.01738	100.	4.	2.60	10.0	0.260	0.917
36599.	0.00190	100.	4.	0.60	20.0	0.030	0.401
50754.	0.00507	100.	4.	1.60	20.0	0.080	0.556
59669.	0.00823	100.	4.	2.60	20.0	0.130	0.654
63430.	0.00201	200.	4.	0.60	20.0	0.030	0.447
87961.	0.00535	200.	4.	1.60	20.0	0.080	0.619
103413.	0.00869	200.	4.	2.60	20.0	0.130	0.728
108266.	0.00127	200.	4.	0.60	30.0	0.020	0.363
150136.	0.00339	200.	4.	1.60	30.0	0.053	0.503
176511.	0.00551	200.	4.	2.60	30.0	0.087	0.592
152696.	0.00134	300.	4.	0.60	30.0	0.020	0.390
211748.	0.00356	300.	4.	1.60	30.0	0.053	0.541
248946.	0.00579	300.	4.	2.60	30.0	0.087	0.636
12625.	0.00333	100.	3.	0.50	10.0	0.050	0.542
18209.	0.00998	100.	3.	1.50	10.0	0.150	0.781
21589.	0.01663	100.	3.	2.50	10.0	0.250	0.926
31454.	0.00159	100.	3.	0.50	20.0	0.025	0.388
45364.	0.00476	100.	3.	1.50	20.0	0.075	0.559
53786.	0.00793	100.	3.	2.50	20.0	0.125	0.663
56686.	0.00166	200.	3.	0.50	20.0	0.025	0.430
81755.	0.00499	200.	3.	1.50	20.0	0.075	0.620
96932.	0.00832	200.	3.	2.50	20.0	0.125	0.735
94750.	0.00106	200.	3.	0.50	30.0	0.017	0.351
136654.	0.00318	200.	3.	1.50	30.0	0.050	0.506
162022.	0.00529	200.	3.	2.50	30.0	0.083	0.600
136459.	0.00111	300.	3.	0.50	30.0	0.017	0.375
196809.	0.00333	300.	3.	1.50	30.0	0.050	0.542
233344.	0.00554	300.	3.	2.50	30.0	0.083	0.642
11076.	0.00264	100.	2.	0.40	10.0	0.040	0.515
16817.	0.00925	100.	2.	1.40	10.0	0.140	0.781
20127.	0.01586	100.	2.	2.40	10.0	0.240	0.935
26494.	0.00129	100.	2.	0.40	20.0	0.020	0.373
40225.	0.00450	100.	2.	1.40	20.0	0.070	0.566
48143.	0.00771	100.	2.	2.40	20.0	0.120	0.678
49731.	0.00132	200.	2.	0.40	20.0	0.020	0.409
75507.	0.00463	200.	2.	1.40	20.0	0.070	0.620
90369.	0.00793	200.	2.	2.40	20.0	0.120	0.742
81475.	0.00085	200.	2.	0.40	30.0	0.013	0.336
123704.	0.00298	200.	2.	1.40	30.0	0.047	0.511
148051.	0.00511	200.	2.	2.40	30.0	0.080	0.611
119718.	0.00088	300.	2.	0.40	30.0	0.013	0.357
181769.	0.00308	300.	2.	1.40	30.0	0.047	0.542
217545.	0.00529	300.	2.	2.40	30.0	0.080	0.648

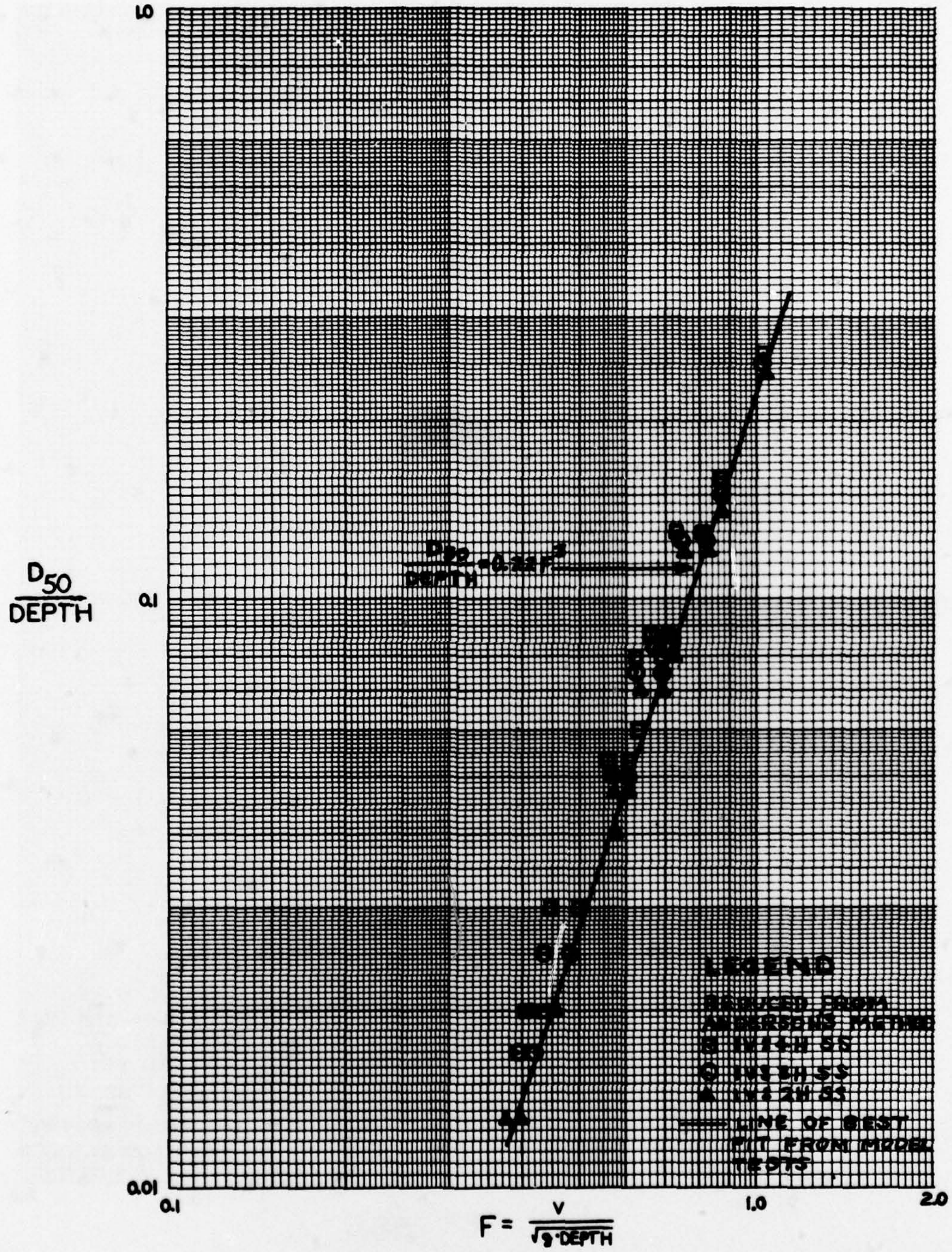


FIGURE 3-3

D_{50}/Depth Versus F - Bottom Riprap, Anderson, Incipient Motion

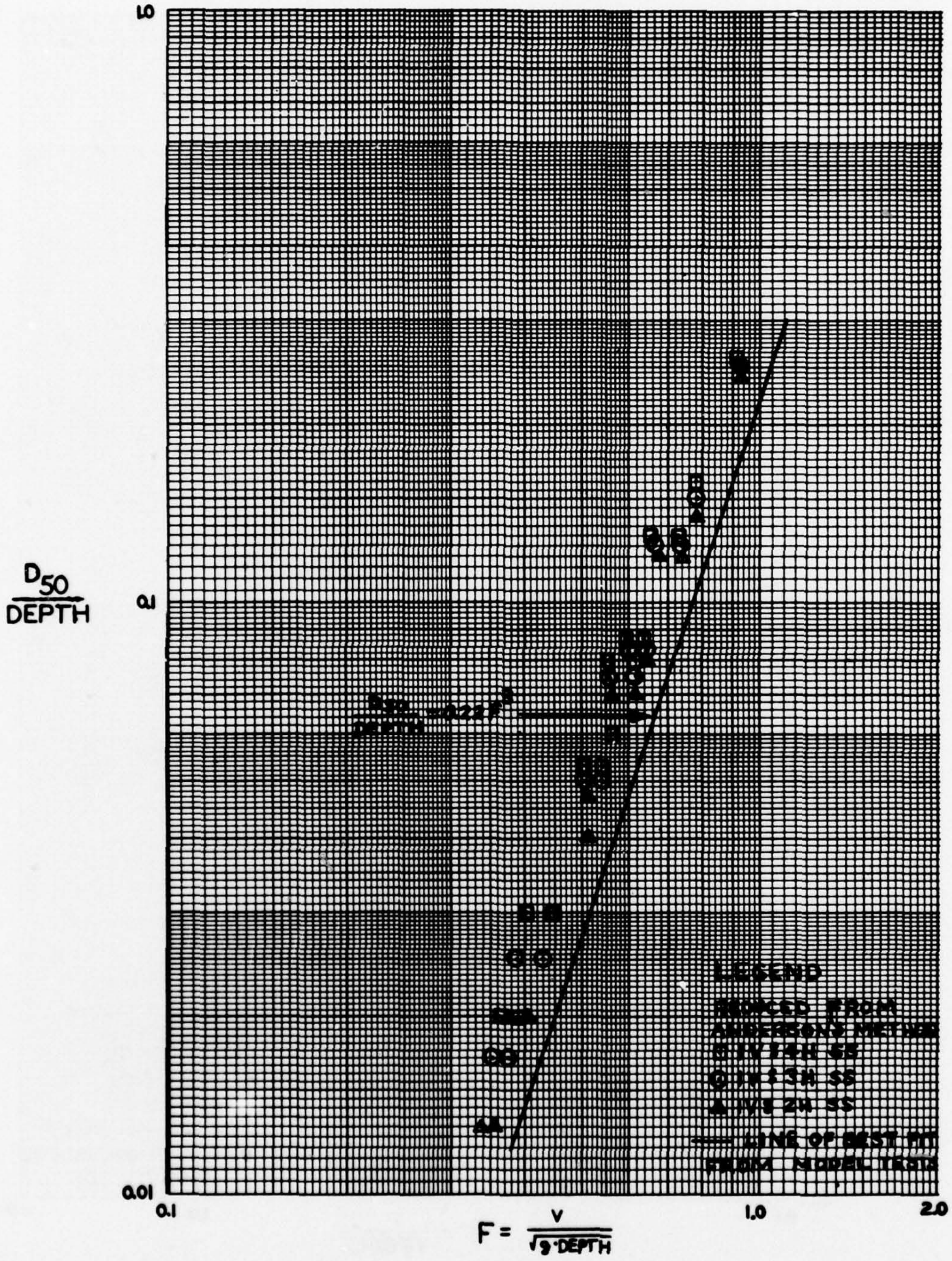


FIGURE 3-4
D_{50}/Depth Versus F - Bottom Riprap, Anderson, Safe Design

Values computed for safe design are on the safe side of the curve predicted by the model tests. A least squares fit of these values results in

$$\frac{D_{50}}{\text{depth}} = 0.323F^{2.87} \tag{11}$$

3-2 Li, Simons, Blinco, Samad

Li, Simons, Blinco, and Samad (3) developed a riprap design method whereby the probability of failure or a safety factor could be incorporated into the design procedure. The tractive force concept is used in this method. The analysis of the forces acting on a single particle includes the lift force that acts on that particle whether on a channel bed or bank. The equation defining the safety factor in the design is

$$\text{F.S.} = \frac{\left[1/6\pi D_{50}^{3}\ (\gamma_s - \gamma_w)\cos\theta - \beta\delta\tau_b\right]\tan\phi}{\left\{\left[1/6\tau D_{50}^{3}\ (\gamma_s - \gamma_w)\sin\theta\right]^2 + \delta^2\tau_b^2\right\}^{1/2}} \tag{12}$$

where

D_{50} = average stone size, ft

γ_s = unit weight of stone, lb/ft^3

γ_w = unit weight of water, lb/ft^2

θ = side slope angle

δ = proportionality number, ft^2

$$\delta = \frac{11.14D_{50}^{2}}{0.85 + \cot\phi} \tag{13}$$

where

ϕ = angle of repose

β = ratio of lift to drag = 0.85

The proportionality number δ relates drag force to shear force. For riprap D_{50} greater than 6 in., $\phi = 41°$. For channel bottom riprap, $\theta = 0°$. For incipient motion, F.S. = 1.0 and $\tau_b = \tau_c$. Substituting into Equation 12 and solving for τ_c

$$\tau_c = 0.047\ (\gamma_s - \gamma_w)D_{50} \qquad (14)$$

This is the Shields' (10) equation as modified by Gessler (11).

The tractive force exerted by the flowing water is

$$\tau_b = \rho \left[\frac{V}{2.5 \ln \left(\dfrac{12.3\ \text{depth}}{D_{50}} \right)} \right]^2 \qquad (15)$$

where

ρ = density of water

V = mean velocity in the vertical, at channel center line, ft/sec

depth = water depth, ft

D_{50} = average stone size, ft

This equation is based on the velocity distribution equation developed by Keulegan (12).

An analysis of the velocity profiles presented in Figures 2-3 to 2-9 show that the mean velocity in the vertical is 1.2 × mean channel velocity. The test channels have an aspect ratio of about 5. For an infinitely wide channel the average velocity in the vertical is equal to the mean channel velocity. Prototype channels generally fall somewhere in between these extremes. In using the Li approach

$$V \text{ (average velocity in vertical)} = 1.1\, V \text{ (average channel velocity)} \qquad (16)$$

Solution of this method requires assuming a D_{50} and determining the proportionality number δ from Equation 13 and the tractive force τ_b from Equation 15. Then the safety factor is determined from Equation 12. The procedure is repeated until the desired safety factor is reached.

Rock sizes for typical channel discharges, bottom widths, side slopes, and channel bottom slopes are determined using the Li approach, and D_{50}/depth and Froude numbers are computed for each condition. Incipient motion conditions are shown in Table 3-3 and plotted in Figure 3-5. Also shown in Figure 3-5 is the curve for incipient motion as determined for the model tests of decelerating flow.

$$\frac{D_{50}}{\text{depth}} = 0.22F^{3} \qquad (3 \text{ bis})$$

Values of D_{50}/depth and Froude numbers computed by the Li approach are less than the incipient motion results obtained from the model tests of riprap stability in decelerating flow. A least-squares fit of these values results in

$$\frac{D_{50}}{\text{depth}} = 0.12F^{3.2} \qquad (17)$$

This further supports the use of a cubic relation in F .

TABLE 3-3

BOTTOM RIPRAP SIZES FOR INCIPIENT MOTION BY LI METHOD

DISCHARGE CFS	BOTTOM SLOPE FT/FT	BOTTOM WIDTH FT	SIDE SLOPE	D50 FT	DEPTH FT	D50/D	F
20681.	0.00488	100.	4.	0.60	10.0	0.060	0.824
27549.	0.01301	100.	4.	1.60	10.0	0.160	1.097
31192.	0.02115	100.	4.	2.60	10.0	0.260	1.242
60105.	0.00244	100.	4.	0.60	20.0	0.030	0.658
82150.	0.00651	100.	4.	1.60	20.0	0.080	0.900
94624.	0.01057	100.	4.	2.60	20.0	0.130	1.036
93497.	0.00244	200.	4.	0.60	20.0	0.030	0.658
127789.	0.00651	200.	4.	1.60	20.0	0.080	0.900
147192.	0.01057	200.	4.	2.60	20.0	0.130	1.036
171084.	0.00163	200.	4.	0.60	30.0	0.020	0.574
236706.	0.00434	200.	4.	1.60	30.0	0.053	0.794
274817.	0.00705	200.	4.	2.60	30.0	0.087	0.922
224547.	0.00163	300.	4.	0.60	30.0	0.020	0.574
310677.	0.00434	300.	4.	1.60	30.0	0.053	0.794
360697.	0.00705	300.	4.	2.60	30.0	0.087	0.922
18131.	0.00407	100.	3.	0.50	10.0	0.050	0.778
25137.	0.01220	100.	3.	1.50	10.0	0.150	1.078
28690.	0.02034	100.	3.	2.50	10.0	0.250	1.231
50250.	0.00203	100.	3.	0.50	20.0	0.025	0.619
71610.	0.00610	100.	3.	1.50	20.0	0.075	0.882
83188.	0.01017	100.	3.	2.50	20.0	0.125	1.025
81656.	0.00203	200.	3.	0.50	20.0	0.025	0.619
116366.	0.00610	200.	3.	1.50	20.0	0.075	0.882
135180.	0.01017	200.	3.	2.50	20.0	0.125	1.025
145554.	0.00136	200.	3.	0.50	30.0	0.017	0.539
210167.	0.00407	200.	3.	1.50	30.0	0.050	0.778
246149.	0.00678	200.	3.	2.50	30.0	0.083	0.911
195745.	0.00136	300.	3.	0.50	30.0	0.017	0.539
282639.	0.00407	300.	3.	1.50	30.0	0.050	0.778
331028.	0.00678	300.	3.	2.50	30.0	0.083	0.911
15576.	0.00325	100.	2.	0.40	10.0	0.040	0.724
22768.	0.01139	100.	2.	1.40	10.0	0.140	1.058
26220.	0.01952	100.	2.	2.40	10.0	0.240	1.218
40743.	0.00163	100.	2.	0.40	20.0	0.020	0.574
61353.	0.00569	100.	2.	1.40	20.0	0.070	0.864
71953.	0.00976	100.	2.	2.40	20.0	0.120	1.013
69845.	0.00163	200.	2.	0.40	20.0	0.020	0.574
105176.	0.00569	200.	2.	1.40	20.0	0.070	0.864
123348.	0.00976	200.	2.	2.40	20.0	0.120	1.013
120664.	0.00108	200.	2.	0.40	30.0	0.013	0.498
184318.	0.00380	200.	2.	1.40	30.0	0.047	0.761
217994.	0.00651	200.	2.	2.40	30.0	0.080	0.900
167073.	0.00108	300.	2.	0.40	30.0	0.013	0.498
255209.	0.00380	300.	2.	1.40	30.0	0.047	0.761
301838.	0.00651	300.	2.	2.40	30.0	0.080	0.900

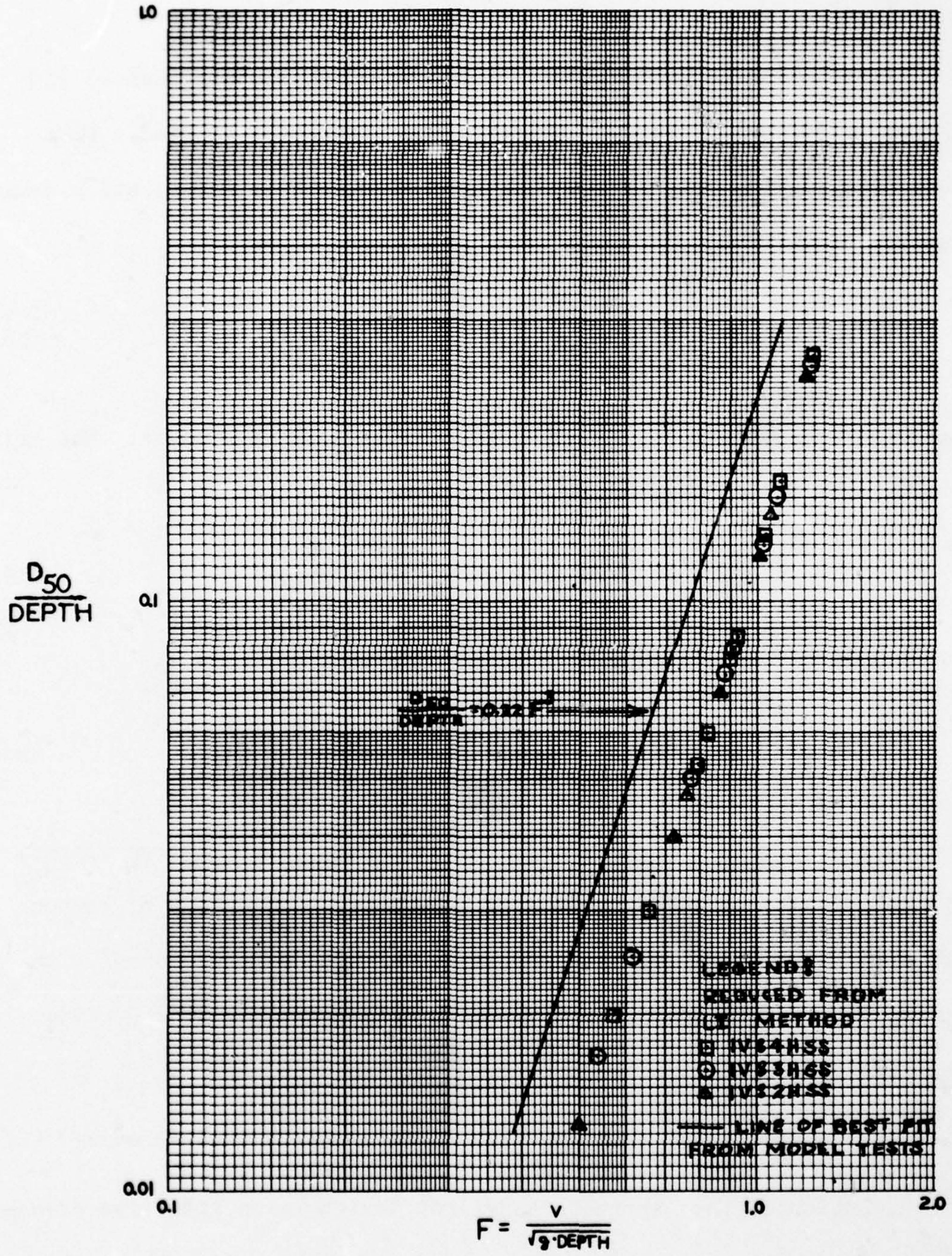


FIGURE 3-5
D_{50}/Depth Versus F - Bottom Riprap, Li, Incipient Motion

3-3 Ramette

Ramette (5) conducted tests of riprap stability for channel side slopes. The shear stress or tractive force approach is used. From Ramette's results for riprap on channel side slopes, the equation developed by Lane (6)

$$f(\theta) = \cos\theta \sqrt{1 - \frac{\tan^2\theta}{\tan^2\phi}} \qquad (18)$$

was used to determine stability criteria for channel bottoms. The critical tractive force as computed by Ramette is

$$\tau_c = 0.02(\gamma_s - \gamma_w)D_{50} \cdot f(\theta) \qquad (19)$$

The tractive force exerted by the flowing water is

$$\tau_b = \rho \left[\frac{V}{8.48 + 5.75 \log\left(\frac{2\ \mathrm{depth}}{D_{50}}\right)}\right]^2 \qquad (20)$$

where V = velocity at 0.8 × depth. For design of side slope riprap, the velocity is taken at the toe of the slope. For design of bottom riprap, the velocity is taken at the center line of the channel. An analysis of the velocity profiles shown in Figures 2-3 to 2-9 gives the relation

V(0.8 depth at center line) = 1.3 × V(average channel velocity) (21)

Solution of this approach to riprap design is an iterative procedure. For a given discharge, channel bottom width, side slope, and channel bottom slope, a D_{50} is assumed and the critical shear stress is computed from Equation 19. The tractive force exerted by the flowing water is determined from Equation 20. If the values obtained agree, the solution is complete. If not, a new D_{50} is assumed and the procedure is repeated.

Rock sizes for typical channel discharges, bottom widths, side slopes, and channel bottom slopes are determined using Ramette's criteria and D_{50}/depth and Froude numbers are computed for each condition. Incipient motion conditions are shown in Table 3-4 and plotted in Figure 3-6. Also shown in Figure 3-6 is the curve for incipient motion as determined from the model tests of riprap stability in decelerating flow.

$$\frac{D_{50}}{\text{depth}} = 0.22F^3 \qquad \text{(3 bis)}$$

Values of D_{50}/depth and Froude numbers computed by the Ramette approach agree for incipient motion of channel bottom riprap. A least-square fit of these values results in

$$\frac{D_{50}}{\text{depth}} = 0.27F^{2.8} \qquad (22)$$

3-4 Corps of Engineers

Corps of Engineers criteria for designing channel riprap is set forth in EM 1110-2-1601 (4). These criteria were amended by ETL 1110-2-120 (1). The shear stress or tractive force approach is used. The critical shear stress is estimated by the Shields' equation.

TABLE 3-4

BOTTOM RIPRAP SIZES FOR INCIPIENT MOTION BY RAMETTE METHOD

DISCHARGE CFS	BOTTOM SLOPE FT/FT	BOTTOM WIDTH FT	SIDE SLOPE	D50 FT	DEPTH FT	D50/D	F
14779.	0.00506	100.	4.	0.60	10.0	0.060	0.589
20704.	0.01350	100.	4.	1.60	10.0	0.160	0.825
24229.	0.02193	100.	4.	2.60	10.0	0.260	0.965
41818.	0.00253	100.	4.	0.60	20.0	0.030	0.458
59471.	0.00675	100.	4.	1.60	20.0	0.080	0.651
70246.	0.01096	100.	4.	2.60	20.0	0.130	0.769
65051.	0.00253	200.	4.	0.60	20.0	0.030	0.458
92510.	0.00675	200.	4.	1.60	20.0	0.080	0.651
109272.	0.01096	200.	4.	2.60	20.0	0.130	0.769
117469.	0.00169	200.	4.	0.60	30.0	0.020	0.394
168310.	0.00450	200.	4.	1.60	30.0	0.053	0.564
199716.	0.00731	200.	4.	2.60	30.0	0.087	0.670
154178.	0.00169	300.	4.	0.60	30.0	0.020	0.394
220907.	0.00450	300.	4.	1.60	30.0	0.053	0.564
262127.	0.00731	300.	4.	2.60	30.0	0.087	0.670
12858.	0.00422	100.	3.	0.50	10.0	0.050	0.552
18818.	0.01265	100.	3.	1.50	10.0	0.150	0.807
22220.	0.02109	100.	3.	2.50	10.0	0.250	0.953
34748.	0.00211	100.	3.	0.50	20.0	0.025	0.428
51684.	0.00633	100.	3.	1.50	20.0	0.075	0.637
61621.	0.01054	100.	3.	2.50	20.0	0.125	0.759
56465.	0.00211	200.	3.	0.50	20.0	0.025	0.428
83986.	0.00633	200.	3.	1.50	20.0	0.075	0.637
100133.	0.01054	200.	3.	2.50	20.0	0.125	0.759
99395.	0.00141	200.	3.	0.50	30.0	0.017	0.368
149045.	0.00422	200.	3.	1.50	30.0	0.050	0.552
178543.	0.00703	200.	3.	2.50	30.0	0.083	0.661
133670.	0.00141	300.	3.	0.50	30.0	0.017	0.368
200440.	0.00422	300.	3.	1.50	30.0	0.050	0.552
240110.	0.00703	300.	3.	2.50	30.0	0.083	0.661
10950.	0.00337	100.	2.	0.40	10.0	0.040	0.509
16975.	0.01181	100.	2.	1.40	10.0	0.140	0.789
20247.	0.02024	100.	2.	2.40	10.0	0.240	0.941
27975.	0.00169	100.	2.	0.40	20.0	0.020	0.394
44141.	0.00590	100.	2.	1.40	20.0	0.070	0.622
53178.	0.01012	100.	2.	2.40	20.0	0.120	0.749
47957.	0.00169	200.	2.	0.40	20.0	0.020	0.394
75671.	0.00590	200.	2.	1.40	20.0	0.070	0.622
91163.	0.01012	200.	2.	2.40	20.0	0.120	0.749
81879.	0.00112	200.	2.	0.40	30.0	0.013	0.338
130353.	0.00394	200.	2.	1.40	30.0	0.047	0.538
157813.	0.00675	200.	2.	2.40	30.0	0.080	0.651
113370.	0.00112	300.	2.	0.40	30.0	0.013	0.338
180489.	0.00394	300.	2.	1.40	30.0	0.047	0.538
218510.	0.00675	300.	2.	2.40	30.0	0.080	0.651

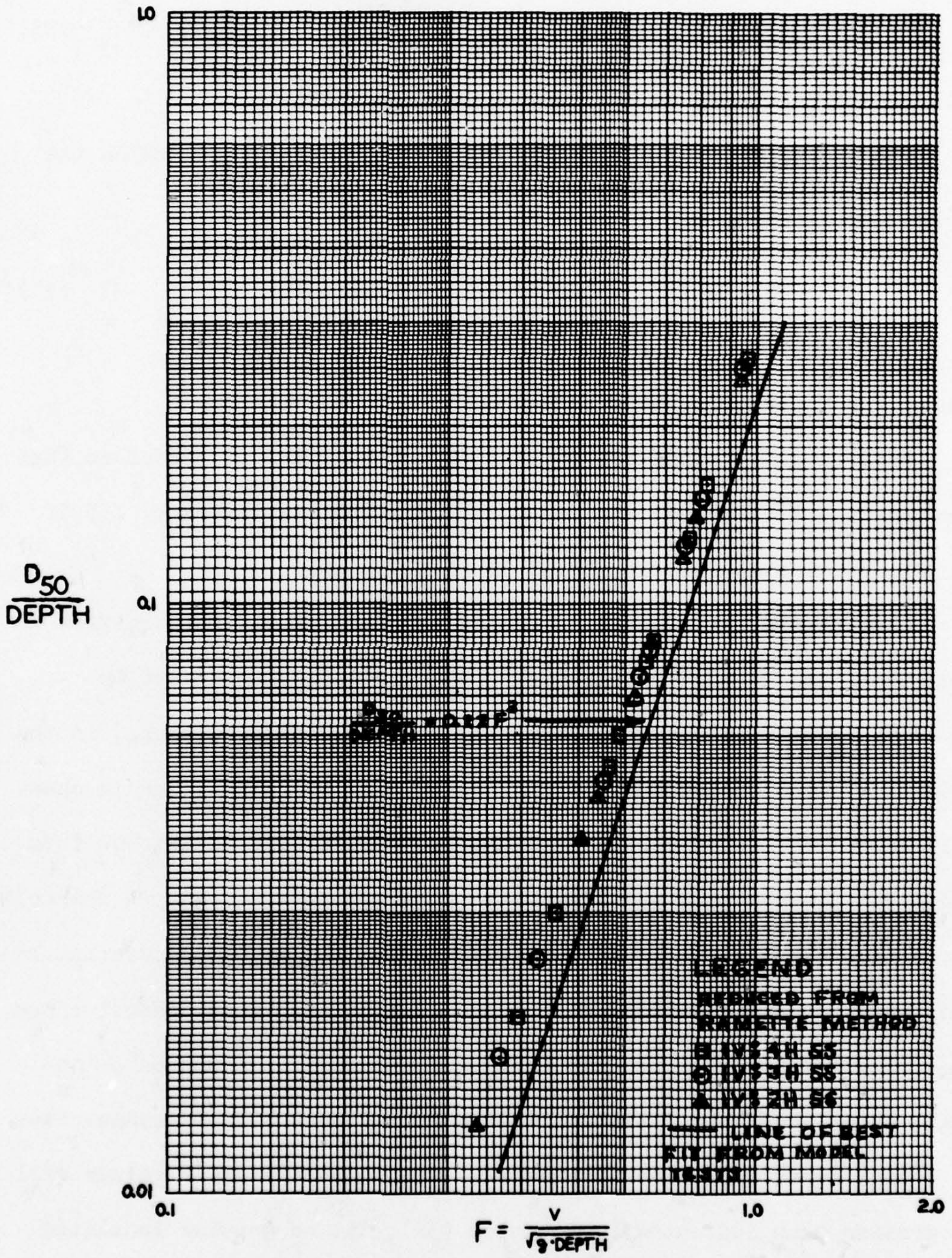


FIGURE 3-6
D_{50}/Depth Versus F - Bottom Riprap, Ramette, Incipient Motion

$$\tau_c = 0.04(\gamma_s - \gamma_w)D_{50} \tag{23}$$

This equation represents the safe design condition.

The tractive force exerted by the flowing water is based on the velocity distribution developed by Keulegan (12).

$$\tau_b = \frac{\gamma\overline{V}^2}{\left(32.6 \log \frac{12.2 \text{ depth}}{D_{50}}\right)^2} \tag{24}$$

where $\overline{V}$ = average velocity in vertical from Equation 16.

Additional guidance set forth in ETL 1110-2-120 (1) requires that the tractive force determined in Equation 24 be multiplied by 1.5 if the flow is not at or near normal depth.

"Equation (32) is based on the assumptions of fully rough flow conditions and normal logarithmic vertical velocity distribution produced by uniform channel flow. Fully rough flow conditions, in the range indicated on Hydraulic Design Chart 631, normally occur in channels which require riprap protection, but significant deviations from the normal logarithmic vertical velocity distribution occur in channels which have nonuniform cross sections, varying slopes, and different bed and bank roughness coefficients. Thus, unless a uniform channel cross section with identical bed and bank riprap material occurs on a constant slope over a sufficient distance to produce uniform channel flow at normal depth and velocity, maximum local boundary shear values will be greater than indicated by Equation (32), due to greater localized velocities and pressure pulsations. As the effects of contributing factors to deviations from normal logarithmic vertical velocity distribution have not been established, values of local boundary shear computed from Equation (32) should be increased by a factor of 1.5, except when flow is at or near normal depth in a channel with uniform cross section and equal bed and side roughness." (1)

By adding the factor outlined in ETL 1110-2-120 (1), the tractive force exerted by the flowing water is

$$\tau_b = 1.5 \frac{\gamma \overline{V}^2}{\left(32.2 \log \frac{12.2 \text{ depth}}{D_{50}}\right)^2} \qquad (25)$$

Solution of this method requires assuming a D_{50} and solving Equation 23 for the critical shear stress and Equation 25 for the tractive force. If the values agree, the solution is complete. If not, a new D_{50} is assumed and the procedure is repeated.

Rock sizes for typical channel discharges, bottom widths, side slopes, and channel bottom slopes are determined using the Corps of Engineers approach and D_{50}/depth and Froude numbers are computed for each condition. Safe design conditions are shown in Table 3-5 and plotted in Figure 3-7. Also shown in Figure 3-7 is the curve for incipient motion as determined from the model test of riprap stability in decelerating flow.

$$\frac{D_{50}}{\text{depth}} = 0.22F^3 \qquad (3 \text{ bis})$$

Values of D_{50}/depth and Froude numbers for safe design computed by the

TABLE 3-5

BOTTOM RIPRAP SIZES FOR SAFE DESIGN BY C.O.E. METHOD

DISCHARGE CFS	BOTTOM SLOPE FT/FT	BOTTOM WIDTH FT	SIDE SLOPE	D50 FT	DEPTH FT	D50/D	F
15524.	0.00415	100.	4.	0.60	10.0	0.060	0.618
20673.	0.01107	100.	4.	1.60	10.0	0.160	0.823
23401.	0.01798	100.	4.	2.60	10.0	0.260	0.932
45126.	0.00207	100.	4.	0.60	20.0	0.030	0.494
61660.	0.00553	100.	4.	1.60	20.0	0.080	0.675
71011.	0.00899	100.	4.	2.60	20.0	0.130	0.778
70196.	0.00207	200.	4.	0.60	20.0	0.030	0.494
95916.	0.00553	200.	4.	1.60	20.0	0.080	0.675
110461.	0.00899	200.	4.	2.60	20.0	0.130	0.778
128457.	0.00138	200.	4.	0.60	30.0	0.020	0.431
177689.	0.00369	200.	4.	1.60	30.0	0.053	0.596
206267.	0.00599	200.	4.	2.60	30.0	0.087	0.692
168600.	0.00138	300.	4.	0.60	30.0	0.020	0.431
233217.	0.00369	300.	4.	1.60	30.0	0.053	0.596
270726.	0.00599	300.	4.	2.60	30.0	0.087	0.692
13611.	0.00346	100.	3.	0.50	10.0	0.050	0.584
18863.	0.01037	100.	3.	1.50	10.0	0.150	0.809
21524.	0.01729	100.	3.	2.50	10.0	0.250	0.923
37728.	0.00173	100.	3.	0.50	20.0	0.025	0.465
53750.	0.00519	100.	3.	1.50	20.0	0.075	0.662
62429.	0.00865	100.	3.	2.50	20.0	0.125	0.769
61309.	0.00173	200.	3.	0.50	20.0	0.025	0.465
87344.	0.00519	200.	3.	1.50	20.0	0.075	0.662
101448.	0.00865	200.	3.	2.50	20.0	0.125	0.769
109292.	0.00115	200.	3.	0.50	30.0	0.017	0.404
157770.	0.00346	200.	3.	1.50	30.0	0.050	0.584
184753.	0.00576	200.	3.	2.50	30.0	0.083	0.684
146980.	0.00115	300.	3.	0.50	30.0	0.017	0.404
212173.	0.00346	300.	3.	1.50	30.0	0.050	0.584
248461.	0.00576	300.	3.	2.50	30.0	0.083	0.684
11694.	0.00277	100.	2.	0.40	10.0	0.040	0.543
17086.	0.00968	100.	2.	1.40	10.0	0.140	0.794
19672.	0.01660	100.	2.	2.40	10.0	0.240	0.914
30591.	0.00138	100.	2.	0.40	20.0	0.020	0.431
46052.	0.00484	100.	2.	1.40	20.0	0.070	0.649
53999.	0.00830	100.	2.	2.40	20.0	0.120	0.760
52442.	0.00138	200.	2.	0.40	20.0	0.020	0.431
78947.	0.00484	200.	2.	1.40	20.0	0.070	0.649
92570.	0.00830	200.	2.	2.40	20.0	0.120	0.760
90607.	0.00092	200.	2.	0.40	30.0	0.013	0.374
138368.	0.00323	200.	2.	1.40	30.0	0.047	0.571
163623.	0.00553	200.	2.	2.40	30.0	0.080	0.675
125455.	0.00092	300.	2.	0.40	30.0	0.013	0.374
191586.	0.00323	300.	2.	1.40	30.0	0.047	0.571
226554.	0.00553	300.	2.	2.40	30.0	0.080	0.675

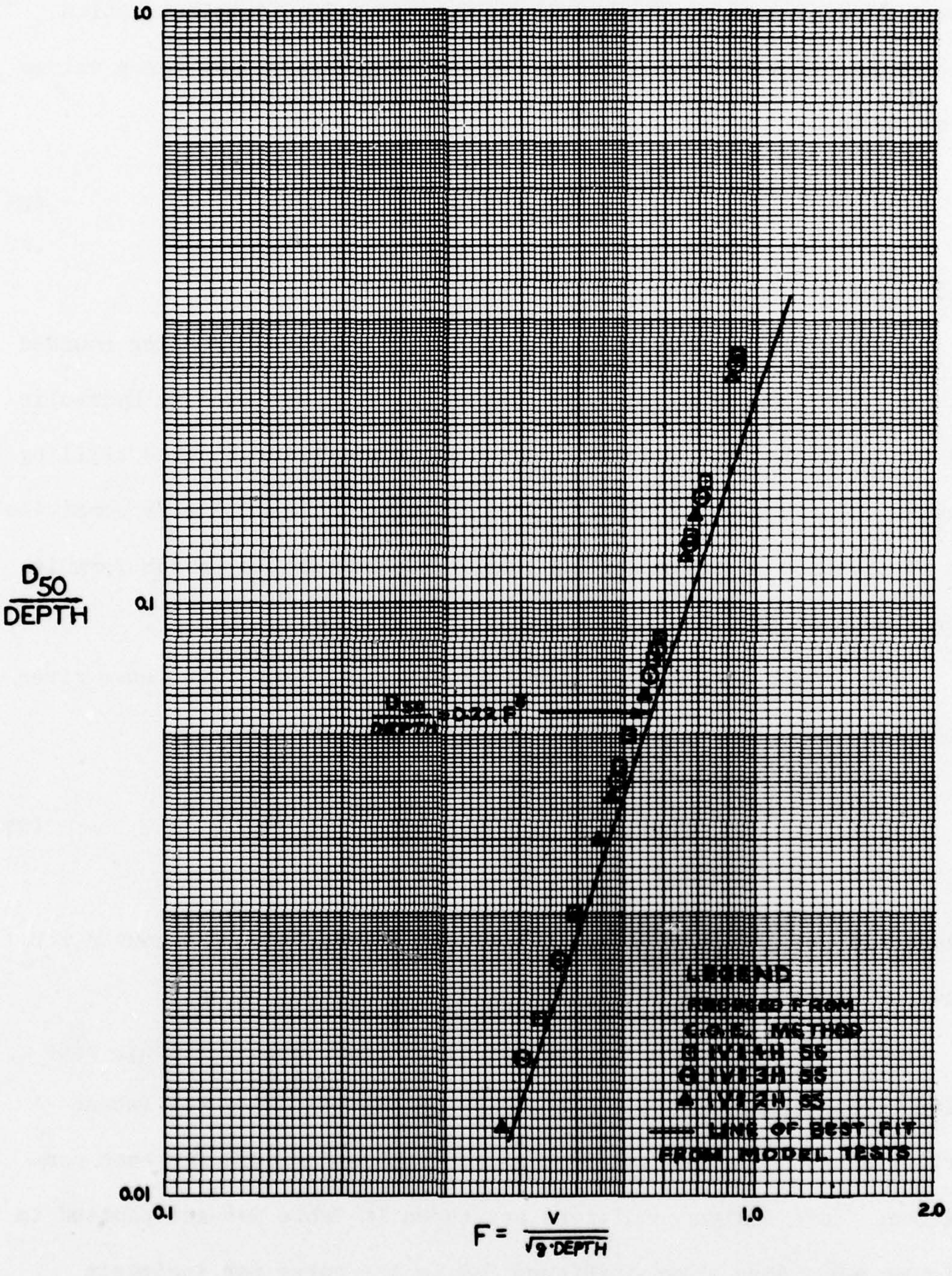


FIGURE 3-7
D_{50}/Depth Versus F - Bottom Riprap, CE, Safe Design

Corps of Engineers approach fall on the curve for incipient motion determined from the model tests. A least-squares fit of these values results in

$$\frac{D_{50}}{\text{depth}} = 0.29F^{3.2} \tag{26}$$

3-5 Isbash

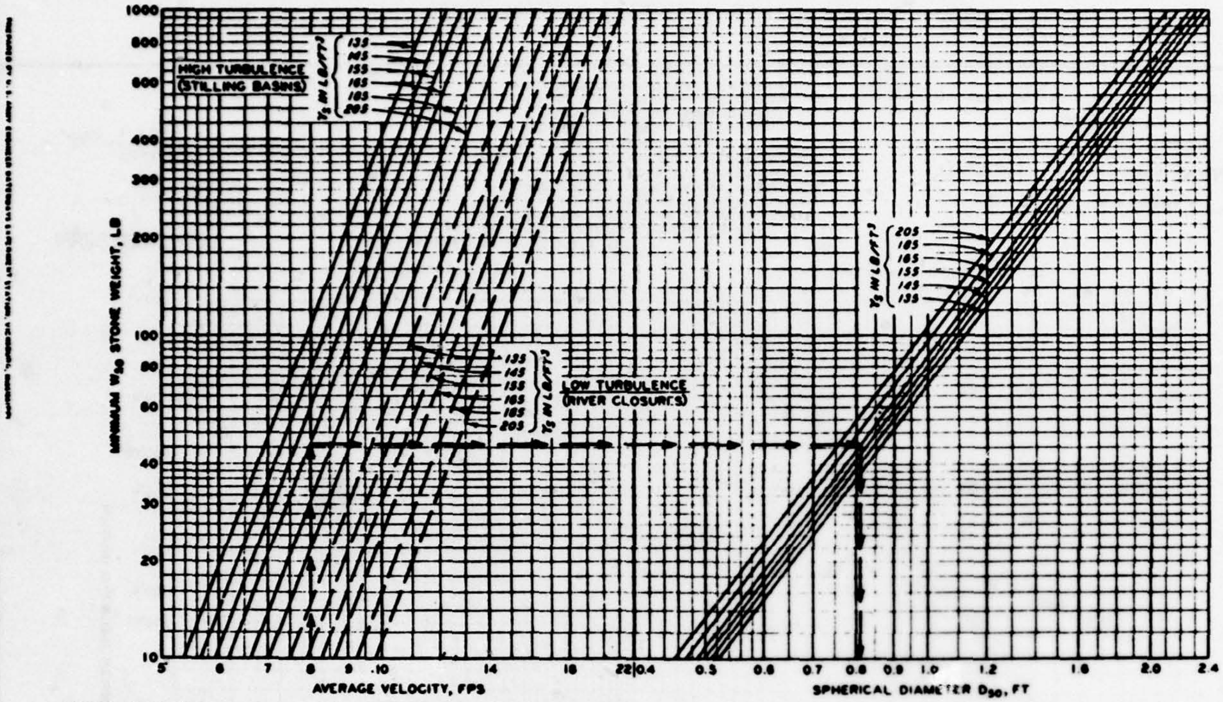
Isbash (13) conducted riprap stability tests by dropping rounded stones into flowing water. The Isbash criteria are used in Hydraulic Design Criteria (14) Sheet No. 712-1 for sizing riprap below stilling basins and for low turbulence river closures. The ASCE task committee on preparation of sedimentation manual recommends the Isbash formula for riprap design.

The Isbash equation for stable rock size in low turbulence river closures is

$$V = 1.2 \left[2g\left(\frac{\gamma_s - \gamma_w}{\gamma_w}\right)\right]^{1/2} (D_{50})^{1/2} \tag{27}$$

Hydraulic Design Chart 712-1 is shown in Figure 3-8. The curves for low turbulence should be used in designing channel riprap.

Rock sizes for typical channel discharges, bottom widths, side slopes, and channel bottom slopes are determined using the Isbash criteria and D_{50}/depth and Froude numbers are computed for each condition. Safe design conditions are shown in Table 3-6 and plotted in Figure 3-9. Also shown in Figure 3-9 is the curve for incipient



BASIC EQUATIONS

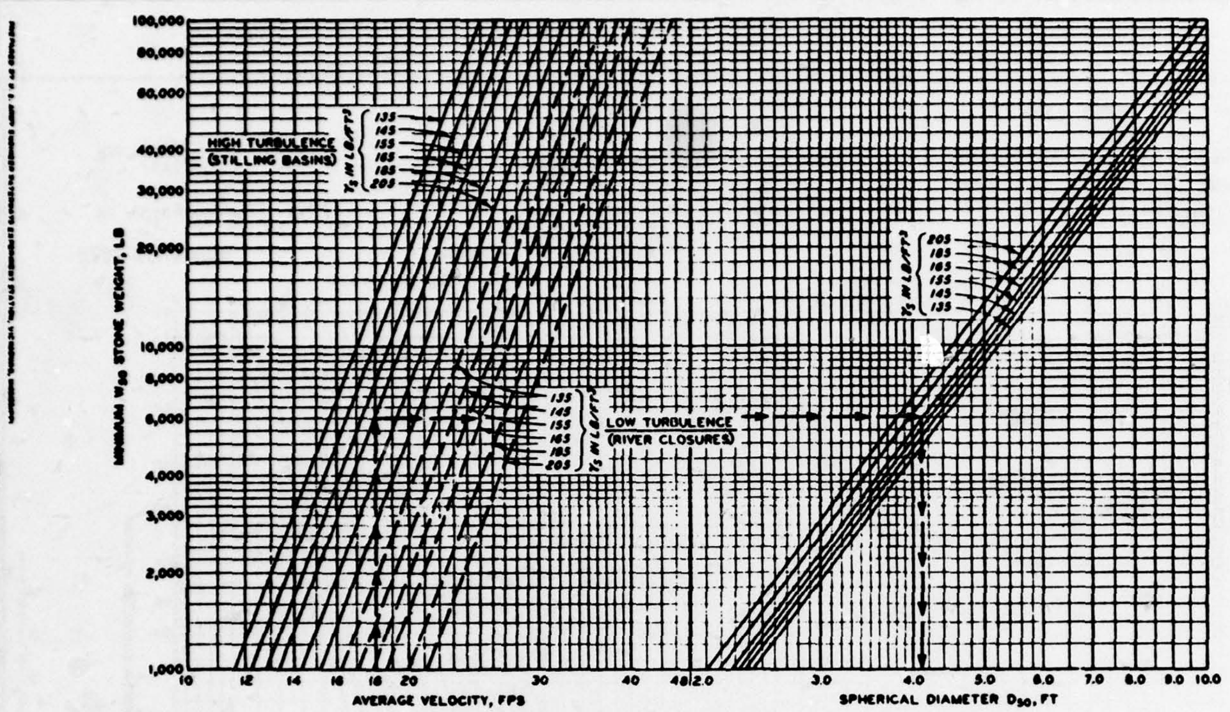
$$V = C\left[2g\left(\frac{\gamma_S-\gamma_W}{\gamma_W}\right)\right]^{1/2}\left(D_{50}\right)^{1/2}$$

$$D_{50} = \left(\frac{6W_{50}}{\pi\gamma_S}\right)^{1/3}$$

WHERE:
V = VELOCITY, FPS
γ_S = SPECIFIC STONE WEIGHT, LB/FT³
γ_W = SPECIFIC WEIGHT OF WATER, 62.5 LB/FT³
W_{50} = WEIGHT OF STONE. SUBSCRIPT DENOTES PERCENT OF TOTAL WEIGHT OF MATERIAL CONTAINING STONE OF LESS WEIGHT.
D_{50} = SPHERICAL DIAMETER OF STONE HAVING THE SAME WEIGHT AS W_{50}
C = ISBASH CONSTANT (0.86 FOR HIGH TURBULENCE LEVEL FLOW AND 1.20 FOR LOW TURBULENCE LEVEL FLOW)
g = ACCELERATION OF GRAVITY, FT/SEC²

STONE STABILITY
VELOCITY VS STONE DIAMETER
HYDRAULIC DESIGN CHART 712-1
(SHEET 1 OF 2)
REV 8-58, 9-70
WES 6-57

FIGURE 3-8 (Sheet 1 of 2)
Isbach - Velocity Versus Stone Diameter (from Hydraulic Design Criteria (14))



BASIC EQUATIONS

$$V = C\left[2g\left(\frac{\gamma_s - \gamma_w}{\gamma_w}\right)\right]^{1/2}(D_{50})^{1/2}$$

$$D_{50} = \left(\frac{6W_{50}}{\pi\gamma_s}\right)^{1/3}$$

WHERE:
V = VELOCITY, FPS
γ_s = SPECIFIC STONE WEIGHT, LB/FT^3
γ_w = SPECIFIC WEIGHT OF WATER, 62.5 LB/FT^3
W_{50} = WEIGHT OF STONE. SUBSCRIPT DENOTES PERCENT OF TOTAL WEIGHT OF MATERIAL CONTAINING STONE OF LESS WEIGHT
D_{50} = SPHERICAL DIAMETER OF STONE HAVING THE SAME WEIGHT AS W_{50}
C = ISBASH CONSTANT (0.86 FOR HIGH TURBULENCE LEVEL FLOW AND 1.20 FOR LOW TURBULENCE LEVEL FLOW)
g = ACCELERATION OF GRAVITY, FT/SEC^2

STONE STABILITY
VELOCITY VS STONE DIAMETER

HYDRAULIC DESIGN CHART 712-1
(SHEET 2 OF 2)

REV 6-58, 9-70 WES 6-57

FIGURE 3-8 (Sheet 2 of 2)
Isbach - Velocity Versus Stone Diameter (from Hydraulic Design Criteria (14))

TABLE 3-6

BOTTOM RIPRAP SIZES FOR SAFE DESIGN BY ISBASH METHOD

DISCHARGE CFS	BOTTOM SLOPE FT/FT	BOTTOM WIDTH FT	SIDE SLOPE	D50 FT	DEPTH FT	D50/D	F
13382.	0.00415	100.	4.	0.60	10.0	0.060	0.533
21853.	0.01107	100.	4.	1.60	10.0	0.160	0.870
27857.	0.01798	100.	4.	2.60	10.0	0.260	1.110
34411.	0.00207	100.	4.	0.60	20.0	0.030	0.377
56192.	0.00553	100.	4.	1.60	20.0	0.080	0.615
71632.	0.00899	100.	4.	2.60	20.0	0.130	0.785
53528.	0.00207	200.	4.	0.60	20.0	0.030	0.377
87410.	0.00553	200.	4.	1.60	20.0	0.080	0.615
111427.	0.00899	200.	4.	2.60	20.0	0.130	0.785
91762.	0.00138	200.	4.	0.60	30.0	0.020	0.308
149846.	0.00369	200.	4.	1.60	30.0	0.053	0.503
191017.	0.00599	200.	4.	2.60	30.0	0.087	0.641
120437.	0.00138	300.	4.	0.60	30.0	0.020	0.308
196673.	0.00369	300.	4.	1.60	30.0	0.053	0.503
250710.	0.00599	300.	4.	2.60	30.0	0.087	0.641
11343.	0.00346	100.	3.	0.50	10.0	0.050	0.487
19647.	0.01037	100.	3.	1.50	10.0	0.150	0.843
25365.	0.01729	100.	3.	2.50	10.0	0.250	1.088
27922.	0.00173	100.	3.	0.50	20.0	0.025	0.344
48363.	0.00519	100.	3.	1.50	20.0	0.075	0.596
62436.	0.00865	100.	3.	2.50	20.0	0.125	0.769
45374.	0.00173	200.	3.	0.50	20.0	0.025	0.344
78589.	0.00519	200.	3.	1.50	20.0	0.075	0.596
101459.	0.00865	200.	3.	2.50	20.0	0.125	0.769
75914.	0.00115	200.	3.	0.50	30.0	0.017	0.281
131486.	0.00346	200.	3.	1.50	30.0	0.050	0.487
169748.	0.00576	200.	3.	2.50	30.0	0.083	0.628
102091.	0.00115	300.	3.	0.50	30.0	0.017	0.281
176826.	0.00346	300.	3.	1.50	30.0	0.050	0.487
228282.	0.00576	300.	3.	2.50	30.0	0.083	0.628
9365.	0.00277	100.	2.	0.40	10.0	0.040	0.435
17521.	0.00968	100.	2.	1.40	10.0	0.140	0.814
22940.	0.01660	100.	2.	2.40	10.0	0.240	1.066
21853.	0.00138	100.	2.	0.40	20.0	0.020	0.308
40882.	0.00484	100.	2.	1.40	20.0	0.070	0.576
53528.	0.00830	100.	2.	2.40	20.0	0.120	0.754
37462.	0.00138	200.	2.	0.40	20.0	0.020	0.308
70084.	0.00484	200.	2.	1.40	20.0	0.070	0.576
91762.	0.00830	200.	2.	2.40	20.0	0.120	0.754
60875.	0.00092	200.	2.	0.40	30.0	0.013	0.251
113887.	0.00323	200.	2.	1.40	30.0	0.047	0.470
149113.	0.00553	200.	2.	2.40	30.0	0.080	0.615
84289.	0.00092	300.	2.	0.40	30.0	0.013	0.251
157690.	0.00323	300.	2.	1.40	30.0	0.047	0.470
206464.	0.00553	300.	2.	2.40	30.0	0.080	0.615

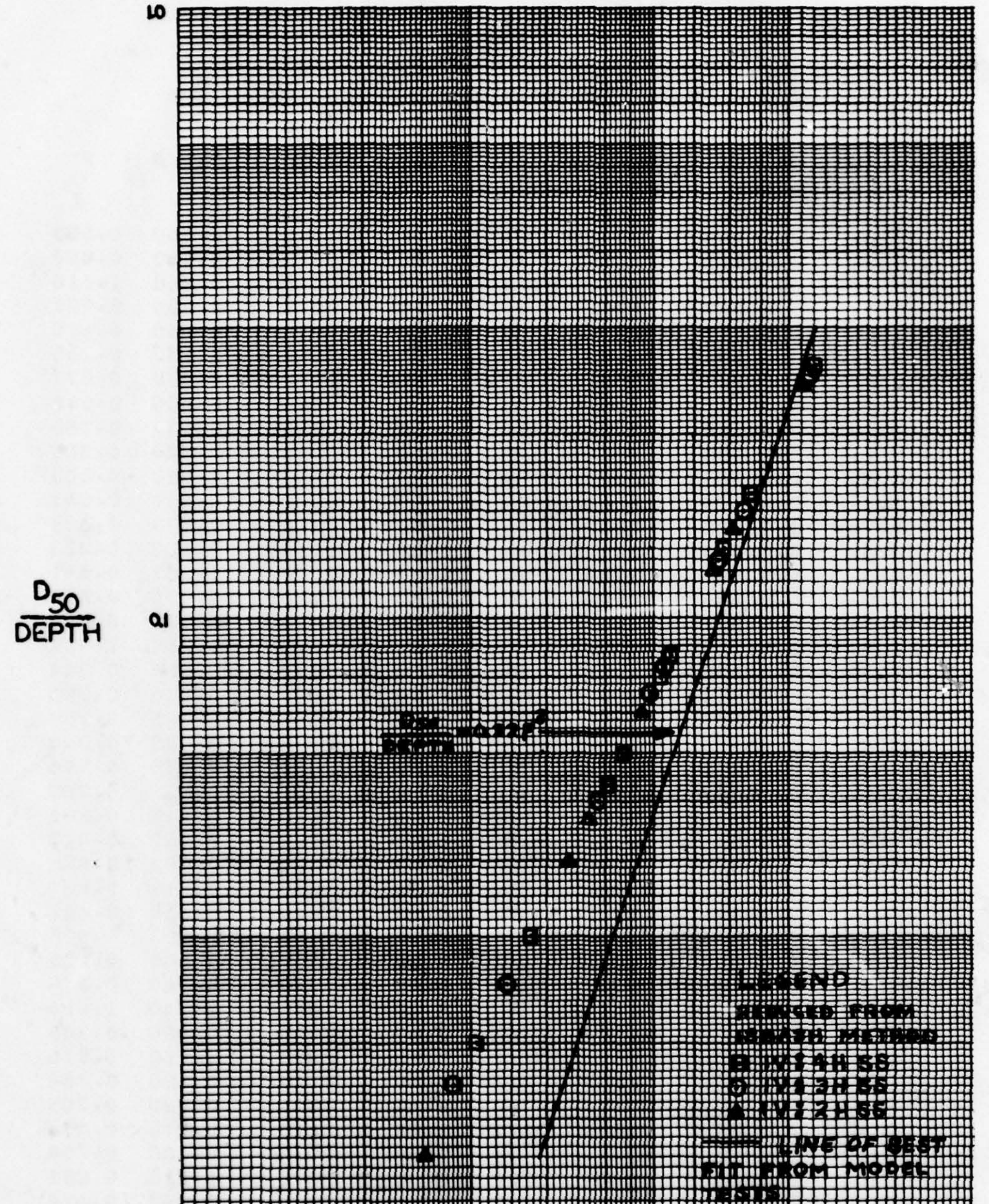


FIGURE 3-9
D_{50}/Depth Versus F - Bottom Riprap, Isbach, Safe Design

motion as determined from the model test of riprap stability in decelerating flow.

$$\frac{D_{50}}{\text{depth}} = 0.22F^{3} \qquad (3\ \text{bis})$$

Values of D_{50}/depth and Froude numbers for safe design computed by the Isbash approach fell on the safe side of the incipient motion curve for Froude numbers less than 1.0. A least-squares fit of these values results in

$$\frac{D_{50}}{\text{depth}} = 0.21F^{2.0} \qquad (28)$$

IV. DEVELOPMENT OF SIDE SLOPE CRITERIA

The coefficient C in Equation 1 will be determined for riprap on channel side slopes. Results from the model tests will be used to determine C and this value will be compared to existing criteria.

4-1 Model Tests

Tests of the 1V:4H and 1V:3H channels showed that failure occurred on both the channel bottom and the channel side slopes. Therefore the equation for channel bottom riprap at incipient motion

$$\frac{D_{50}}{\text{depth}} = 0.22F^3 \qquad \text{(3 bis)}$$

is applicable to channel side slope riprap at incipient motion for side slopes of 1V:3H or flatter.

The results of the model tests of the 1V:2H channel are shown in Table 2-1. In every test, the 1V:2H channel failed on the side slope only. A plot of D_{50}/depth versus Froude number for these tests is shown in Figure 4-1. The relationship for incipient motion for riprap on a 1V:2H side slope as shown in Figure 4-1 is

$$\frac{D_{50}}{\text{depth}} = 0.25F^3 \qquad (29)$$

4-2 Existing Criteria

Anderson's criteria for sizing riprap on channel side slopes are also based on the tractive force or shear stress method. The critical shear stress that is required to initiate motion is reduced by the

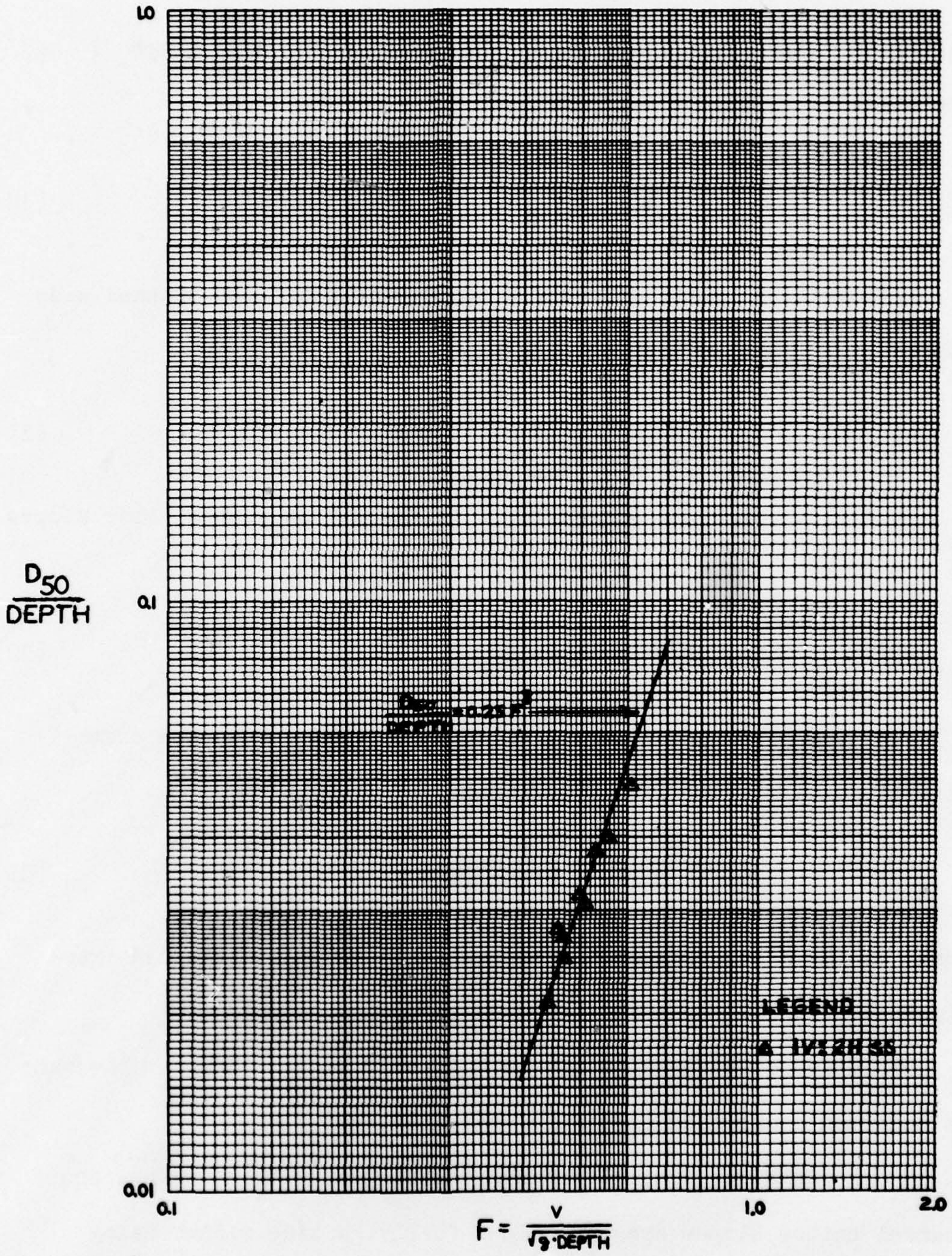


FIGURE 4-1
D_{50}/Depth Versus F - 1V:2H Side
Slope Riprap, Model Tests, Incipient Motion

factor K which is a function of the angle of the side slope θ and the angle of repose of the material ϕ .

$$K = \sqrt{1 - \frac{\sin^2 \theta}{\sin^2 \phi}} \qquad (30)$$

The critical shear stress for incipient motion for channel side slopes is

$$\tau_c = 5 \cdot D_{50} \cdot K \qquad (31)$$

The critical shear stress for safe design for channel side slopes is

$$\tau_c = 4 \cdot D_{50} \cdot K \qquad (32)$$

The tractive force exerted by the flowing water on the channel side slope is

$$\tau_s = C\gamma RS \qquad (33)$$

where C is a function of the aspect ratio and is determined from Figure 4-2.

Solution of Anderson's approach to side slope riprap is the same as Anderson's approach to channel bottom riprap.

Rock sizes for typical channel discharges, bottom widths, and channel bottom slopes are determined for 1V:2H side slopes using Anderson's approach and D_{50}/depth and Froude numbers are computed for

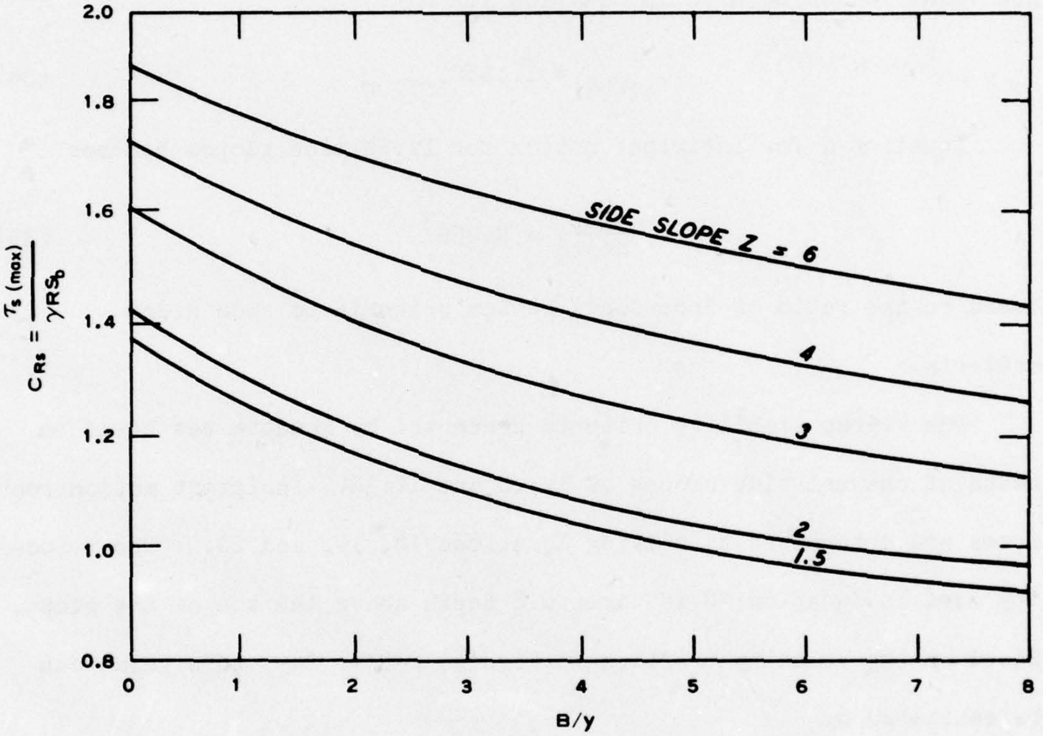


FIGURE 4-2
Maximum Boundary Shear Stress on
Sides of Trapezoidal Channels (After Anderson (2))

each condition. Incipient motion conditions are shown in Table 4-1. By comparing incipient motion conditions for 1V:2H side slopes from Table 4-1 to incipient motion conditions for channel bottoms from Table 3-1, a relation between the two conditions can be determined for the value C to be used in Equation 1.

$$C_{1:2SS} = 1.135C_{BOTTOM} \tag{34}$$

Equation 1 for incipient motion for 1V:2H side slopes becomes

$$\frac{D_{50}}{\text{depth}} = 0.25F^3 \tag{35}$$

based on the ratio of Anderson's bottom criteria to side slope criteria.

The riprap stability criteria presented by Ramette was based on tests of channel side slopes of 1V:2H and 1V:3H. Incipient motion rock sizes are determined by solving Equations 18, 19, and 20. The velocity used in Equation 20 is taken 0.8 depth above the toe of the slope. Based on the velocity profiles in Figures 2-3 to 2-9, this value can be estimated by

$$V(0.8 \text{ depth above toe}) = 1.2V(\text{average channel velocity}) \tag{36}$$

Incipient motion rock sizes for typical channel discharges, bottom widths, and channel bottom slopes are determined for 1V:2H side slopes using Ramette's approach and D_{50}/depth and Froude numbers are computed for each condition as shown in Table 4-2. By comparing rock

TABLE 4-1

SIDE SLOPE RIPRAP SIZES FOR INCIPIENT MOTION BY ANDERSON METHOD

DISCHARGE CFS	BOTTOM SLOPE FT/FT	BOTTOM WIDTH FT	SIDE SLOPE	D50 FT	DEPTH FT	D50/D	F
11873.	0.00304	100.	2.	0.40	10.0	0.040	0.552
18027.	0.01063	100.	2.	1.40	10.0	0.140	0.838
21575.	0.01822	100.	2.	2.40	10.0	0.240	1.003
28399.	0.00148	100.	2.	0.40	20.0	0.020	0.400
43119.	0.00517	100.	2.	1.40	20.0	0.070	0.607
51606.	0.00886	100.	2.	2.40	20.0	0.120	0.727
53309.	0.00152	200.	2.	0.40	20.0	0.020	0.438
80939.	0.00531	200.	2.	1.40	20.0	0.070	0.665
96869.	0.00911	200.	2.	2.40	20.0	0.120	0.796
87335.	0.00098	200.	2.	0.40	30.0	0.013	0.360
132602.	0.00342	200.	2.	1.40	30.0	0.047	0.547
158701.	0.00587	200.	2.	2.40	30.0	0.080	0.655
128330.	0.00101	300.	2.	0.40	30.0	0.013	0.383
194844.	0.00354	300.	2.	1.40	30.0	0.047	0.581
233193.	0.00607	300.	2.	2.40	30.0	0.080	0.695

TABLE 4-2

SIDE SLOPE RIPRAP SIZES FOR INCIPIENT MOTION BY RAMETTE METHOD

DISCHARGE CFS	BOTTOM SLOPE FT/FT	BOTTOM WIDTH FT	SIDE SLOPE	D50 FT	DEPTH FT	D50/D	F
10048.	0.00337	100.	2.	0.40	10.0	0.040	0.467
15575.	0.01181	100.	2.	1.40	10.0	0.140	0.724
18577.	0.02024	100.	2.	2.40	10.0	0.240	0.863
25668.	0.00169	100.	2.	0.40	20.0	0.020	0.361
40502.	0.00590	100.	2.	1.40	20.0	0.070	0.570
48794.	0.01012	100.	2.	2.40	20.0	0.120	0.687
44003.	0.00169	200.	2.	0.40	20.0	0.020	0.361
69432.	0.00590	200.	2.	1.40	20.0	0.070	0.570
83646.	0.01012	200.	2.	2.40	20.0	0.120	0.687
75128.	0.00112	200.	2.	0.40	30.0	0.013	0.310
119606.	0.00394	200.	2.	1.40	30.0	0.047	0.494
144801.	0.00675	200.	2.	2.40	30.0	0.080	0.598
104023.	0.00112	300.	2.	0.40	30.0	0.013	0.310
165608.	0.00394	300.	2.	1.40	30.0	0.047	0.494
200494.	0.00675	300.	2.	2.40	30.0	0.080	0.598

sizes for 1V:2H side slopes from Table 4-2 with rock sizes for channel bottom riprap from Table 3-4, a relation between the two conditions can be determined for the value C to be used in Equation 1.

$$C_{1:2SS} = 1.29C_{BOTTOM} \tag{37}$$

Equation 1 for incipient motion for 1V:2H side slopes becomes

$$\frac{D_{50}}{\text{depth}} = 0.284F^3 \tag{38}$$

based on the ratio of Ramette's bottom criteria to side slope criteria.

Side slope criteria used by the Corps of Engineers in EM 1110-2-1601 (4) is similar to that used by Ramette. The critical shear stress determined from Equation 23 is reduced by K given in Equation 30.

$$\tau_c = 0.04(\gamma_s - \gamma_w)D_{50} \cdot K \tag{39}$$

The velocity used in Equation 25 is the average velocity in the vertical at the toe of the slope. Based on the velocity profiles in Figures 2-3 to 2-9

$$V(0.6 \text{ depth at toe}) = V(\text{average channel velocity}) \tag{40}$$

Rock sizes for typical channel discharges, bottom widths, and channel bottom slopes are determined for 1V:2H side slopes using the Corps approach and D_{50}/depth and Froude numbers are computed for each condition as shown in Table 4-3. By comparing rock sizes for 1V:2H side slope from Table 4-3 with rock sizes for channel bottom riprap

TABLE 4-3

SIDE SLOPE RIPRAP SIZES FOR SAFE DESIGN BY C.O.E. METHOD

DISCHARGE CFS	BOTTOM SLOPE FT/FT	BOTTOM WIDTH FT	SIDE SLOPE	D50 FT	DEPTH FT	D50/D	F
10897.	0.00198	100.	2.	0.40	10.0	0.040	0.506
15921.	0.00695	100.	2.	1.40	10.0	0.140	0.740
18331.	0.01191	100.	2.	2.40	10.0	0.240	0.852
28507.	0.00099	100.	2.	0.40	20.0	0.020	0.401
42914.	0.00347	100.	2.	1.40	20.0	0.070	0.604
50319.	0.00595	100.	2.	2.40	20.0	0.120	0.709
48869.	0.00099	200.	2.	0.40	20.0	0.020	0.401
73567.	0.00347	200.	2.	1.40	20.0	0.070	0.604
86261.	0.00595	200.	2.	2.40	20.0	0.120	0.709
84432.	0.00066	200.	2.	0.40	30.0	0.013	0.348
128938.	0.00232	200.	2.	1.40	30.0	0.047	0.532
152472.	0.00397	200.	2.	2.40	30.0	0.080	0.629
116906.	0.00066	300.	2.	0.40	30.0	0.013	0.348
178530.	0.00232	300.	2.	1.40	30.0	0.047	0.532
211115.	0.00397	300.	2.	2.40	30.0	0.080	0.629

from Table 3-5, a relation between the two conditions can be determined for the value C to be used in Equation 1.

$$C_{1.2SS} = 1.236C_{BOTTOM} \tag{41}$$

Equation 1 for incipient motion for 1V:2H side slopes becomes

$$\frac{D_{50}}{\text{depth}} = 0.272F^3 \tag{42}$$

based on the ratio of EM 1110-2-1601 (4) bottom criteria to side slope criteria.

4-3 Design Curves

A summary of the values of C for incipient motion on 1V:2H side slopes is as follows:

Method	C
Model tests	0.25
Anderson	0.25
Ramette	0.284
EM 1110-2-1601	0.272

For this investigation a C value of 0.26 will be used. Equation 1 for incipient motion on 1V:2H side slopes as shown in Figure 4-3 is

$$\frac{D_{50}}{\text{depth}} = 0.26F^3 \tag{43}$$

The curve for safe design with a factor of 1.5 × incipient motion for 1V:2H side slopes based on the average stone weight is

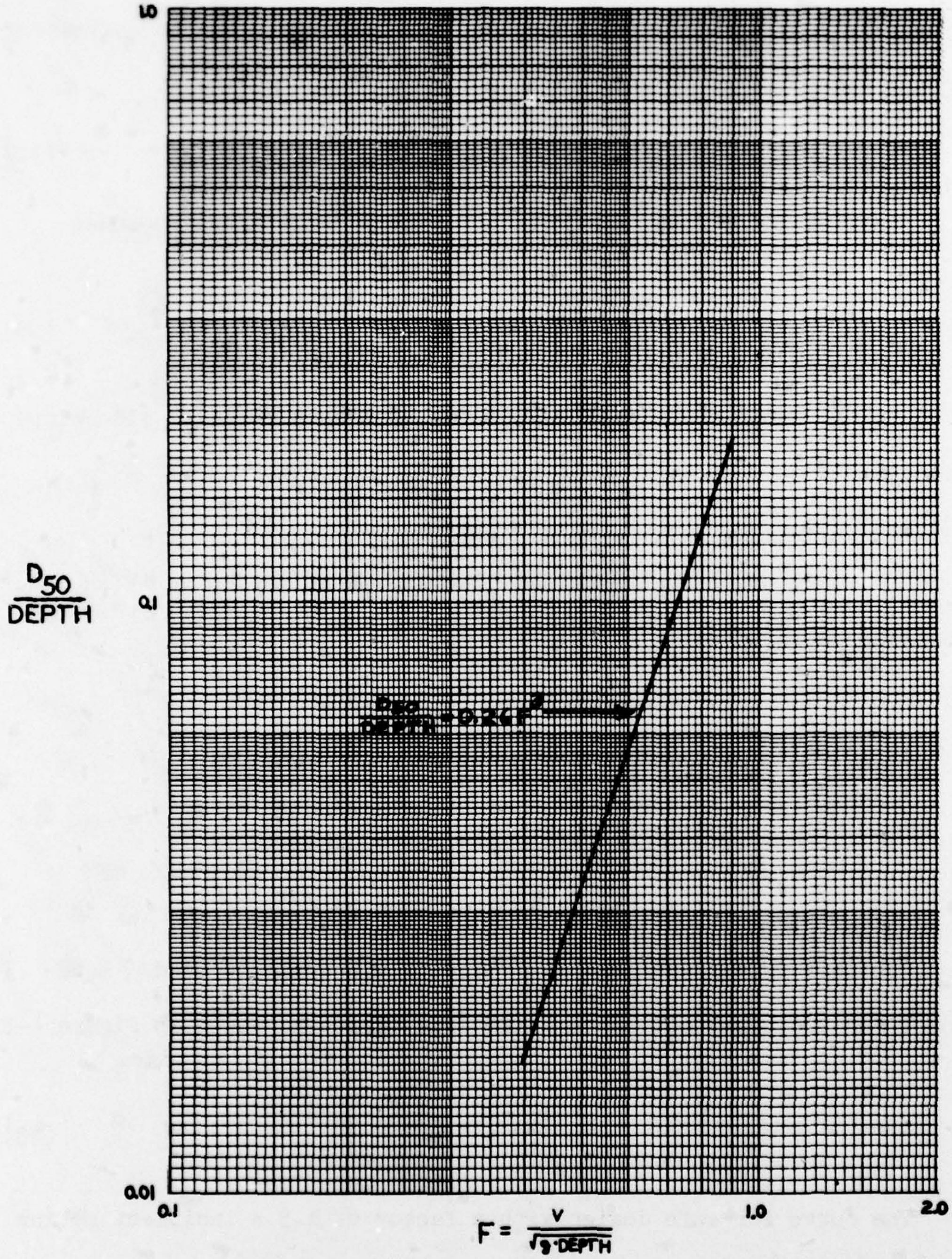


FIGURE 4-3
D_{50}/Depth Versus F - 1V:2H Side Slope Riprap, Incipient Motion

$$\frac{D_{50}}{\text{depth}} = 0.30F^3 \qquad (44)$$

and a factor of 2.0 × incipient motion for 1V:2H side slopes based on the average stone weight is

$$\frac{D_{50}}{\text{depth}} = 0.33F^3 \qquad (45)$$

V. DEVELOPMENT OF BEND CRITERIA

Information on sizing riprap in channel bends is relatively scarce. In Figure 5-1 the shear distribution in a channel bend is shown as presented in EM 1110-2-1601 (4). The maximum shear in a channel bend as a function of bend radius and water surface width is shown in Figure 5-2. This figure was taken from EM 1110-2-1601 and is a good summary of the work previously conducted in the field of shear distribution in channel bends. Additional research is needed to determine the effects of total bend angle and side slope angle on the shear distribution in a channel bend. Figure 5-2 was based on a channel with 1V:2H side slopes and a 60° bend angle. Figure 5-2 was used to determine tentative values of C in Equation 1 for sizing riprap in channel bends.

The equation for rough channel conditions as shown in Figure 5-2 is

$$\frac{\tau_b}{\tau_o} = 3.2 \left(\frac{r}{w}\right)^{-0.5} \tag{46}$$

where

τ_b = maximum boundary shear as affected by bend

τ_o = average boundary shear in approach channel

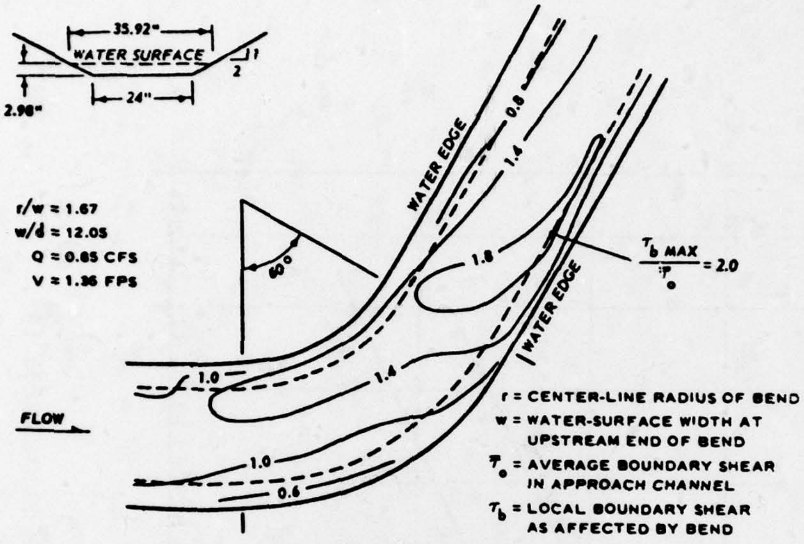
r = center line radius of bend

w = water surface width at upstream end of bend

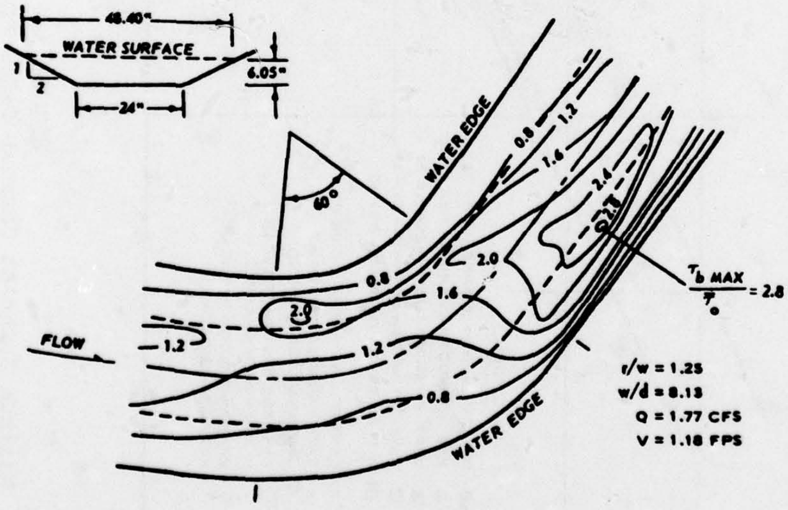
The Shields' equation for the critical shear stress is

$$\tau_o = 0.04(\gamma_s - \gamma_w)D_{50_{APPROACH}} \tag{47}$$

in the approach channel and



A. SMOOTH CHANNEL



B. ROUGH CHANNEL

NOTE: FIGURES REPRODUCED FROM REF 53.

FIGURE 5-1
Shear Distribution in Channel Bends (from EM 1110-2-1601 (4))

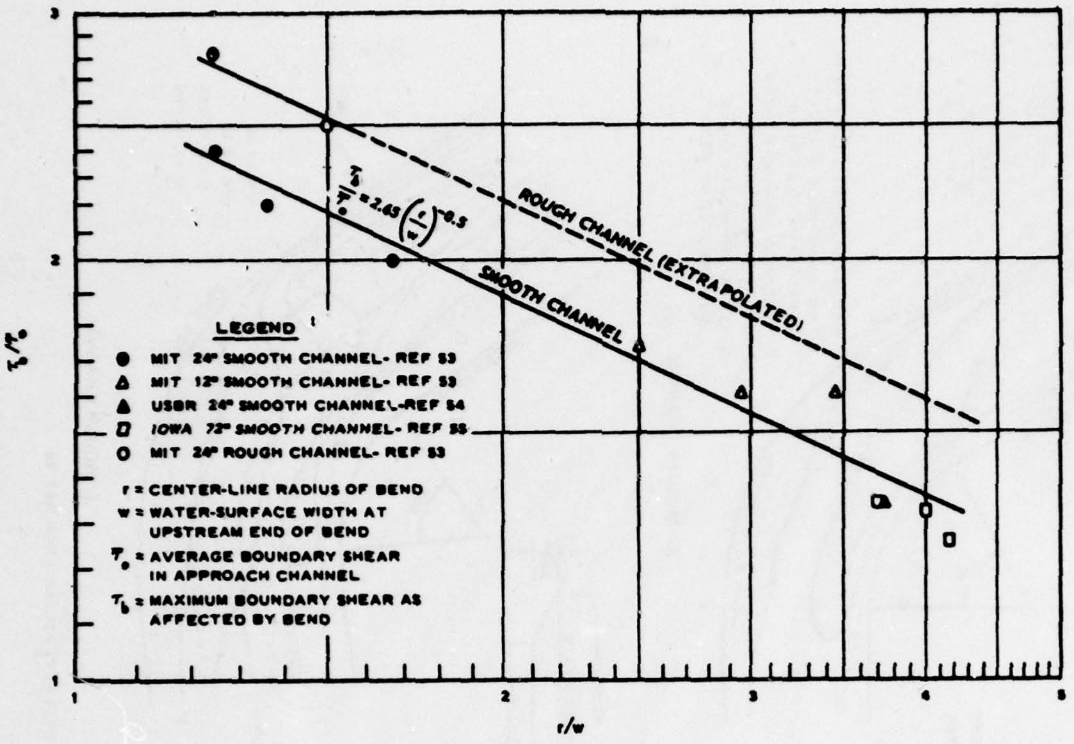


FIGURE 5-2
Maximum Shear at Channel Bends (from EM 1110-2-1601 (4))

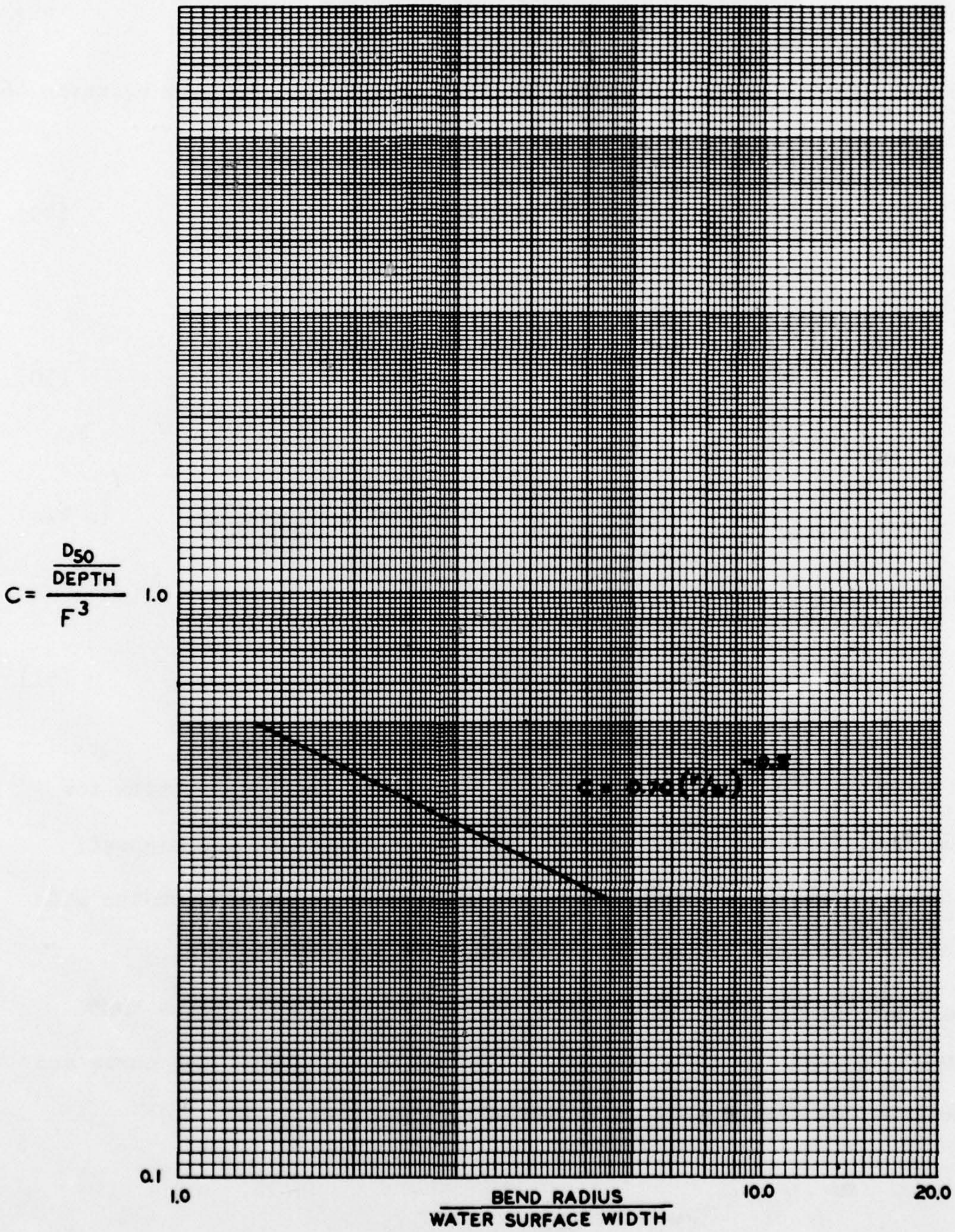


FIGURE 5-3
C Versus Bend Radius/Water Surface Width, Incipient Motion

$$\tau_b = 0.04(\gamma_s - \gamma_w)D_{50_{bend}} \tag{48}$$

in the channel bend. Substituting Equations 47 and 48 into equation 46

$$\frac{D_{50_{bend}}}{D_{50_{APPROACH}}} = 3.2 \frac{r}{w}^{-0.5} \tag{49}$$

From Equation 1, let

$$D_{50_{bend}} = C_{bend} \text{ depth } F^3 \tag{50}$$

and

$$D_{50_{APPROACH}} = 0.22 \text{ depth } F^3 \tag{3 bis}$$

Substituting

$$C_{bend} = 0.70 \frac{r}{w}^{-0.5} \tag{51}$$

as shown in Figure 5-3. This curve represents incipient motion for only the point on the curve where the shear stress is the highest. Based on Figure 5-1 the point of maximum shear is located on the side slope of the outside bank at the downstream end of the bend.

Additional work is needed to determine the coefficients that should be used for safe design for the entire length of the curve and the area downstream that is affected by the curve.

VI. SUMMARY AND SAMPLE PROBLEM

A summary of the coefficients determined in this investigation for the equation for riprap stability

$$\frac{D_{50}}{\text{depth}} = CF^3 \qquad (1)$$

is as follows:

Condition	Coefficient C
Straight channel, bottom riprap, incipient motion	0.22
Straight channel, bottom riprap, F.S. = 1.5	0.25
Straight channel, bottom riprap, F.S. = 2.0	0.28
Straight channel, 1V:3HSS or flatter, incipient motion	0.22
Straight channel, 1V:3HSS or flatter, F.S. = 1.5	0.25
Straight channel, 1V:3HSS or flatter, F.S. = 2.0	0.28
Straight channel, 1V:2HSS, incipient motion	0.26
Straight channel, 1V:2HSS, F.S. = 1.5	0.30
Straight channel, 1V:2HSS, F.S. = 2.0	0.33
Curved channel, incipient motion* $C = 0.70(r/w)^{-0.50}$	

* Incipient motion for only the point on the curve where the shear is highest.

A sample problem to illustrate the use of the Froude number approach is as follows:

Design Data--Straight channel
100-ft bottom width
1V:3H side slopes
0.004 ft/ft bottom slope
Design discharge = 30,000 cfs

Determine the required rock size to provide a safety factor of 1.5 and the depth of flow at the design discharge.

Solution: Assume $D_{50} = 1.0$ ft

$$n = 0.0395D_{50}^{1/6} \qquad (9\ \text{bis})$$

$$n = 0.0395$$

From Manning's equation

Normal depth = 16.2 ft

Velocity = 12.5 ft/sec

$F = 0.55$

From Froude's number concept

$$\frac{D_{50}}{\text{depth}} = 0.25F^3 \qquad (4\ \text{bis})$$

$$D_{50} = 0.67\ \text{ft}$$

This D_{50} is not close enough to the assumed D_{50} .

Assume $D_{50} = 0.75$ ft

$$n = 0.0395D_{50}^{1/6}$$

$$n = 0.038$$

From Manning's equation

Normal depth = 15.9 ft

Velocity = 12.8 ft/sec

$F = 0.57$

From Froude's number concept

$$\frac{D_{50}}{\text{depth}} = 0.25F^3$$

$$D_{50} = 0.72\ \text{ft}$$

The assumed D_{50} of 0.75 ft is close enough to the computed $D_{50} = 0.72$ ft. The channel requires a riprap blanket with a 9-in. D_{50} on both the channel bottom and side slope.

VII. CONCLUSIONS

The results of this investigation show that riprap stability can be described by parameters that are known or easily computed. Froude number and depth of flow are used to determine stable riprap size. Comparison of the Froude number approach with existing shear stress design methods shows that Froude number and depth of flow properly describe riprap stability.

The model tests show that riprap on channel side slopes of 1V:3H or flatter require no increase in rock size to maintain stability. Appropriate relations for determining stable rock sizes on 1V:2H side slopes were developed from the model test and existing design concepts.

Additional research is needed so that stable rock sizes in channel bends can be determined.

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In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Maynord, Stephen T

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Bibliography: p. 65-66.

1. Riprap. I. United States. Army. Corps of Engineers. II. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Miscellaneous paper ; H-78-7.
TA7.W34m no.H-78-7