VELOCITY FORCES ON SUBMERGED ROCKS

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PREFACE

The study described in this report was made under the Corps of Engineers Civil Works Investigation 804, "Analysis of Hydraulic Experimental Data (Model and Prototype) and Development of Design Criteria." The Waterways Experiment Station is assigned the responsibility of developing "Hydraulic Design Criteria."

A chart to be used as a guide for rock size criteria for river closures and riprap is included in the seventh issue of Hydraulic Design Criteria. The investigation and research that were necessary to develop this chart are summarized herein.

The investigation was made by Mr. R. G. Cox, Chief, Analysis Section, under the supervision of Mr. F. B. Campbell, Chief, Hydraulic Analysis Branch. The work was performed during the period June to December 1956.

CONTENTS

NOTATIONS

A	Cross-sectional area, ft^2
$C_{1,2}$	Constants
C_D	Drag coefficients
d	Depth of flow, ft
d_g	Diameter of stone, ft
D	Height of cube, ft
F	Force, lb
g	Gravity, 32 ft per sec^2
H	Wave height, ft
K'	Constant in modified Iribarren equation
ℓ_f	Moment arm of actuating force
ℓ_r	Moment arm of resisting force
M_f	Forcing moment, ft-lb
M_r	Resisting moment, ft-lb
n	Roughness coefficient, Manning's
s	Slope of energy gradient
V	Mean velocity, ft per sec
V_c	Critical mean velocity at which movement begins, ft per sec
V_s	Velocity acting directly on stone projection, ft per sec
V_o	Approach velocity, ft per sec
W	Weight of rock, lb
y	The Isbash constant, 1.20 and 0.86 for maximum and minimum stone stability
μ	Coefficient of friction
τ	Tractive force, lb per ft^2
τ_c	Critical tractive force, lb per ft^2
γ	Specific weight of water, 62.4 lb per ft^3
γ_s	Specific weight of stone, 165 lb per ft^3
ρ	Density of fluid, $\frac{\gamma}{g}$, slugs per ft^3
α	Angle of repose

SUMMARY

The development of interest in the hydraulic forces acting on a body in a moving fluid from the seventeenth century to the present time is traced. Various formulas pertaining to bed-load movement, rock-filled dams, breakwaters, and drag coefficients are studied. The formulas are transposed to show their interrelationship.

Available data pertinent to the design of riprap and river closures are discussed and summarized. Suggested design curves are given. The effect of bed slope on rock stability is considered.

VELOCITY FORCES ON SUBMERGED ROCKS

PART I: INTRODUCTION

Scope of Study

1. Modern use of rock for river closures, breakwaters, and riprap has stimulated interest in the hydraulic forces that act on submerged bodies. This interest led to the development of a hydraulic design criteria chart for use by the Corps of Engineers as a guide in river closure and riprap design problems. In the development of this chart material from many sources was compiled and is listed in Appendix A. In addition, a study was made of various formulas commonly used in the solution of these and similar hydraulic problems. The results of this study are summarized herein.

Historical Background

2. Interest in the hydraulic forces acting on a submerged body in a moving fluid dates back to the seventeenth century. Late in the eighteenth century Dubuat published the first reliable data on the transportation of solid particles by flowing water and derived an equation attempting to define the laws of movement of material along the bed of a stream. Study of the movement of material in canals and rivers during the nineteenth century resulted in many observations by independent investigators. Much of the data resulting from these tests remains valid today. In 1896, E. H. Hooker[10] made a comprehensive summary of the data and theories of these early investigators.

3. In the first half of the twentieth century many studies relating to specific problems were undertaken. While major efforts were directed toward the study of the mechanics of sediment transportation, the problems of riprap and revetment design as well as of river closures and breakwaters received considerable attention. The advent of the airplane and the resulting aerodynamic research contributed much to the knowledge of fluid forces acting on bodies.

PART II: THEORY

4. The study of the hydraulic forces that act on bodies submerged in a fluid in motion can be divided into three general categories. First, the movement or transportation of material in a stream is of interest in the study of natural river phenomena such as the formation of sand bars, crossings, and deltas. Second, the stability of a rock structure or an individual stone is important in the design and construction of rock dams, revetments, riprap, and breakwaters. Third, the form resistance of a body or structure to flow is important in the design of piers, baffle blocks, and hydrofoils. While the general phenomena in each case are the same, different approaches have resulted in numerous definitions and formulas. However, since each case involves common actuating forces, the resulting equations can often be interrelated.

Transportation

5. Submerged material transported by a fluid moves either along the boundary or in suspension. Movement of particles along the boundary is more commonly defined as bed load in a natural stream. The movement is related to the shear force of the fluid boundary in which the material moves. Duboys recognized this phenomenon in 1879 and introduced the term tractive force. The formula for this force is (fig. 1):

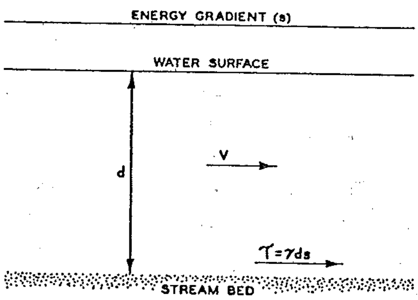


Fig. 1

$$\tau = \gamma ds \qquad (1)$$

Studies by L. G. Straub,[19] by A. Shields, and others have determined that the critical tractive force for particles of 0.03-ft diameter or greater can be expressed as:

$$\tau_c = 0.06\ (\gamma_s - \gamma)\ d_g \qquad (2)$$

The Manning equation for two-dimensional open channel flow is:

$$V = \frac{1.486\ s^{1/2}\ d^{2/3}}{n} \qquad (3)$$

The investigations of Chang[5] and others indicate that the Manning n for a movable bed can be expressed as a function of the mean grain-size diameter of the bed material. Straub's[19] expression for this relationship is:

$$n = 0.0432\, d_g^{1/6} \tag{4}$$

The theoretical critical mean velocity at which bed material will begin to move was obtained by Straub by substituting equations 1, 2, and 4 into equation 3. The resulting equation is:

$$V_c = 8.45 \sqrt{\frac{\gamma_s - \gamma}{\gamma}} \left(\frac{d}{d_g}\right)^{1/6} \sqrt{d_g} \tag{5}$$

For specific weight of stone and water of 165 lb per ft^3 and 62.4 lb per ft^3, respectively, equation 5 can be reduced to

$$\left(\frac{d_g}{d}\right)^{1/6} V_c = 10.8\, d_g^{1/2} \tag{6}$$

The term $(d_g/d)^{1/6}$ appears to be a velocity distribution factor which translates the mean velocity to the shear velocity acting on the particles at the boundary.

Stability

6. Adequate design of riprap, revetments, breakwaters, and rock-fill dams requires knowledge of the stability of large size material in fluids in motion. Two of the better known investigators in these fields are S. V. Isbash[13,14] and R. Iribarren Cavanilles.[11] In 1932 Isbash published the results of his extensive experiments on the construction of rock dams in flowing water. His basic equation for stone stability is (fig. 2):

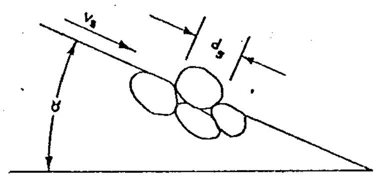


Fig. 2

$$V_s = y \sqrt{2\, g\, \frac{\gamma_s - \gamma}{\gamma}} \sqrt{\cos \alpha - \sin \alpha} \sqrt{d_g} \tag{7}$$

Equation 7 can be further simplified for 165 lb per ft^3 stone and on a horizontal surface in fresh water to:

$$V_s = 12.35\, d_g^{1/2} \text{ (embedded stone)} \tag{8}$$

and

$$V_s = 8.85\ d_g^{1/2}\ \text{(nonbedded stone)} \quad (9)$$

7. The Iribarren formula for the design of rubble-mound breakwaters was published by Prof. Ramon Iribarren Cavanilles in 1938. The coefficient in the Iribarren formula as determined from observations on actual breakwaters was dimensional. In 1952, R. Y. Hudson[11] published a more general form of this equation which is dimensionally homogeneous. The Iribarren formula as modified by Hudson is (fig. 3):

$$W = \frac{K'\ \gamma_s\ \gamma^3\ \mu^3\ H^3}{(\gamma_s - \gamma)^3\ (\mu \cos \alpha - \sin \alpha)^3} \quad (10)$$

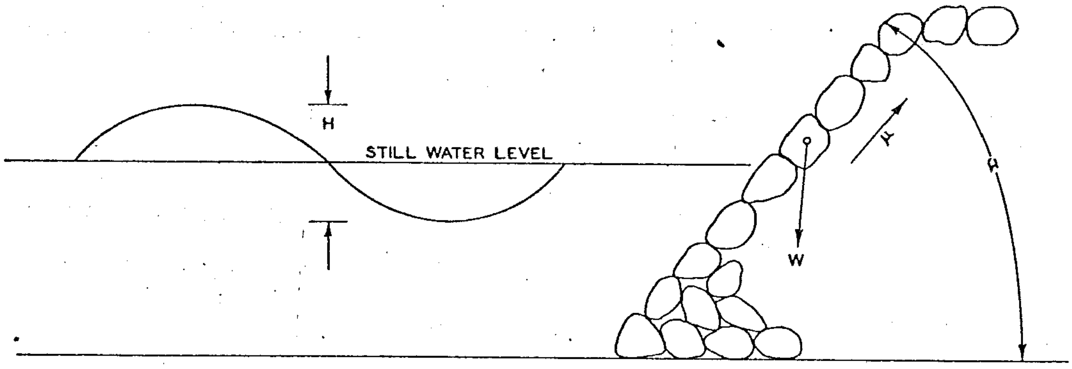


Fig. 3

8. Mr. P. T. Bennett of the Omaha District, CE, demonstrated some years ago that the Iribarren formula could be transferred into the Isbash type formula by making the following simplifying assumptions:

Let:

$$W = D^3\ \gamma_s$$
$$V^2 = 2gH$$
$$\mu = 1.0$$

Then

$$D^3\ \gamma_s = \frac{K'\ \gamma_s\ H^3}{(\cos \alpha - \sin \alpha)^3} \left(\frac{\gamma}{\gamma_s - \gamma}\right)^3$$

$$D = \frac{\sqrt[3]{K'}\ H}{(\cos \alpha - \sin \alpha)}\ \frac{\gamma}{\gamma_s - \gamma}$$

and

$$\frac{V^2}{2g} = \frac{D\ (\cos\alpha - \sin\alpha)}{\sqrt[3]{K'}}\ \frac{\gamma_s - \gamma}{\gamma}$$

$$V = \sqrt{\frac{1}{\sqrt[3]{K'}}}\ \sqrt{2g}\ \sqrt{\frac{\gamma_s - \gamma}{\gamma}}\ \sqrt{\cos\alpha - \sin\alpha}\ \sqrt{D} \qquad (11)$$

Equation 11 compares with equation 7 when

$$y = \sqrt{\frac{1}{\sqrt[3]{K'}}} = (K')^{-1/6}$$

and

$$d_g = 1.24\ D$$

9. The modified Iribarren formula can also be written for a spheroidal stone on zero slope as:

$$\frac{\pi\ \gamma_s\ d_g^{\ 3}}{6} = \frac{K'\ \gamma_s\ \gamma^3\ (V_s^{\ 2}/2g)^3}{(\gamma_s - \gamma)^3} \qquad (12)$$

or

$$V_s = 9.2 \left(\frac{d_g}{\sqrt[3]{K'}}\right)^{1/2}$$

The average value of K' for natural and artificial breakwater rock has been determined as 0.017. Equation 12 thus becomes

$$V_s = 18.2\ d_g^{\ 1/2} \qquad (13)$$

Resistance

10. The longitudinal force on an immersed body is equal to:

$$F = C_D\ A\ \rho\ \frac{V_o^{\ 2}}{2} \qquad (14)$$

The cross-sectional area of an embedded stone on which the force F acts can be expressed as (fig. 4):

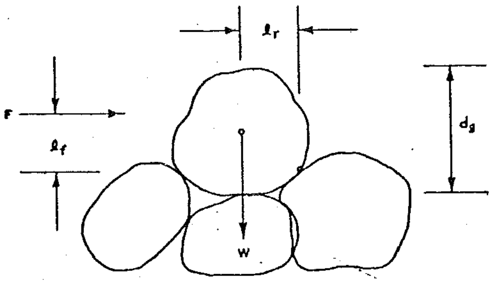


Fig. 4

$$A = C_1 \pi d_g^2$$

The moment arm of the force F acting on the embedded stone is a function of the stone diameter:

$$\ell_f = C_2 d_g$$

Therefore, the forcing moment can be written as:

$$M_f = FC_2 d_g = \frac{C_D C_1 \pi d_g^2 \gamma V_o^2}{2g} \times C_2 d_g \qquad (15)$$

The resisting moment of the stone to overturning depends upon the resisting moment arm (ℓ_r) which is a function of the stone diameter ($C_3 d_g$) and upon the submerged weight of the stone.

$$M_r = \frac{\pi d_g^3}{6} (\gamma_s - \gamma) C_3 d_g \qquad (16)$$

Incipient overturning of the stone results when the forcing moment equals the resisting moment:

$$M_f = M_r = F \ell_f = W \ell_r$$

or

$$\frac{C_D C_1 \pi d_g^2 V_o^2 \gamma C_2}{2g} d_g = \frac{\pi d_g^3}{6} (\gamma_s - \gamma) C_3 d_g \qquad (17)$$

Equation 17 can be reduced to:

$$V_o^2 = \frac{2g (\gamma_s - \gamma) C_3 d_g}{6 C_D C_1 \gamma C_2}$$

For a specific condition let:

$$\frac{2g C_3}{6 C_D C_1 C_2} = \frac{1}{C'_D}$$

Then

$$V_o = \sqrt{\frac{1}{C'_D}} \sqrt{d_g} \sqrt{\frac{\gamma_s - \gamma}{\gamma}} \qquad (18)$$

For $\gamma_s = 165$ lb per ft^3 and $\gamma = 62.4$ lb per ft^3

$$V_o = 1.28 \frac{1}{\sqrt{C'_D}} \sqrt{d_g} \tag{19}$$

11. It has been shown that y in the Isbash equation is the same as $\sqrt{\frac{1}{\sqrt[3]{K'}}}$ in the Iribarren equation when $d_g = 1.24$ D (paragraph 9). This relationship can be extended to include the function of the drag coefficient of equation 18.

$$y = \sqrt{\frac{1}{\sqrt[3]{K'}}} = \frac{1}{\sqrt{C'_D}}$$

or

$$\frac{1}{C'_D} = \frac{1}{\sqrt[3]{K'}} = y^2$$

and

$$C'_D = \sqrt[3]{K'} = \frac{1}{y^2}$$

The relationship between the Isbash, Iribarren, and drag coefficient formulas is also shown by equations 7, 13, and 19. These equations can be related to each other by proper manipulation of the coefficients.

PART III: DERIVATION OF DESIGN CURVES

Hydraulic Design Chart 712-1: River Closures - Velocity vs Stone Weight

12. "Hydraulic Design Chart 712-1: River Closures - Velocity vs Stone Weight" (plate 1) summarizes the results of a study of available data pertaining to river closure and riprap problems. The data shown on this chart are believed to include the most reliable observations and investigations from 1786 to the present time.

Basic data

13. The plotted data in plate 1 are from 16 independent investigations. Material sizes ranged from pebbles in models to 2.7-ft boulders in high river velocities. A specific weight of 165 lb per cu ft has been used to simplify comparison. Forty-one points of the plotted data are based on bottom velocity measurements. The remaining sixteen points are believed to be based on mean velocities. All data plotted on the chart are tabulated in Appendix B.

a. Foreign.[10] Fourteen observations result from tests by six investigators prior to 1896. They appear to be observations on isolated bodies. Bottom velocities were measured in eight instances. The velocity location is not identified for the remaining data. However, the general agreement indicates bottom velocities were observed in most cases.

b. Bonneville Flume.[9] Twenty-six observations were made on graded stone 0.026 to 0.459 ft in diameter. The stone was placed as a bed on the floor of a large flume and subjected to mean velocities up to 8 ft per sec. The bottom velocities resulting in displacement of the various sized stone were measured.

c. Bonneville Closure.[9] Twenty-four-inch quarry rock was observed to remain in place with velocities estimated at 24 ft per sec during closure of a breach in the north main channel cofferdam at Bonneville Dam. It was also observed that 11-in. boulders in the partly eroded cofferdam in the back channel resisted velocities estimated at 9 ft per sec.

d. Columbia River.[9] A large natural revetment of cobblestone 6 to 8 in. in diameter remained stable while subjected to velocities estimated at 7 ft per sec.

e. Los Angeles District.[9] The Los Angeles District, CE, placed stones weighing up to 400 lb in a flood-control channel.

Movement of the 400-lb stone occurred with average velocities of 16-18 ft per sec.

f. Zuider Zee.[9] The data on the Zuider Zee closure indicate stones 1.77 ft in diameter on fascine mattresses were stable in currents of 9.85 ft per sec.

g. Passamaquoddy.[9] Tests were made on a 1:50-scale model of the Passamaquoddy rock-fill dam at the Alden Hydraulic Laboratory. Stone sizes varied from 0.062 to 0.167 ft in diameter.

h. Stilling Basin.[28] Tests were made on a 1:36-scale model at the Waterways Experiment Station on 0.028- to 0.083-ft-diameter crushed rock in a channel immediately below a stilling basin. Velocities were measured one prototype foot above the bottom when stone movement occurred.

i. Channel.[28] These data were obtained in conjunction with h above. Observations were made downstream from the area of stilling basin turbulence.

j. McNary Dam.[24] This observation is based on a general comment on the action of concrete tetrahedrons in the model closure study.

Design curves

14. Three design curves are shown in plate 1. The Isbash curve is considered applicable to conditions where turbulence is not excessive and the stones are embedded. It was derived from equation 8 in the following manner:

$$\text{Let stone weight } (W) = \frac{\pi d_g^3}{6} \gamma_s$$

then

$$W = \frac{165 \pi d_g^3}{6} = 86.5 d_g^3$$

and

$$d_g = \frac{W^{1/3}}{4.42}$$

Equation 8

$$V = 12.35 d_g^{1/2}$$

or

$$V = \frac{12.35\ W^{1/6}}{(4.42)^{1/2}}$$

and

$$W = 2.44 \times 10^{-5}\ V^6 \qquad (20)$$

15. The USBR curve[29] is the tentative design curve recommended by the Bureau of Reclamation for riprap design below stilling basins. It is considered applicable under conditions of excessive turbulence. The Isbash formula (equation 9) for minimum stone stability approximates the Bureau's tentative design curve.

16. The third curve on the graph shows the velocity required to overturn an isolated cube. This curve was developed from data presented in Wind Tunnel Studies of Pressure Distribution on Elementary Building Forms.[6] The pressure distribution and the pressure resultants obtained on the five exposed surfaces of the cube used in this investigation are shown in plate 2. The incipient overturning moment is the summation of the moments on the upstream, top, and downstream faces of the cube. The resisting moment is the submerged weight of the cube times one-half the cube height. For 165 lb per ft^3 rock, the equation of incipient overturning on a level bed is:

$$W = 1.2 \times 10^{-3}\ V^6 \qquad (21)$$

Slope Effect

17. The data shown in plate 1 apply to horizontal or gently sloping surfaces. Where steep slopes with uniform flow are encountered, the effect of slope on the stability of the structure should be considered. The curves in plate 3 illustrate this effect. A constant depth and an Isbash coefficient of 1.20 was assumed in the development of these curves.

PART IV: CONCLUSIONS

18. Considerable data are available to assist in the design of river closures, breakwaters, and bank and channel protection. However, final design, to a large extent, depends upon practical experience and experimental studies. Local conditions and availability of material may control the type of structure to be built.

River Closures

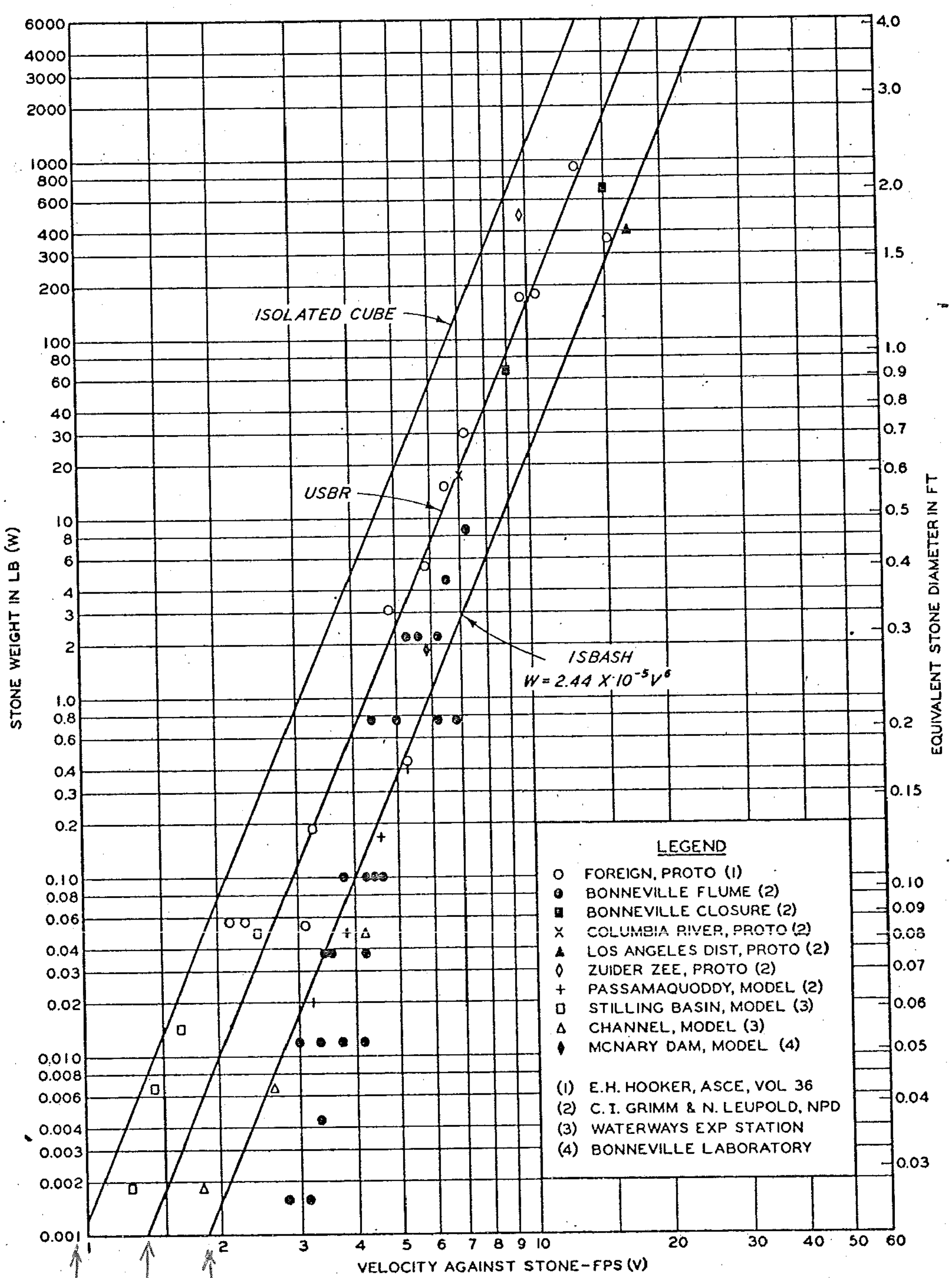
19. Model studies of planned river closures are often desirable to determine velocities that will be encountered during different stages of closure. They can be used for planning closure construction methods and schedules.

Bank and Channel Protection

20. The degree of turbulence expected in an open channel is an important factor in selection of the size of riprap for bottom and side protection. The selection of the proper blanket thickness and gradation to protect the underlying material is important in designing riprap.

Breakwaters

21. Present-day knowledge is adequate for the design of conventional breakwaters where stone size, shape, specific weight, and method of placement can be rigidly controlled. However, extensive research[12] is now in progress to provide data to meet the need for more economical designs.



2,1 1,4 0,7

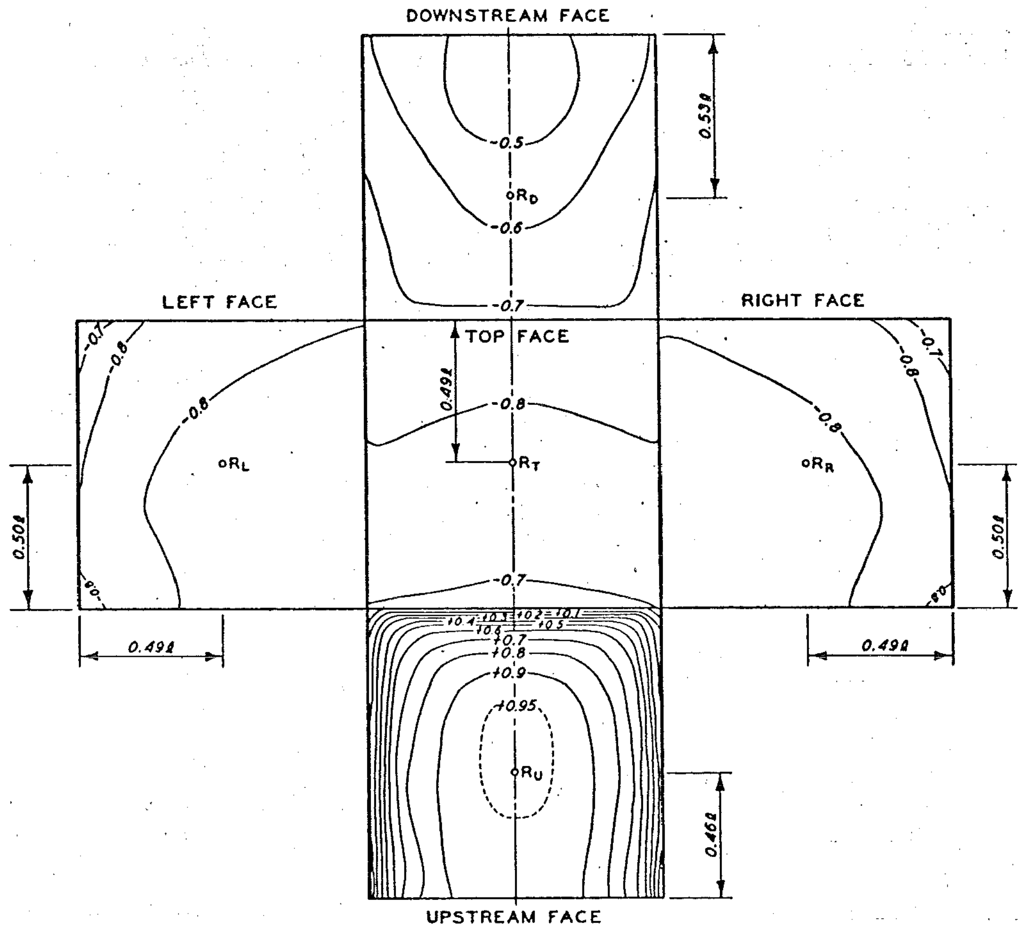
NOTE: SPECIFIC WEIGHT OF ROCK = 165 LB/CU FT.

$V = 1{,}7 \cdot \sqrt{\Delta g\, d_g}$

$V = 1{,}2 \cdot \sqrt{\Delta g\, d_g}$

RIVER CLOSURES
VELOCITY VS STONE WEIGHT
HYDRAULIC DESIGN CHART 712-1

WES 6-57



PRESSURE PATTERN
(C_p CONTOURS)

BASIC EQUATIONS

$$C_p = \frac{\Delta_p}{\frac{\rho V^2}{2}} \; ; \; F = R \ell^2 \frac{\rho V^2}{2}$$

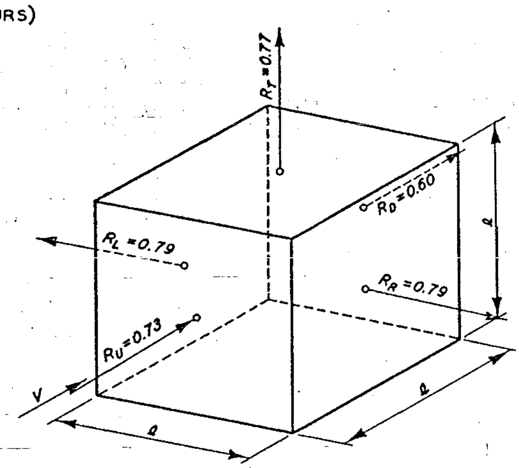
WHERE:

C_p = PRESSURE COEFFICIENT
Δ_p = DIFFERENCE IN PRESSURE BETWEEN ANY POINT ON CUBE AND THAT IN THE UNDISTURBED FLOW IN LB PER SQ IN.
V = VELOCITY UPSTREAM FROM CUBE, FPS
ρ = DENSITY OF FLUID IN SLUGS PER CU FT
F = FORCE ON FACE IN LB
R = RESULTANT OF AVERAGE C_p FOR FACE
ℓ = DIMENSION OF CUBE IN FT

NOTE:

DATA FROM "WIND TUNNEL STUDIES OF PRESSURE DISTRIBUTION ON ELEMENTARY BUILDING FORMS". N. CHIEN, Y. FENG, H. J. WANG, AND T. T. SIAO, IOWA INSTITUTE OF HYDRAULIC RESEARCH.

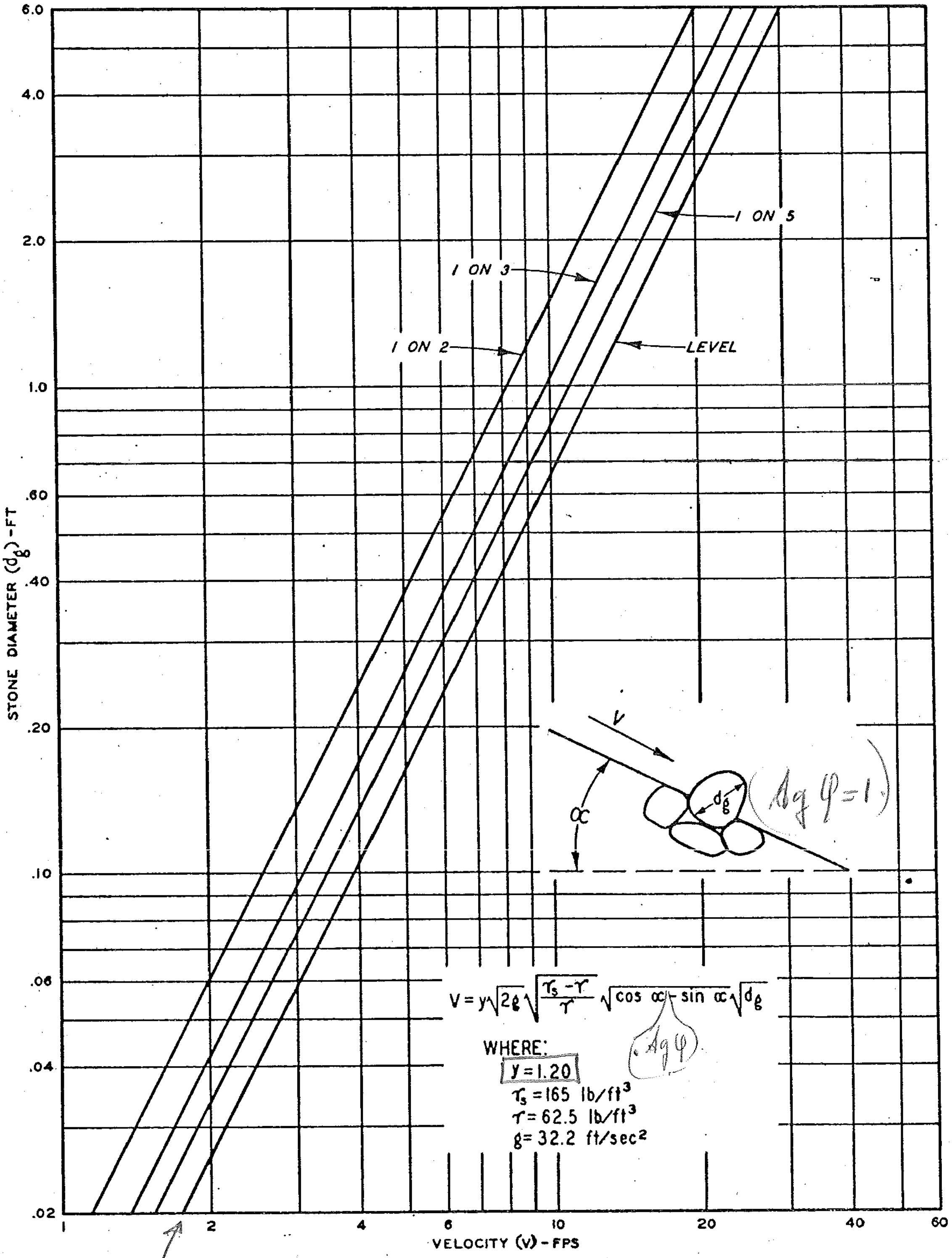
REYNOLDS NUMBER OF TEST FLOW APPROX 4×10^4



PRESSURE RESULTANTS
(AVERAGE C_p VALUES)

FORM RESISTANCE OF SINGLE CUBE FLOW NORMAL TO FACE

PLATE 2



$\alpha = 0 \rightarrow V_{cr} = 1{,}2 \cdot \sqrt{2g\Delta d_g} \simeq 1{,}7\sqrt{\Delta . g . d_g}$

Heen in bed!

EFFECT OF SLOPE

PLATE 3

APPENDIX A: ANNOTATED LIST OF REFERENCES

1. American Society of Civil Engineers, Review of Slope Protection Methods, Report of the Subcommittee on Slope Protection of the Committee on Earth Dams of the Soils Mechanics and Foundation Division. Vol 74, No. 6, June 1948.

"A summary of available information on protection of slopes of dams against the disrupting effects of waves and the erosive effect of rain, wind and frost." Article evaluates various wave height formulas in terms of current velocity. No experimental data tabulated.

2. Blanchet, Ch., "Formation and destruction of stone masses by a water current" ("Formation et destruction par un courant d'eau de massif en pierres"). La Houille Blanche, New Series No. 2 (March 1946), p 141. U. S. Army Engineer Waterways Experiment Station Translation No. 50-5, 1950, translated by W. W. Geddings.

Part I of three parts. Discusses equilibrium of stones in flowing water. Equates forces acting on stones for various conditions of flow and stone positions.

3. __________, "Technique for the construction of rock-fill dams in flowing water" ("Technique de la construction des barrages en pierres lancées dans l'eau courante"). La Houille Blanche, vol 1 (November-December 1946), pp 393-405. U. S. Army Engineer Waterways Experiment Station Translation No. 52-1, 1952, translated by Jan C. Van Tienhoven.

Illustrated discussion of the theory of the formation of rock dams. Chapter 1 gives equations for computing the configuration of a dam under construction. Phenomena observed in the construction of dams. Chapter II discusses flow conditions, seepage, etc., during construction. This is apparently Part II of item 2.

4. __________, "Technique for the construction of rock-fill dams in flowing water" ("Technique de la construction des barrages en pierres lancées dans l'eau courante"). La Houille Blanche, vol 2 (January-February 1947), pp 41-47. U. S. Army Engineer Waterways Experiment Station Translation No. 52-1, 1952, translated by Jan C. Van Tienhoven.

Chapter III and Part III of items 2 and 3. Illustrative application of theory and design to a prototype problem.

5. Chang, Y. L., "Laboratory investigation of flume traction and transportation." Transactions, American Society of Civil Engineers, vol 104 (1939).

Paper presents results of a laboratory investigation of tractive and transportation factors determined for numerous sizes of bed materials.

6. Chien, Ning, Feng, Yin, Wang, Huang-Ju, and Siao, Tien-To, Wind Tunnel Studies of Pressure Distribution on Elementary Building Forms. Iowa Institute of Hydraulic Research for the Office of Naval Research, 1951.

Experimental investigation of wind forces on various simply shaped objects simulating buildings. Piezometric pressures measured on surfaces of buildings and pressure contours developed. For use on Chart 712-1, the pressure data on a cube were evaluated in terms of the overturning force. The required size of a stable cube having a specific weight of 165 lb per cu ft was computed for various velocities. The resulting curve is shown on Chart 712-1 as the isolated cube curve.

7. Gilbert, G. K., The Transportation of Debris by Running Water. United States Geodetic Survey Professional Paper 86, 1914.

Principal interest is discussion of bed load and suspended load motion. No basic data tabulated.

8. Gontcharov, V. N., "Flow around a cube fixed to bottom of flume." Transactions, Scientific Research Institute of Hydrotechnics, vol 17 (1935), pp 77-112. Translated from Russian by Dr. A. Lukseh, Associate Research Engineer, Iowa Institute of Hydraulic Research, University of Iowa.

Paper presents results of extensive studies of pressures on cubes fixed to the bottom of a flume. Various patterns of cube arrangements were investigated from the isolated cube to completely flooring the flume bottom with cubes. The effects of various cube spacing were studied. The results are presented in terms of average pressures on the faces of the test cubes.

9. Grimm, C. I., and Leupold, Norbert, Hydraulic Data Pertaining to the Design of Rock Revetment. U. S. Army Engineer Division, North Pacific, CE, 1939.

Discusses current revetment practices. Tabulates and plots available laboratory data of movement of solids by flowing water. Evaluates Bonneville, Passamaquoddy, Isbash, WES, Groat, and Hooker data. Includes observed prototype data on Columbia River, Zuider Zee, and in the Los Angeles District.

10. Hooker, E. H., "The suspension of solids in flowing water." Transactions, American Society of Civil Engineers, vol XXXVI (1896).

Historical review of knowledge on movements of solids in fluids. Describes types of movement. Discusses experiments and results of numerous investigations. Major portion limited to sand studies. Page 308 tabulates results of early investigators for observed bottom velocities in which various materials including boulders 2.7 ft in diameter were moved.

11. Hudson, R. Y., "Wave forces on breakwaters." Transactions, American Society of Civil Engineers, vol 118 (1953), p 653.

Reviews common theories for computing wave forces on vertical walls and sloping rubble-mound breakwaters. Compares and evaluates various formulas. Gives a dimensionless form of the Iribarren formula and coefficient values which vary with slope for natural rock. The Isbash curve shown on Chart 712-1 is similar to Iribarren's equation with K' = 0.017.

12. __________, Laboratory Investigations of Rubble-mound Breakwaters. Paper presented at 3-7 June 1957 American Society of Civil Engineers Meeting, Buffalo, New York. WES MP 2-224, June 1957.

Paper describes laboratory investigation at the Waterways Experiment Station, Vicksburg, Mississippi, to determine the criteria for the design and construction of rubble-mound breakwaters. A new formula is derived which it is believed with new experimental coefficients will increase considerably the accuracy of the design of rubble-mound breakwaters.

13. Isbash, S. V., Construction of Dams by Dumping Stones into Flowing Water, translated by A. Doujikov. Corps of Engineers, U. S. Army, Eastport District, Eastport, Maine, 1935.

Complete design investigation of rock dams built in flowing water including study of forces acting on individual stones, quantity of percolation, overflow discharge, required cross sections. Design criteria developed mathematically and verified experimentally in laboratory with models of different scales. Numerous charts and graphs for design of rock dams. No basic laboratory data tabulated.

14. __________, "Construction of dams by depositing rock in running water." Transactions, Second Congress on Large Dams (1936).

Summarizes experiments for construction of dams by depositing rock in running water. Author briefly reviews theory resulting from small-scale experiments and gives equations applicable to various stages of construction. Riprap composed of 15- to 500-lb rock. Large rock not moved. No basic data given in report. A tentatively recommended curve for riprap design appears to closely follow data discussed in item 10.

15. Mavis, F. T., Liu, T. Y., and Soucek, E., The Transportation of Detritus by Flowing Water. University of Iowa Bulletin 11, September 1937.

Continuation of work discussed in item 16. Studies extended sizes of solids but sizes and velocities relatively small.

16. Mavis, F. T., and Tu, Y. C., The Transportation of Detritus by Flowing Water. University of Iowa Bulletin 5, March 1935.

Reviews and evaluates previous work on bed load transportation. Discussion is restricted to some of the problems of transportation of solid particles which are rolled or dragged along the bed of a channel in traction. Includes investigation of Ho and Tu at University of Iowa. Data limited to small grain sizes and velocities.

17. Office of the Chief of Engineers, Slope Protection. Civil Works Engineer Bulletin 52-15, 2 June 1952.

Bulletin gives data for design of slope protection for dams, railroad and highway embankments, and channels.

18. Peixotto, E. D., and Roberge, R. A., Similitude of Incipient Motion. Master of Science Thesis, Massachusetts Institute of Technology, 1956.

Thesis is a laboratory investigation of conditions controlling incipient motion of graded rock particles composing the bed of a turbulent stream. A resistance coefficient was obtained for various sized material and plotted against Reynolds number.

19. Straub, L. G., "Dredge fill closure of Missouri River at Fort Randall." Proceedings, Minnesota International Hydraulic Conference, IAHR (September 1953).

Describes actual prototype closure with illustrations. Discusses basic principles of design of closure involving critical tractive force, critical velocity, and surface roughness of fill material. Closure made by hydraulic fill. Maximum size boulder capacity of dredge was 14 in.

20. Torpen, B. E., "Large rocks in river control works." Civil Engineering, vol 26, No. 9 (Sept 1956), pp 57-61. (Mr. Torpen was formerly with North Pacific Division, CE.)

Article describes closure operations at McNary, Chief Joseph, and Albeni Falls Dams and Bonneville cofferdam repairs. During Chief Joseph Dam closure velocities approaching 20 ft per sec occurred and only selected rocks of 15 to 20 tons would remain in closure gap. Cables were fastened to large rocks to assist in stabilizing smaller rocks. It is to be noted the equivalent diameters of 15- and 20-ton rock are 7 and 7.7 ft. These values exceed the limits of Chart 712-1 but would plot close to the isolated cube curve extended.

21. U. S. Army Engineer District, Portland, CE, Report on Channel Protection against High Velocity Flow (Civil Works Project). 1 July 1951.

Studies of velocities along ten major revetments on rivers in Idaho and Oregon. Field observations showed that an 18-in. layer of dumped stone graded from 50 to 300 lb was generally adequate with maximum observed velocities of 10 ft per sec provided no undermining occurred or underlying material washed out through the voids of the riprap.

22. ________, Report on High Velocity Revetment Tests. CWI 485, 1 January 1952.

Prototype tests on dumped graded riprap in a specially built channel below Dorena Dam. Four classes of graded rock, 20 to 400 lb, were placed in blankets 12-24 in. thick and tested under velocities of 7 to 20 ft per sec. Study planned for revetment failure rather than movement of individual rocks. No specific data recorded for rock movement. Experienced failures resulted from removal of fines actuating failure rather than displacement of large size rock by velocity forces.

23. U. S. Army Engineer District, Portland, CE, Bonneville Hydraulic Laboratory, The Dalles Rock Fill Model. Memorandum report 2-2, 27 October 1954.

Describes results on model closure using quarry run rock (1/2 ton and smaller prototype) and 3-ton rock on higher lifts. No study made of independent stone action. General procedure satisfactory.

24. ________, McNary Dam--Second-step Cofferdam Closure. May 1956.

Describes model tests made in conjunction with actual river closure by use of 12-ton tetrahedrals. Most of report concerned with methods of making closure. Laboratory tests indicated tetrahedrals stable for velocity of 20 ft per sec but moved from crest of fill with velocity of 29 ft per sec. Prototype confirmation of model closure procedure.

25. U. S. Army Engineer District, Walla Walla, CE, Report on Closure of the Second-step Cofferdam--McNary Lock and Dam. July 1951.

Report on actual closure procedure and results. No data on individual tetrahedrals.

26. U. S. Army Engineer Waterways Experiment Station, CE, Experiments to Determine the Effectiveness of Tetrahedral Blocks as Revetment. Technical Memorandum No. 26-2, January 1933.

Investigation of single course of tetrahedrals for revetment use. Investigation centered on removal of filler material from between and under blocks. No study made of bottom velocities required to move tetrahedrals. Tractive force measured on individual tetrahedrals.

27. ________, Critical Tractive Force Tests of Coarse Material. Technical Memorandum No. 69-1, January 1935.

Measurement of tractive forces on solids from sand grains up to 2.3-in. stone. No bottom velocities measured. Drift of material measured.

28. ________, Unpublished data.

Model tests were made on graded dumped riprap below a stilling basin and in the channel downstream. Blanket thickness varied from 1 to 2 ft (prototype). Bottom velocity measurements observed as material moved.

29. U. S. Bureau of Reclamation, Stilling Basin Performance--An Aid in Determining Riprap Sizes. Hydraulic Laboratory Report No. HYD-409, 23 February 1956.

Discusses and compares model and prototype results of impact-type stilling basins on relatively small canal-type structures. Comparative photographs of flow and scour conditions below Picacho Arroyo Control, North Branch Dam. Prototype riprap designed for velocity of 30 ft per sec. Prototype velocities computed to be 37 ft per sec.

30. __________, Hydraulic Model Studies of Robles Diversion Dam Spillway. Hydraulic Laboratory Report No. HYD-427, 8 November 1956.

A 1:12-scale section model of Robles Diversion Dam Spillway was tested to determine discharge coefficients of rock blanket spillways of various sized rock. Flow conditions and rock stability were checked.

31. Webster, M. J., "The Dalles diversion made with rock-fill dam." Civil Engineering, vol 99 (Feb 1957).

Article discusses closure using end-dump method. Extensive use was made of a 1:40-scale model to determine the best closure procedure. The conditions tested in the model showed a very close correlation with the prototype.