Technical Supplement 14C

Stone Sizing Criteria

Issued August 2007

Cover photo: Stone may be needed as a foundation on which to implement other restoration features such as soil bioengineering practices. Stone may also be needed to form an erosion resistant layer. How large, how thick, and how deeply keyed-in are questions that are addressed in the design.

Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

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Contents

Purpose **TS14C–1**

Introduction **TS14C–1**

Basic concepts **TS14C–1**

Description of forces on a stone TS14C–1

Flow conditions TS14C–2

Sizing techniques **TS14C–3**

Summary guide of selected techniques **TS14C–11**

Factor of safety **TS14C–12**

Example calculations TS14C–12

Conclusion **TS14C–13**

Tables

Table TS14C–1	High-energy vs. low-energy conditions	TS14C–2
Table TS14C–2	Federal Highway Administration techniques	TS14C–11
Table TS14C–3	Summary of techniques	TS14C–11

Figures

Figure TS14C–1	Forces on a submerged stone	TS14C–1
Figure TS14C–2	Riprap used to control a headcut	TS14C–2
Figure TS14C–3	Riprap used to prevent erosion from flow from a side inlet to a channel	TS14C–2
Figure TS14C–4	Toe of the slope lined with stone to control erosion	TS14C–2
Figure TS14C–5	Rock size based on Isbash Curve	TS14C–3
Figure TS14C–6	Graphical solution for Isbash technique	TS14C–4
Figure TS14C–7	Rock chute spreadsheet	TS14C–9
Figure TS14C–8	Lane's method	TS14C–10

Technical Supplement 14C

Stone Sizing Criteria

Purpose

Many channel protection techniques involve rock or stone as a stand-alone treatment or as a component of an integrated system. Stone used as riprap can also be a component of many streambank soil bioengineering projects. Many Federal and state agencies have developed methods and approaches for sizing riprap, and several of those techniques are briefly described in this document. Stone sizing methods are normally developed for a specific application, so care should be exercised in matching the selected method with the intended use. While many of these were developed for application with stone riprap revetments, they are also applicable for other designs involving rock, as well.

Introduction

When the attacking forces of flowing water exceed the resisting forces of the existing channel material, channel protection is needed as part of a restoration design. Channel protection typically ranges from soil bioengineering treatments to more traditional armoring methods. Numerous methods have been developed for the design and sizing of riprap. Several common techniques for estimating the required stone size are briefly outlined in this document. The designer is encouraged to review the complete development of a selected method and assess the relevance of the assumptions behind that selected method to their application. In this document, the words rock and stone are used interchangeably.

Size is one of many considerations when designing riprap for use in protecting channel bed and banks. The designer must also address issues such as material strength, density, angularity, durability, length-to-width ratio, gradation, bedding, piping potential, and channel curvature. These important design and construction considerations are addressed in NEH654 TS14K.

Basic concepts

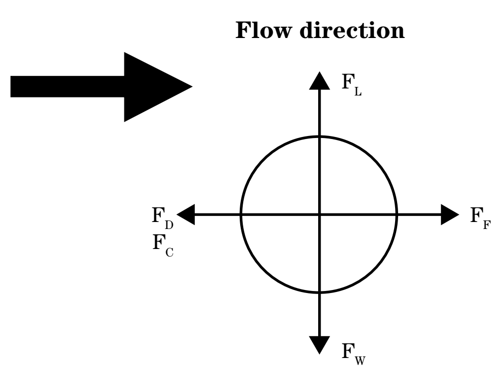
Description of forces on a stone

A rock will be stable until the lift and drag forces of moving water exceed a critical value or threshold. Therefore, for a given rock size subjected to a given force of moving water, there is some unit discharge where the rock will move and become unstable. Forces on a submerged stone, as indicated in figure TS14C–1, typically consist of the force exerted by the flowing water (F_F), drag force (F_D) associated with flow around the object (skin friction and form drag), lift force (F_L) associated with flow around the particle (pressure differences caused by streamline curvature and increased velocity around a particle), submerged weight of the stone (F_W), and resisting force due to the particle interlock and/or contact between stones (F_C).

While some methods are based on a particle force balance, all rock sizing methods are essentially empirical techniques. Field performance data, physical models, and theoretical developments have all contributed to the diverse set of approaches used to determine stable stone sizes for restoration designs.

Velocity-based approaches and boundary shear or stress-based approaches are the two prominent classes of methods that have been used to evaluate the erosion resistance of materials. While shear or stress-based approaches are considered more academically correct, velocity-based methods are still widely used. The design stress and the design discharge do not necessarily represent the same conditions.

Figure TS14C–1 Forces on a submerged stone



Flow conditions

The flow conditions associated with a particular application will have a major influence on selecting the right rock sizing method. While it is difficult to select a single criterion that separates rock sizing methods, high energy and low energy are used in this development. For example, a technique developed for the design of a riprap blanket revetment in a low-energy environment would not necessarily be suitable for estimating the minimum stone size in a high-energy environment, where the stone projects into the flow. Such applications, including instream habitat boulders, grade stabilization, and stream barbs, should be addressed with impinging flow design techniques. Table TS14C–1 lists some of the flow descriptors that can be associated with high- and low-energy flow conditions. Photographs of the different energy conditions where stone is applied as part of the solution are shown in figures TS14C–2 through 4. In figure TS14C–2, riprap is used to control a headcut. Riprap chutes can be used to control erosion from a headcut in a channel or in a side inlet to a channel. Riprap for this type of structure would fall in the steep-slope, high-energy design. Figure TS14C–3 shows riprap used to prevent erosion from flow from a side inlet to a channel. This structure also prevents a headcut from moving into the field. As illustrated in figure TS14C–4, if the toe of the slope is eroding, and it cannot be controlled with bioengineering alone, lining the toe of the slope with stone may be a solution. Riprap for this type of structure would fall in the mild slope, low-energy design.

The appropriate rock sizing method must consider the flow energy associated with the particular application. While there are exceptions, most rock sizing methods were developed for either a high- or low-energy flow condition.

Table TS14C–1 High-energy vs. low-energy conditions

High energy	Low energy
Supercritical flow	Subcritical flow
Steep slope	Mild slope
High turbulence	Low turbulence
Impinging flow	Parallel flow
Rapidly varied flow	Uniform or gradually varied flow
Unsteady flow	Steady flow

Figure TS14C–2 Riprap used to control a headcut

Figure TS14C–3 Riprap used to prevent erosion from flow from a side inlet to a channel

Figure TS14C–4 Toe of the slope lined with stone to control erosion

Sizing techniques

There are many techniques for sizing stone, and each method has advantages and disadvantages. Many techniques were derived under specific conditions and developed for particular applications. While this list is not complete and the description is not exhaustive, several commonly used methods are presented. The designer should review the applicability of a technique before choosing it to size stone for a particular project. Following is a brief description of several rock sizing techniques.

Isbash method

The Isbash formula (Isbash 1936) was developed for the construction of dams by depositing rocks into moving water. The Isbash curve should only be used for quick estimates or for comparisons. A coefficient is provided to target high- and low-turbulence flow conditions, so this method can be a high- or low-energy application. The equation is:

$$V_c = C \times \left(2 \times g \times \frac{\gamma_s - \gamma_w}{\gamma_w}\right)^{0.50} \times \left(D_{50}\right)^{0.50} \quad \text{(eq. TS14C–1)}$$

where:
V_c = critical velocity (ft/s)
C = 0.86 for high turbulence
C = 1.20 for low turbulence
g = 32.2 ft/s^2
γ_s = stone density (lb/ft^3)
γ_w = water density (lb/ft^3)
D_{50} = median stone diameter (ft)

A graphical solution is provided in figure TS14C–5 (ch. 16 of the Engineering Field Manual) This graph should be used only for quick estimates at a conceptual design level.

The U.S. Army Corps of Engineers (USACE) provides additional guidance for the use of the Isbash technique in EM 1110–2–1601. The required inputs are channel velocity, specific gravity of the stone, and a turbulence coefficient. The turbulence coefficient has two values that represent either high turbulence or low turbulence. The graphical solution for this is shown in figure TS14C–6(a) and (b).

Figure TS14C–5 Rock size based on Isbash curve

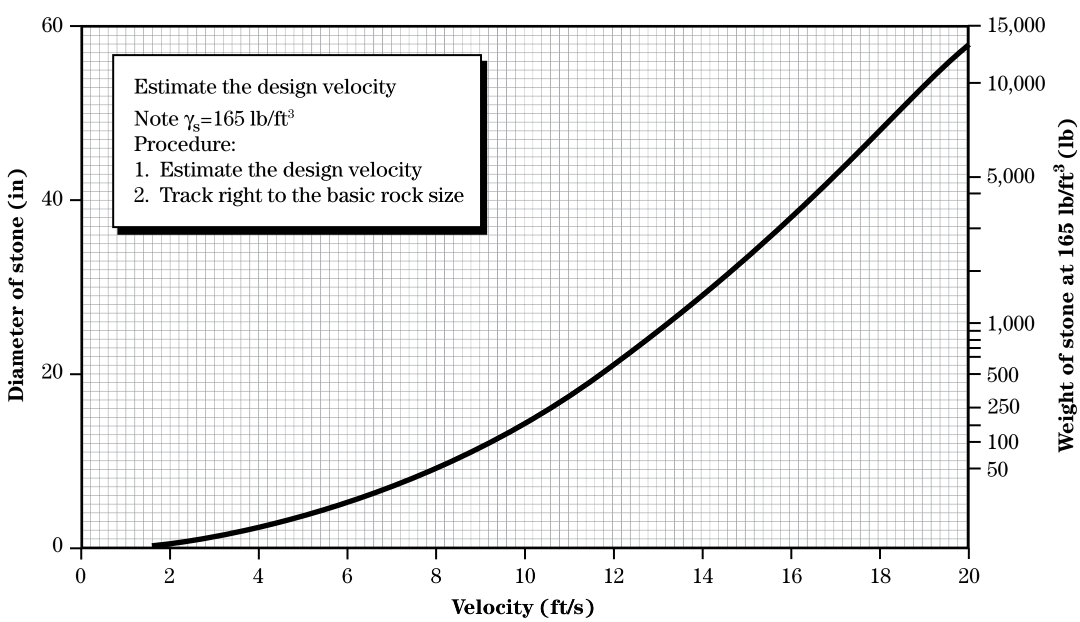
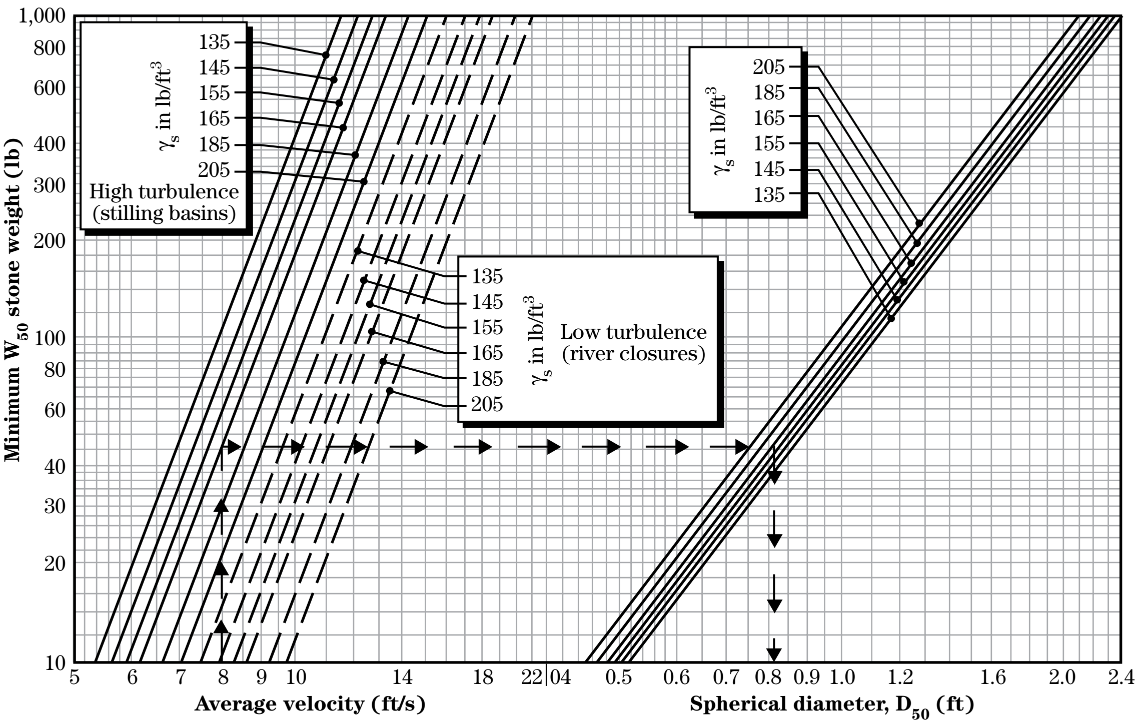


Figure TS14C–6 Graphical solution for Isbash technique

(a)



Basic equations :

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

$$D_{50} = \left(\frac{8W_{50}}{\pi\gamma_s}\right)^{\frac{1}{3}}$$

where:

V = Velocity, ft/s

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)

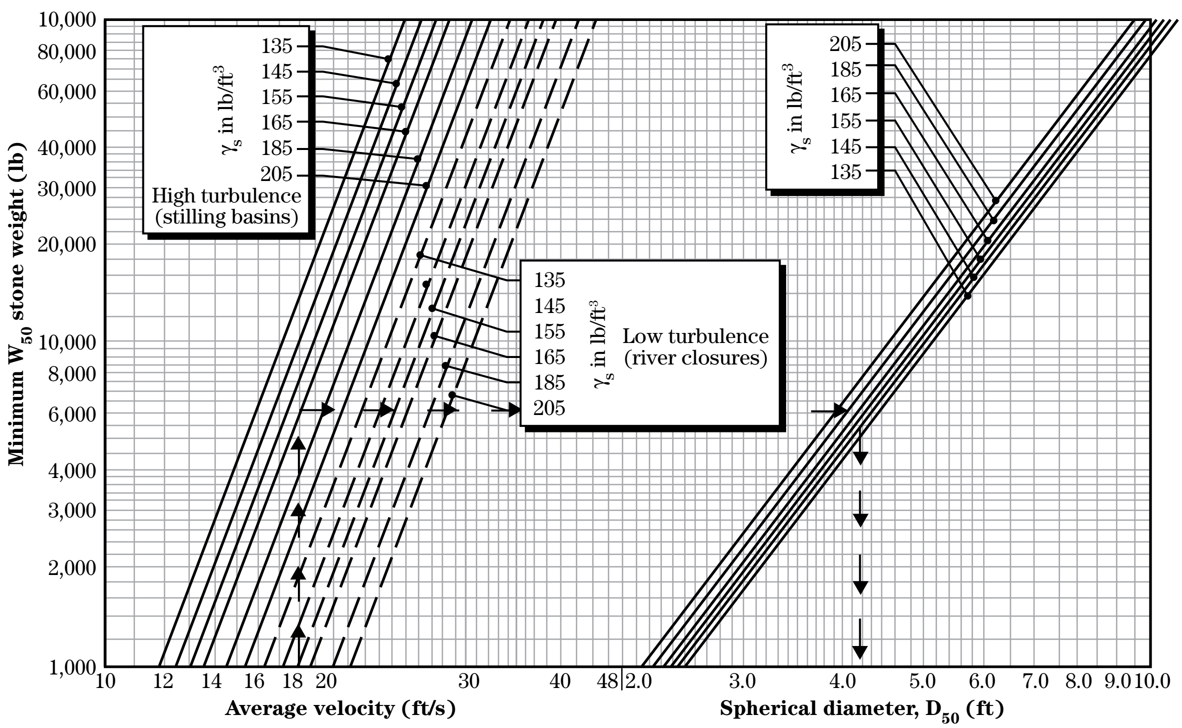
g = Acceleration of gravity, ft/s^2

Stone stability velocity vs. stone diameter

Hydraulic design chart 712–1
(Sheet 1 of 2)

Figure TS14C–6 Graphical solution for Isbash technique—Continued

(b)



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C = Isbash constant (0.86 for high turbulence level flow and 1.20 for low turbulence level flow)

g = Acceleration of gravity, ft/s^2

Stone stability velocity vs. stone diameter

Hydraulic design chart 712-1
(Sheet 2 of 2)

National Cooperative Highway Research Program Report 108

This method (Anderson, Paintal, and Davenport 1970) is suggested for design of roadside drainage channels handling less than 1,000 cubic foot per second and a maximum slope of 0.10 foot per foot. Therefore, this application can be used for high- or low-energy applications. Photo documentation shows that most of the research was done on rounded stones. This method will give more conservative results if angular rock is used.

$$\tau_o = \gamma R S_e \qquad \text{(eq. TS14C–2)}$$

$$\tau_c = 4D_{50} \qquad \text{(eq. TS14C–3)}$$

therefore,

$$D_{50} = \frac{\gamma R S_e}{4} \qquad \text{(eq. TS14C–4)}$$

τ_c = critical tractive stress
γ = 62.4 lb/ft^3
R = hydraulic radius (ft)
S_e = energy slope (ft/ft)
D_{50} = median stone diameter (ft)

A similar approach has been proposed by Newbury and Gaboury (1993) for sizing stones in grade control structures. This relationship is:

tractive force (kg/m^2) = incipient diameter (cm)

USACE—Maynord method

This low-energy technique for the design of riprap is used for channel bank protection (revetments). This method is outlined in USACE guidance as provided in EM 1110–2–1601, and is based on a modification to the Maynord equation:

$$D_{30} = FS \times C_S \times C_v \times C_T \times d \times \left[\left(\frac{\gamma_W}{\gamma_S - \gamma_w} \right)^{0.5} \times \frac{V}{\sqrt{K_1 \times g \times d}} \right]^{2.5} \qquad \text{(eq. TS14C–5)}$$

where:
D_m = stone size in ft; m percent finer by weight
d = water depth (ft)
FS = factor of safety (usually 1.1 to 1.5), suggest 1.2
C_s = stability coefficient Z=2 or flatter C=0.30, (0.3 for angular rock, 0.375 for rounded rock)
C_v = velocity distribution coefficient (1.0 for straight channels or inside of bends, calculate for outside of bends)
C_T = thickness coefficient (use 1.0 for 1 D_{100} or 1.5 D_{50}, whichever is greater))
γ_w = specific weight of water (lb/ft^3)
γ_s = specific weight of stone (lb/ft^3)
V = local velocity; if unknown use 1.5 $V_{average}$
g = 32.2 ft/s^2
K_1 = side slope correction as computed below

$$K_1 = \sqrt{1 - \frac{\sin^2 \theta}{\sin^2 \phi}} \qquad \text{(eq. TS14C–6)}$$

where:
θ = angle of rock from the horizontal
ϕ = angle of repose (typically 40°)

Note that the local velocity can be 120 to 150 percent of the average channel velocity or higher. The outside bend velocity coefficient and the side slope correction can be calculated:

$$C_V = 1.283 - 0.2 \log \left(\frac{R}{W} \right) \qquad \text{(eq. TS14C–7)}$$

where:
R = centerline bend radius
W = water surface width

In the analysis used to develop this formula, failure was assumed to occur when the underlying material became exposed. It should be noted that while many of the other techniques specify a D_{50}, Maynord (1992) specifies a D_{30} which will typically be 15 percent smaller than the D_{50}. This assumes a specific gradation of:

$$1.8D_{15} < D_{85} < 4.6D_{15} \qquad \text{(eq. TS14C–8)}$$

The USACE developed this method for the design of riprap used in either constructed or natural channels which have a slope of 2 percent or less and Froude numbers less than 1.2. As a result, this technique is not appropriate for high-turbulence areas.

Maynord's side-slope and invert equation is for cases where the protective blanket is constructed with a relatively smooth surface and has no significant projections. It is appropriate for use to size stone-toe protection. However, it has been suggested that with some adjustment to the coefficients (typically using a velocity coefficient of 1.25 and a local velocity equal to 160% of the channel velocity), Maynord's method can be used for exposed boulders or stones exposed to impinging flow.

U.S. Bureau of Reclamation method

This high-energy technique is outlined in U.S. Bureau of Reclamation (USBR) EM–25 (Peterka 1958) and was developed for sizing riprap below a stilling basin. It was empirically developed using 11 prototype installations with velocities ranging from 1 foot per second to 20 foot per second. The formula is:

$$D_{50} = 0.0122V^{2.06} \qquad \text{(eq. TS14C–9)}$$

where:
D_{50} = median stone diameter (ft)
V = average channel velocity (ft/s)

U.S. Geological Survey method (Blodgett 1981)

This technique is based on analysis of field data of 39 large events from sites in Arizona, Washington, Oregon, Nevada, and California. Riprap protection failed in 14 of the 39 cases. An envelope curve was empirically developed to represent the difference between sites that performed without damage and those that were damaged by particle erosion. The formula is:

$$D_{50} = 0.01V^{2.44} \qquad \text{(eq. TS14C–10)}$$

where:
D_{50} = median stone diameter (ft)
V = average channel velocity (ft/s)

This method typically provides overly conservative results.

Tillatoba model study

This study (Blaisdell 1973) provides an equation for sizing stone to remain stable in the turbulent flow found below stilling basins. This high-energy technique results in an estimate for D_{50}.

$$D_{50} = 0.00116\frac{V^3}{\sqrt{d}} \qquad \text{(eq. TS14C–11)}$$

where:
V = velocity (ft/s)
d = flow depth (ft)
D_{50} = stone diameter (ft)

USACE steep slope riprap design

This high-energy technique is outlined in standard USACE guidance as provided in EM 1110–2–1601. It is designed for use on slopes from 2 to 20 percent. However, the side slopes should be 1V:2.5H or flatter. A typical application would be a rock-lined chute. The formula is:

$$D_{30} = \frac{1.95S^{0.555}(Cq)^{\frac{2}{3}}}{g^{\frac{1}{3}}} \qquad \text{(eq. TS14C–12)}$$

where:
D_{30} = stone size; m percent finer by weight
S = channel slope
q = unit discharge (q = Q/b, where b = bottom width of chute and Q is total flow)
C = flow concentration factor (usually 1.25, but can be higher if the approach is skewed)
g = gravitational constant

This equation is applicable to thickness = 1.5 D_{100}, angular rock, unit weight of 167 pounds per cubic foot, D_{85}/D_{15} from 1.7 to 2.7, slopes from 2 to 20 percent, and uniform flow on a downslope with no tailwater. This equation typically predicts conservative sizes.

USACE habitat boulder design

This technique is outlined in USACE guidance provided in EMRRP–SR–11. It is developed for sizing boulder clusters in a channel for habitat enhancement. This high-energy relationship is an incipient motion relation for fully immersed boulders in turbulent flow on a flat bed. This method is for impinging flow. The formula is:

$$D = \frac{18(\text{depth})S_f}{(SG-1)} \qquad \text{(eq. TS14C–13)}$$

where:
D = minimum stone size
depth = channel depth
S_f = channel friction slope
SG = specific gravity of the stone

This equation has also been used to size stones for use in low instream weirs. However, estimating the friction slope across a drop can be difficult.

Abt and Johnson (1991)

Abt and Johnson (1991) conducted near-prototype flume studies to determine riprap stability when subjected to overtopping flows such as in spillway flow or in sloping loose-rock grade control structures. Slopes varied from 2 to 20 percent. Riprap design criteria for overtopping flows were developed for two conditions: stone movement and riprap layer failure. Criteria were developed as a function of median stone size, unit discharge, and embankment slope. The equation is:

$$D_{50} = \left(q_{design}\right)^{0.56} \times S^{0.43} \times 5.23 \qquad \text{(eq. TS14C–14)}$$

where:
D_{50} = stone size in inches; m percent finer by weight
q_{design} = unit discharge (ft^3/s/ft)
S = channel slope (ft/ft) and S between 0.02 and 0.20 ft/ft

$$\left(q_{design}\right) = \frac{\left(q_{failure}\right)}{0.74} = 1.35 q_{failure} \qquad \text{(eq. TS14C–15)}$$

Stone movement occurred at approximately 74 percent of the flow, causing layer failure. It was determined from testing that rounded stone should be oversized by approximately 40 percent to provide the same protection as angular stone.

ARS rock chutes

This design technique (Robinson, Rice, and Kadavy 1998) is primarily targeted at high-energy applications. Loose riprap with a 2 D_{50} blanket thickness composed of relatively uniform, angular riprap was tested to overtopping failure in models and field scale structures. This method applies to bed slopes of 40 percent and less. This technique can be used for low slope, and thus, low-energy applications, but it is particularly useful for slopes greater than 2 percent. A factor of safety appropriate for the project should be applied to the predicted rock size. The equations are:

for S <0.1

$$D_{50} = 12\left(1.923 q S^{1.5}\right)^{0.529} \qquad \text{(eq. TS14C–16)}$$

0.10<S<0.40

$$D_{50} = 12\left(0.233 q S^{0.58}\right)^{0.529} \qquad \text{(eq. TS14C–17)}$$

where:
D_{50} = median stone size (in)
q = highest stable unit discharge (ft^3/s/ft)
S = channel slope (ft/ft)

A spreadsheet program (Lorenz, Lobrecht, and Robinson 2000) is available to assist in sizing riprap on steep slopes. A screen capture of this spreadsheet program is shown in figure TS14C–7.

This method is best used in steep slopes for grade control, embankment overtopping, or on side inlets from fields to a major drainage outlet. The spreadsheet provides much additional information related to rock chutes such as guidance on inlet and outlet conditions, quantity estimates, and hydrology.

California Department of Transportation RSP

This technique was developed by the California Department of Transportation (CALTRANS) for designing rock slope protection (RSP) for streams and riverbanks. Unlike most of the other available techniques, it results in a recommended minimum weight of the stone. The equation is:

$$W = \frac{0.00002}{\left(G_S - 1\right)^3} \times \frac{VM \times V^6 \times G_S}{\sin^3\left(r - a\right)} \qquad \text{(eq. TS14C–18)}$$

where:
W = minimum rock weight (lb)
V = velocity (ft/s)
VM = 0.67 if parallel flow
VM = 1.33 if impinging flow
G_S = specific gravity of rock (typically 2.65)
r = angle of repose (70° for randomly placed rock)
a = outside slope face angle to the horizontal (typically a maximum of 33°)

The weight indicated by this method should be used in conjunction with standard CALTRANS specifications and gradations.

Far West states (FWS)—Lane's Method

Vito A. Vanoni worked with the Northwest E&WP Unit to develop the procedure from the ASCE paper entitled "Design of Stable Alluvial Channels" (Lane 1955a). The equation is:

$$D_{75} = \frac{3.5}{C \times K} \times \gamma_w \times D \times S_f \qquad \text{(eq. TS14C–19)}$$

where:
D_{75} = stone size, (in)
C = correction for channel curvature
K = correction for side slope
S_f = channel friction slope (ft/ft)
d = depth of flow (ft)
γ_w = density of water

This is generally considered to be a conservative technique. It assumed that the stress on the sides of the channel were 1.4 times that of the bottom. This

Figure TS14C–7 Rock chute spreadsheet

Rock Chute Design Data

(Version 4.01 - 04/23/03, Based on Design of Rock Chutes by Robinson, Rice, Kadavy, ASAE, 1998)

Project: *Spillway protection* **County:** *Woodbury*
Designer: *Jim Villa* **Checked by:**
Date: 3/30/2006 **Date:**

Input Channel Geometry

Inlet Channel	Chute	Outlet Channel
Bw = *20.0* ft.	Bw = *20.0* ft.	Bw = *40.0* ft.
Side slopes = *4.0* (m:1)	Factor of safety = *1.20* (F_s)	Side slopes = *4.0* (m:1)
n-value = *0.035*	Side slopes = *4.0* (m:1) → ***2.0:1 max.***	n-value = *0.045*
Bed slope = *0.0060* ft./ft.	Bed slope (5:1) = *0.200* ft./ft. → ***2.5:1 max.***	Bed slope = *0.0050* ft./ft.
Freeboard = *0.5* ft.	Outlet apron depth, d = *1.0* ft.	Base flow = *0.0* cfs

Design Storm Data (Table 2, NHCP, NRCS Grade Stabilization Structure No. 410)

Drainage area = *450.0* acres   Rainfall = ○ 0 - 3 in. ◉ 3 - 5 in. ○ 5+ in.

Apron elev. --- Inlet = *105.0* ft. --- Outlet = *99.0* ft. --- (H_{drop} = 5 ft.)

Chute capacity = Q5-year
Total capacity = Q10-year
Minimum capacity (based on a 5-year, 24-hour storm with a 3 - 5 inch rainfall)

Q_{high} = *330.0* cfs   High flow storm through chute → Tw (ft.) = *Program*   0.20

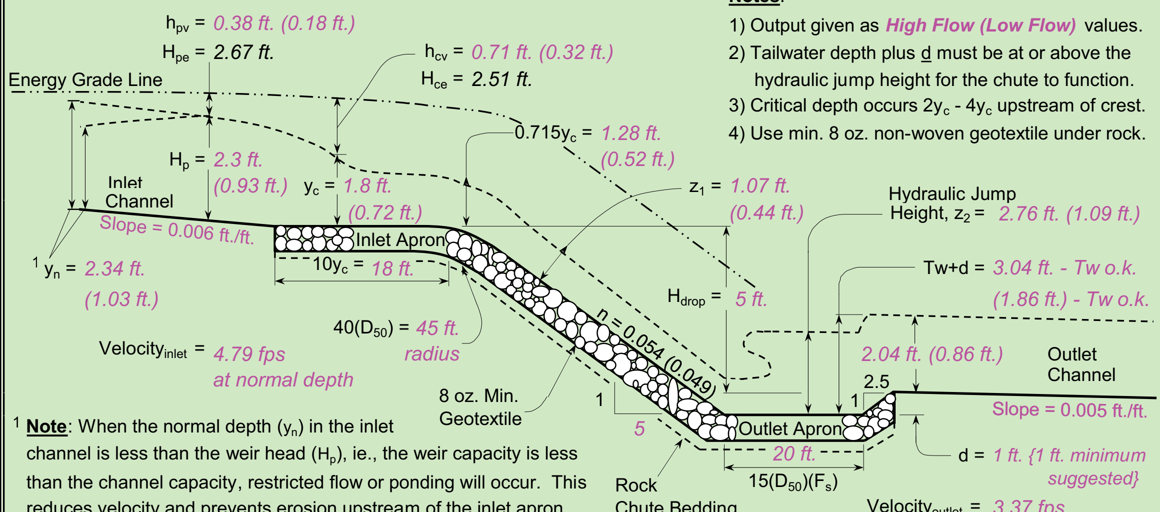
Q_{low} = *75.0* cfs   Low flow storm through chute → Tw (ft.) = *Program*

Note*: The total required capacity is routed through the chute (principal spillway) or in combination with an auxiliary spillway.*

Input tailwater (Tw)*:*

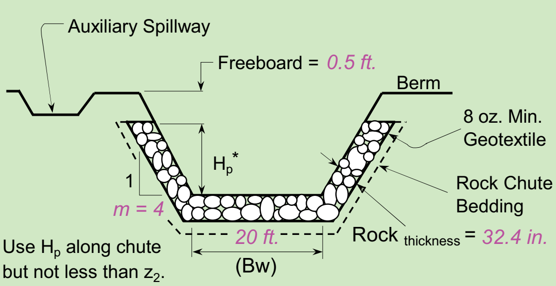
Profile and Cross Section (Output)

Notes:
1) Output given as ***High Flow (Low Flow)*** values.
2) Tailwater depth plus d must be at or above the hydraulic jump height for the chute to function.
3) Critical depth occurs $2y_c$ - $4y_c$ upstream of crest.
4) Use min. 8 oz. non-woven geotextile under rock.



[1] **Note**: When the normal depth (y_n) in the inlet channel is less than the weir head (H_p), ie., the weir capacity is less than the channel capacity, restricted flow or ponding will occur. This reduces velocity and prevents erosion upstream of the inlet apron.

Profile Along Centerline of Chute



* Use H_p along chute but not less than z_2.

Typical Cross Section

q_t =	*13.65 cfs/ft.*	Equivalent unit discharge
F_S =	*1.20*	Factor of safety (multiplier)
z_1 =	*1.07 ft.*	Normal depth in chute
n-value =	*0.054*	Manning's roughness coefficient
$D_{50}(F_s)$ =	*16.2 in. (309 lbs. - 50% round / 50% angular)*	
$2(D_{50})(F_s)$ =	*32.4 in.*	Rock chute thickness
Tw + d =	*3.04 ft.*	Tailwater above outlet apron
z_2 =	*2.76 ft.*	Hydraulic jump height
****** The outlet***	***will***	***function adequately***

High Flow Storm Information

is about 1.8 times the actual stress on the sides of a straight channel. It is very close to the stresses on the sides in a curved channel reach. The curved corrections included in the procedure only make the conservative answer even more conservative. In addition, it was developed for stones with a specific gravity of 2.56. However, it has been successfully applied on many projects. This procedure may be used with figure TS14C–8 and is:

Step 1 Enter figure TS14C–8 with energy slope (channel grade) and flow depth.

Step 2 Track right to side slope.

Step 3 Track up to ratio of curve radius to water surface width.

Step 4 Track right to estimate required riprap size.

Figure TS14C–8 Lane's method

$$D_{75} = \frac{3.5}{C \times K} \times \gamma_w \times d \times S$$

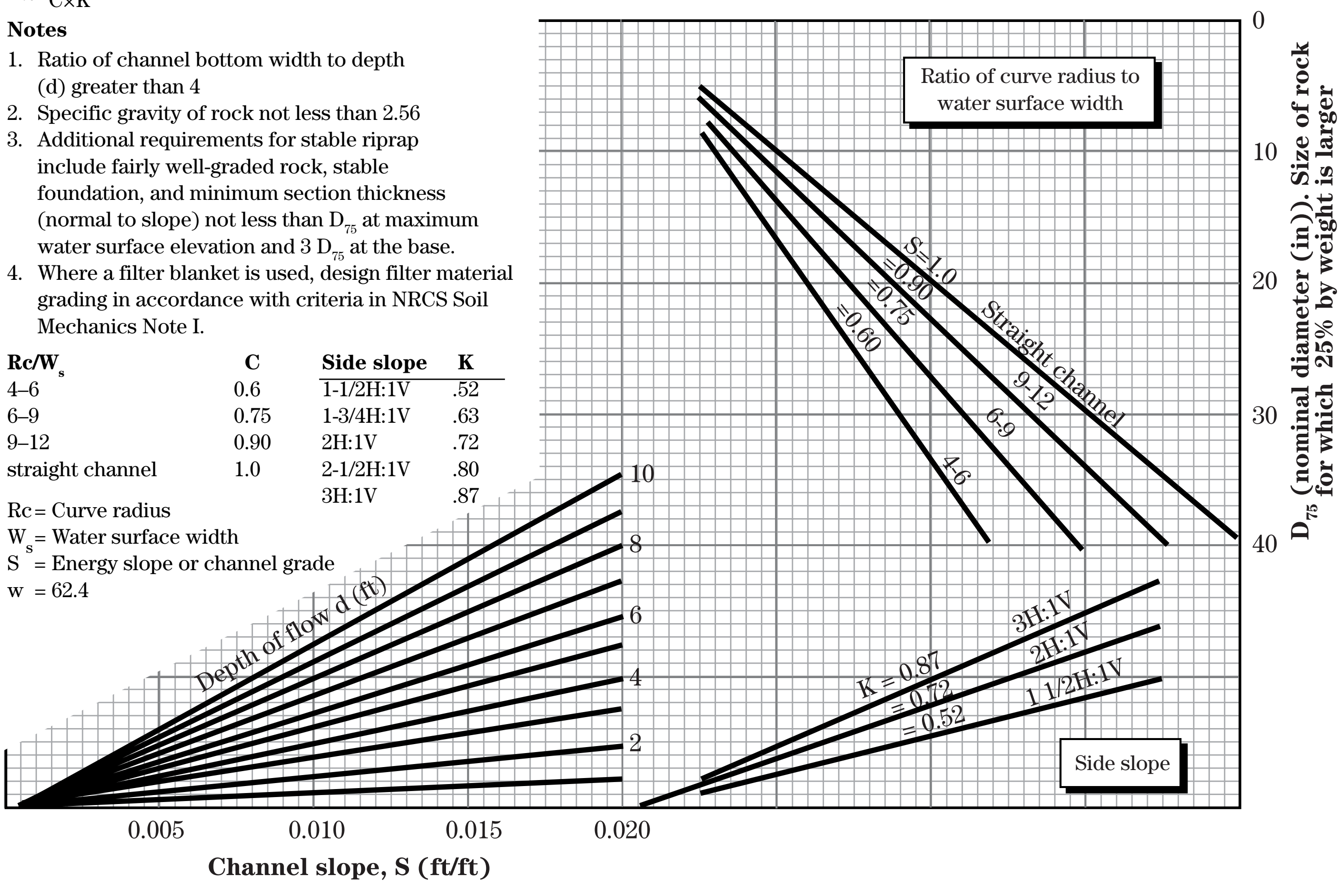
Notes

1. Ratio of channel bottom width to depth (d) greater than 4
2. Specific gravity of rock not less than 2.56
3. Additional requirements for stable riprap include fairly well-graded rock, stable foundation, and minimum section thickness (normal to slope) not less than D_{75} at maximum water surface elevation and 3 D_{75} at the base.
4. Where a filter blanket is used, design filter material grading in accordance with criteria in NRCS Soil Mechanics Note I.

Rc/W_s	C
4–6	0.6
6–9	0.75
9–12	0.90
straight channel	1.0

Side slope	K
1-1/2H:1V	.52
1-3/4H:1V	.63
2H:1V	.72
2-1/2H:1V	.80
3H:1V	.87

Rc = Curve radius
W_s = Water surface width
S = Energy slope or channel grade
w = 62.4



U.S. Department of Transportation Federal Highway Administration techniques

Several additional computational techniques for designing riprap are available from the U.S. Department of Transportation Federal Highway Administration (FHWA). While these are not described in detail, a brief description of each is provided in table TS14C–2.

Review the references (FHWA HEC 1987, 1988, 2001a, 2001b) to obtain the design relationships and application manuals for these methods.

Summary guide of selected techniques

Attributes of selected methods are summarized in table TS14C–3 to allow the user to quickly select a method.

The designer should not be surprised if the different techniques produce different answers. The user needs to recognize the limits and applicability of each technique and match it to the site and project conditions.

Table TS14C–2 Federal Highway Administration techniques

HEC–11	This technique was developed for use on natural streams or rivers with a flow greater than 50 ft^3/s. It is limited to straight or mildly curving reaches with relatively uniform cross sections. This method calculates a D_{50} based on average channel velocity, side slope, riprap angle of repose, specific gravity of the stone, and average channel depth
HEC–15	This technique was developed for use on small, constructed channels with a flow less than 50 ft^3/s
HEC–18	This technique was developed for design of stone at bridge piers and abutments

Table TS14C–3 Summary of techniques

Technique	High or low energy	Slopes	Typical application(s)
Isbash	Both	Not specified	Rock revetment, stilling basins, river closures
108 Report	Both	<10%	Quick assessments for stable stone requirements
Maynord	Low	<2%	Rock revetment, bank protection, stone toe
Abt and Johnson	High	2% to 20%	Overtopping, grade protection
ARS – rock chute	High	2% to 40%	Overtopping, rock chutes, grade protection
USBR	High	Not specified	Riprap below a stilling basin
USGS Blodgett	Both	Not specified	Riprap stability
USACE Steep Slope Riprap	High	2% to 20%	Rock chutes, grade protection
USACE Habitat Boulder	High	Not specified	Instream boulders for habitat enhancement
CALTRANS RSP	Low	<2%	Rock revetment, bank protection, stone toe
Lane's (FWS)	Low	<2%	Stone bank protection, stream barbs with adjustments

Factor of safety

Stone sizing should be approached with care because rock treatments can be expensive and can give a false sense of security if not applied appropriately. A factor of safety is often advisable to account for unknowns and uncertainty. In some cases, the factor of safety is part of the sizing formulas provided. Where a factor of safety is not built into the procedure, the designer should multiply the resulting size by an appropriate value. Appropriate engineering judgment should be applied when assigning a factor of safety. Maynord (1992) suggests a minimum factor of safety of 1.1. Typically, a factor of safety will range from 1.1 to 1.5. The risk and uncertainty associated with a project should be reflected in the factor of safety.

Example calculations

Example calculations are presented for selected methods to illustrate the variability associated with rock sizing methods. The examples may also provide a new user with confirmation that they are correctly applying a method.

Example problem: Mild slope

Problem: For the following flow conditions, determine the required rock size for stone toe protection.

G_s = 2.65 or γ_s=165.36 lb/ft^3
Width = 40 ft
n = 0.045
Slope = 0.01 ft/ft
Depth = 6 ft

Solution: Solve relevant hydraulic parameters

Vel = 9.1 ft/s
Q = 2,200 ft^3/s
Y_{crit} = 4.54 ft

The riprap size determined from several methods is:

Isbash	D_{50} = 6.5 in
Maynord	D_{30} = 4.6 in, D_{50}= 5.5 in
Lane's (FWS)	D_{75} = 15 in, D_{50} = 12.7 in
Abt and Johnson	D_{50} = 8.1 in
ARS rock chute	D_{50} = 3.6 in

Discussion: The computed critical depth indicates that this is a subcritical flow. The design calls for a revetment-type protection, so the stones are not projecting into the flow. Therefore, this is a low-energy flow condition. The Isbash (1936) and the Maynord (1992) methods both indicate a D_{50} of about 5.5 to 6.5 inches. These methods were developed for conditions that are similar to those in the problem statement. Therefore, a stone size of 6 inches with an appropriate factor of safety should be acceptable.

Lane's (1955a) FWS method provides a conservative estimate of 12.7 inches. While this technique is used in similar situations, a conservative answer is expected. The Abt and Johnson (1991) method and the ARS method (Robinson, Rice, and Kadavy 1998) were developed for steeper high-energy flow conditions (>2%); therefore, use of these methods would not be advisable for this application.

Example problem: Steep slope

Problem: For the following flow conditions, determine the required rock size for a rock chute.

G_s = 2.65 or γ_s=165.36 lb/ft^3
Width = 40 ft
n = 0.045
Slope = 0.06 ft/ft
Depth = 3.5 ft

Solution: Solve relevant hydraulic parameters

Vel = 16.7 ft/s
Q = 2,340 ft^3/s
Y_{crit} = 4.7 ft

The riprap size determined from several methods is:

Isbash	D_{50} = 1.6 ft
Maynord	D_{30} = 1.6 ft, D_{50} = 1.9 ft
Lane's (FWS)	D_{75} = 3.7 ft, D_{50} = 3.2 ft
Abt and Johnson	D_{50} = 1.3 ft
ARS rock chute	D_{50} = 1.1 ft

Discussion: The computed critical depth indicates that this is a supercritical flow. While similar in prediction, the Isbash and the Maynord (1992) methods were not developed for conditions that are described in the problem statement. The Abt and Johnson (1991), as well as the ARS rock chute methods (Robinson, Rice, and Kadavy 1998), were derived for similar conditions to the problem statement. Therefore, the 1.1 to 1.3 foot D_{50} riprap with an appropriate factor of safety should be acceptable.

Conclusion

Rock is often used where long-term durability is needed, velocities are high, periods of inundation are long, and there is a significant threat to life and property. Whether a streambank project involves the use of rock as part of a stand-alone treatment or as a component of an integrated system, the determination of the required stone size requires engineering analysis. Stone sizing should be approached with care because rock treatments can be expensive and can give a false sense of security if not applied appropriately. Since stone sizing methods are normally developed for a specific application, care should be exercised matching the selected method with the project purpose and site condition. Therefore, the intended application should dictate which rock sizing technique is used. By using several methods, the designer will often see a convergence of rock sizes for a given application.