RECLAMATION

Managing Water in the West

Design Standards No. 13

Embankment Dams

Chapter 7: Riprap Slope Protection
Phase 4 (Final)

U.S. Department of the Interior
Bureau of Reclamation

May 2014

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Design Standards Signature Sheet

Design Standards No. 13

Embankment Dams

DS-13(7)-2.1: Phase 4 (Final)
May 2014

Chapter 7: Riprap Slope Protection

Revision Number DS-13(7)-2.1

Summary of revisions:

- In the rollout presentation of the Riprap Design Standard, Chapter 7, Bobby Rinehart of the labs commented that ASTM standards are now being used as much, or more than, USBR laboratory testing procedures. Therefore, the ASTM test procedure numbers should be included in the Design Standard. The ASTM Standard Test Numbers will be added to the Riprap Quality Tests along with the currently cited only with USBR designations test numbers. These are in section 7.2.5, pages 10 and 11, and will be rewritten as follows:
    - Specific gravity (ASTM C127, USBR 4127)
    - Absorption (ASTM C127, USBR 4127)
    - Sodium sulfate soundness (ASTM C88, ASTM D5240, USBR 4088)
    - Los Angeles abrasion (ASTM C131, ASTM C535, USBR 4131)
    - Freeze-thaw durability (ASTM D5312, USBR 4666)

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Foreword

Purpose

The Bureau of Reclamation (Reclamation) design standards present technical guidance, requirements and processes to enable design professionals to prepare design documents and reports necessary to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public. Compliance with these design standards assists in the development and improvement of Reclamation facilities in a way that protects the public's health, safety, and welfare; recognizes needs of all stakeholders; and achieves lasting value and functionality necessary for Reclamation facilities. Responsible designers accomplish this goal through compliance with these design standards and all other applicable technical codes, as well as incorporation of the stakeholders' vision and values, that are then reflected in the constructed facilities.

Application of Design Standards

Reclamation design activities, whether performed by Reclamation or by a non-Reclamation entity, must be performed in accordance with established Reclamation design criteria and standards, and approved national design standards, if applicable. Exceptions to this requirement shall be in accordance with provisions of *Reclamation Manual Policy*, Performing Design and Construction Activities, FAC P03.

In addition to these design standards, designers shall integrate sound engineering judgment, applicable national codes and design standards, site-specific technical considerations, and project-specific considerations to ensure suitable designs are produced that protect the public's investment and safety. Designers shall use the most current edition of national codes and design standards consistent with Reclamation design standards. Reclamation design standards may include exceptions to requirements of national codes and design standards.

Deviations and Proposed Revisions

Reclamation designers should inform the Technical Service Center (TSC), via Reclamation's Design Standards Website notification procedure, of any recommended updates or changes to Reclamation design standards to meet current and/or improved design practices.

Chapter Signature Sheet
Bureau of Reclamation
Technical Service Center

Design Standards No. 13

Embankment Dams

Chapter 7: Riprap Slope Protection

DS-13(7)-2.1:[1] Phase 4 (Final)
May 2014

Chapter 7 – Riprap Slope Protection of Design Standards No. 13 was revised to include:

- Results of the most current research by the U.S. Army Corps of Engineers on wind generated waves. This research was published in the 2008 and 2011 versions of the *Coastal Engineering Manual*, EM-1110-2-1100 [3].

- The 10-percent wave height is recommended to compute the W_{50} (median riprap rock weight).

- A maximum W_{50} of 2,000 pounds and a minimum W_{50} of 160 pounds is recommended.

- Additional information addressing rock durability, including Appendix B, "Procedure for Sampling and Quality Evaluation Testing of Rock for Riprap Slope Protection," USBR (United States Bureau of Reclamation) Designation 6025-09 [7].

- Appendix C, which illustrates application of the design standard chapter for a slope protection design using riprap.

- Appendix D, which details research into the history of Reclamation's riprap sizing and an evaluation of riprap performance. This information was used to recommend the most reasonable and cost-effective selection of the design wave height for riprap design.

[1] DS-13(7)-2.1 refers to Design Standards No. 13, Chapter 7, revision 2,

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Chapter 7

Riprap Slope Protection

7.1 Introduction

7.1.1 Purpose

The upstream slopes of embankment dams and dikes typically require protection against the damaging effects of wave action, surface runoff, weathering, ice, and floating debris. This chapter presents guidelines for site-specific design of riprap slope protection (figure 7.1.1-1) subject to wave action. The primary focus is the prevention of riprap rock displacement and bedding erosion by wave action. This chapter also presents a discussion of other major considerations and procedures for design and construction of riprap slope protection to achieve acceptable performance consistent with reasonable construction and maintenance costs.

Figure 7.1.1-1. Riprap slope protection of an embankment dam.

7.1.2 Scope

Criteria and procedures are presented for developing wind and reservoir operation data significant to riprap design, and evaluating the impact of other factors on the design. Procedures for determining adequate riprap sizes, gradation, and bedding requirements are discussed.

Methods and/or requirements for designing other types of slope protection, such as soil cement[2] are not detailed in this design standard chapter. Section 7.5, "Alternative Slope Protection Methods," mentions some alternative methods and references.

7.1.3 Applicability

This design standard chapter is applicable to the design of riprap slope protection used on embankment structures subjected to wave action. It is not applicable to riprap erosion control for stilling basins or channels.

7.1.4 Background of General Design Procedures

The primary purpose of riprap or other slope protection elements on the upstream slope of an embankment dam is to prevent erosion and damage to the embankment from wave action. Because slope protection can represent a significant cost, the design requires a proper balance between the initial cost for construction and future maintenance costs, while ensuring safety of the structure.

Riprap design involves the following general procedures:

- Evaluating site information to determine wind data necessary for design (using one or more wind data stations).
- Determining the reservoir fetch length (see section 7.3.2)
- Determining the design wind velocity (see section 7.3.3).
- Determining wave characteristics and design wave heights based on the design wind velocity (see section 7.3.4).
- Determining riprap requirements (tolerable and zero damage equations; see section 7.3.5) to adequately resist the forces produced by waves within a reservoir. The riprap requirements include size, durability, gradation, and layer thickness (section 7.3.5). The wave forces acting on the riprap elements are included in a riprap stability equation that is discussed in section 7.3.1.
- Plotting the gradations using the estimated rock weights (see section 7.3.6).

[2] See *Design Standard No. 13, Embankment Dams*, Chapter 17, "Soil-Cement" [1].

- Determining the gradation and physical properties of bedding layer(s) to place beneath the riprap to ensure proper performance of the riprap material (see section 7.3.7). Thickness of the bedding layer(s) should be derived from table 7.3.7.6-1, which appears later in this chapter.

7.2 Factors that Influence Riprap Design

7.2.1 General

There are many factors which influence the stability of riprap on an embankment slope. These include:

- Wind velocity, duration, and direction
- Wave height
- Wave period
- Reservoir shape
- Reservoir depth
- Reservoir fetch
- Direction of wave attack
- Manner in which waves impinge on the embankment (breaker type)
- Number of waves striking the embankment
- Embankment slope
- Roughness of riprap surface
- Porosity of riprap layer
- Rock particle weight, dimensions, and shape
- Density of rock
- Keying of rock particles
- Thickness of riprap layer
- Support provided by bedding
- Gradation of bedding
- Thickness of bedding

Many of these factors are interrelated, and some can be mathematically defined. It is neither feasible nor practical to account specifically for all the factors in the riprap design process; however, the designers must be aware of the influence of these factors on riprap performance. Most of the factors are discussed within the sections related to wave characteristics, reservoir operation, embankment design, and rock quality.

7.2.2 Wave Characteristics

As presented above, the stability of riprap on a slope is dependent on many factors, including the characteristics of the waves that are crashing into it. Such characteristics include the wave height, wavelength and period, the type of breaking action, and the general distribution of waves crashing into the slope. These characteristics are influenced primarily by wind velocity, sustained wind duration, the distance the wind travels over open water (fetch), and the wind direction with respect to the embankment slope.

The wave characteristic most significant to riprap design is the wave height, which is influenced by wind velocity, duration, and fetch distance (calculation of these factors is discussed in sections 7.3.2 through 7.3.4). Higher velocity winds are able to produce larger wave heights, as long as the wind is sustained for a long enough duration for the waves to develop. If the wind velocity is not sustained long enough, maximum wave heights for that wind velocity will not be produced. Fetch distance is important because it represents the over-water distance which the wind is able to act upon. Inland reservoirs (particularly those that are narrow with irregular shorelines) have smaller water surfaces for wind to act upon; therefore, they typically produce smaller wave heights than large, open bodies of water.

Model studies use waves of essentially uniform wavelength. It is reasonable to assume that waves produced in nature would have wavelengths that are less uniform than those of waves produced mechanically. The effect of wavelength on the stability of riprap has not been well established. However, wavelength is related to the period of the wave, and the effects of wave period have been studied. In general, longer period waves cause more instability of slope protection (than shorter period waves) due to the way in which they break.

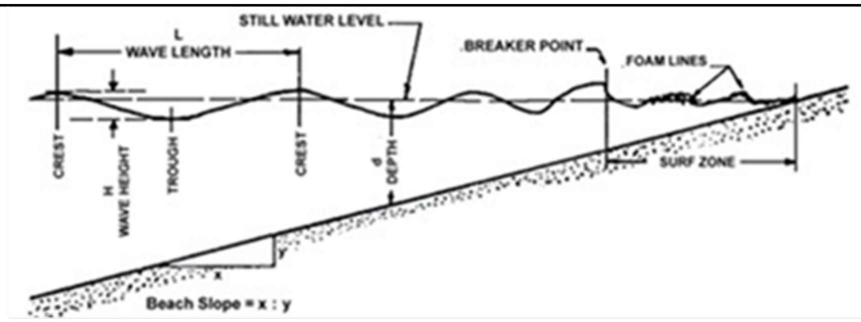
As waves approach a beach (or embankment), they typically deform and break. There are four types of breaking waves, referred to as “breakers” (figures 7.2.2-1 and 7.2.2-2):

1. Spilling: Occurs gradually as the wave crest becomes unstable and flows down the front face of the wave, producing an irregular, foamy water surface.

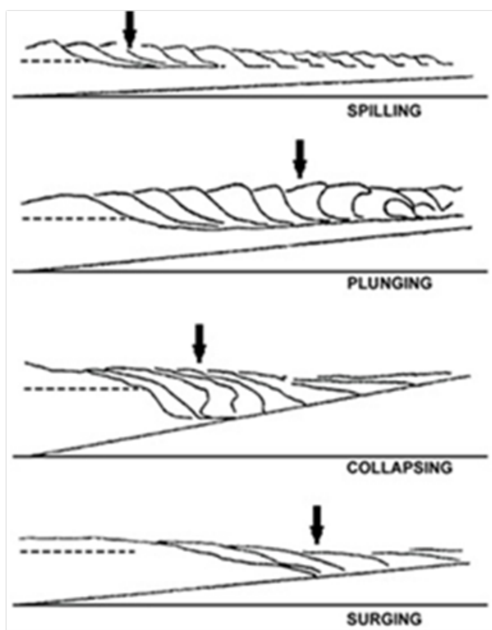
2. Plunging: Occurs when the wave crest curls over the front face and falls into the base of the wave, resulting in a high splash. Plunging breakers are characterized by curling over the top of the crest and a plunging down of this mass of water. This is the type of wave typically associated with surfing.

3. Surging: Occurs when the wave crest remains unbroken, while the base of the front face of the wave advances up the beach with minor breaking. Surging breakers peak as if to break in the manner of a plunging breaker; however, the base of the wave surges up the beach face with the resultant disappearance of the collapsing wave crest.

4. Collapsing: Occurs when the wave crest remains unbroken and relatively flat, while the lower part of the front face steepens and then falls, forming an irregular turbulent water surface that slides up the beach. Collapsing breakers are a cross between plunging and surging breakers.

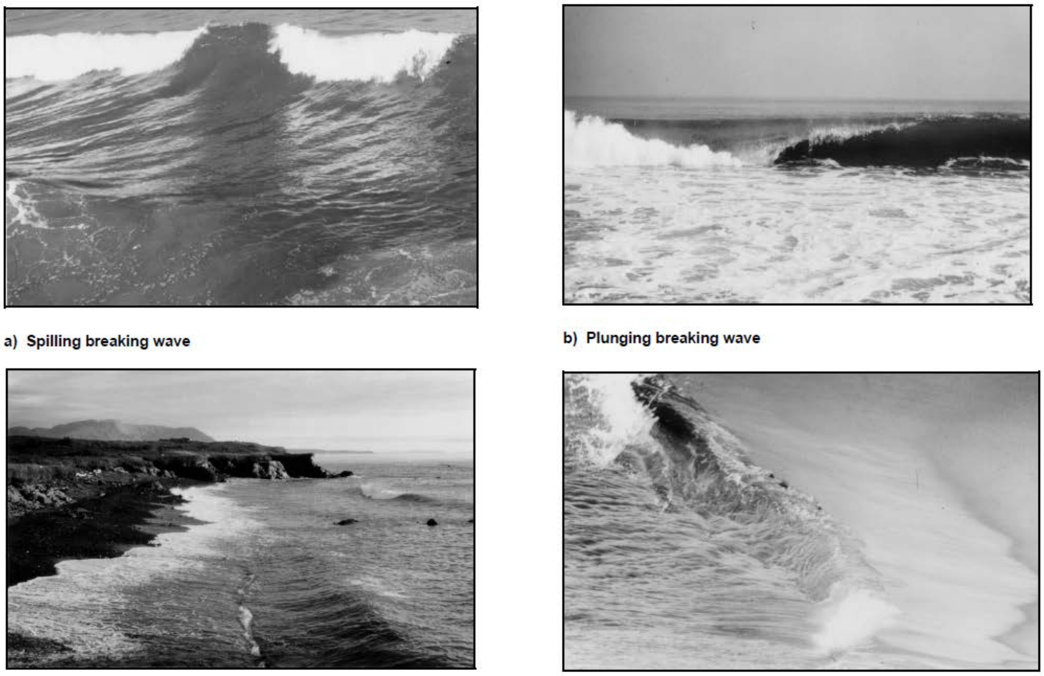


(a) Section through a beach.



(b) Comparison of the water surface at equal time increments (arrows show breaking points), as traced from video of waves breaking on laboratory beaches. Dashed horizontal line is the still-water level.

Figure 7.2.2-1. Wave breaker types.



a) Spilling breaking wave

b) Plunging breaking wave

c) Surging breaking wave

d) Collapsing breaking wave

Figure 7.2.2-2. Photos of wave breakers.

In addition to wave period, the way that a wave breaks depends on other factors such as the slope of the embankment, the speed of the wave, and the depth of the water. The wave periods and embankment slopes typically observed on inland reservoirs generally produce either plunging or collapsing breakers. Surging breakers can occur for long-period waves (long fetch and high wind velocities) or for very steep embankment slopes (1:1 or steeper). Plunging and surging breakers are less damaging within the limits of slopes usually used on embankment dams.

The collapsing breaker produces the most severe loading, and is therefore the condition normally used in model studies to develop appropriate coefficient and exponents for riprap stability equations.

Wave height distributions produced in wave tank modeling studies tend to be fairly uniform compared to actual distributions observed on inland reservoirs. For long period waves (wave periods greater than 3 seconds), the differences are considered to be minimal and have little effect on riprap design. However, for short period waves (wave periods less than 3 seconds), the differences could be significant. When short period waves are expected, additional studies should be performed to determine if the significant wave height (defined in later sections) should be used as the design wave height [3]. The fetch-limited peak wave period (in seconds) can be estimated by:

$$T = 0.464\, F^{1/3}\, VMPH^{1/3} (1.1 + 0.0156 VMPH)^{1/6} \qquad (1)$$

Where:

T	=	Peak wave period (seconds)
VMPH	=	Design wind velocity over water (miles per hour [mi/h])
F	=	Fetch (mi)

The variables *VMPH* and *F* are discussed in detail in sections 7.3.2 to 7.3.4 of this chapter. Equations for sizing riprap presented in this design standard chapter do not incorporate wave period directly. Riprap would be oversized using the equations in this design standard chapter to protect an embankment slope against short period waves (wave periods less than 3 seconds). If riprap is to be designed to protect against short period waves, U.S. Army Corps of Engineers (USACE) references should be used [3].

Selection of the design wind should consider a relatively remote/severe design wind event (high wind velocity) associated with a fetch for the reservoir level at the top of active conservation or the joint-use pool (see figure 7.2.2-3). This is further discussed in sections 7.2.3 and 7.3.3

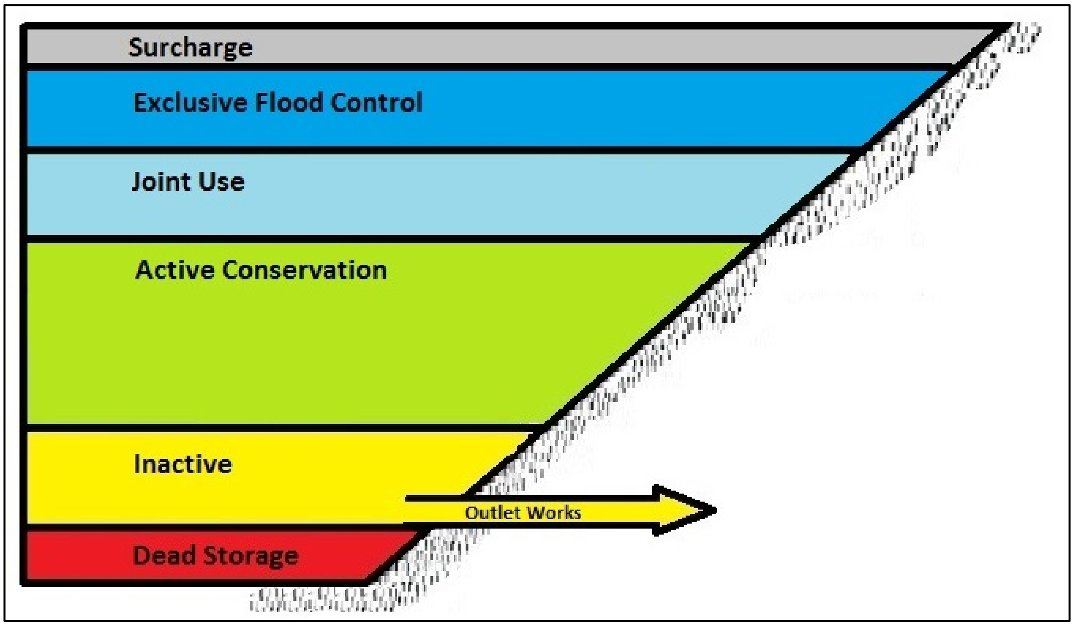


Figure 7.2.2-3. Typical reservoir storage allocation within Reclamation's reservoirs.

7.2.3 Reservoir Operation

Bureau of Reclamation (Reclamation) reservoirs allocate water storage space (figure 7.2.2-3) for specific purposes. Typical designations for these storage-allocations are defined as:

1. Dead storage: The top of dead storage is set at the lowest elevation from which controlled discharges can be made. Reservoir water surfaces below the top of dead storage usually occur only during construction and first filling.

2. Inactive conservation capacity: Inactive capacity is the reservoir storage space from which water is not normally available for use for project purposes. The inactive conservation capacity is the reservoir storage space between the top of dead storage and bottom of active conservation capacity. Water surfaces within these limits are very infrequent; primarily during construction, first filling, and drawdown for inspection or maintenance. On rare occasions, such as periods of drought, the water may be used to partially fulfill project requirements.

3. Active conservation capacity: This reservoir storage space is allocated to fulfill all project requirements exclusive of flood control. During normal reservoir operations, the water surface would be within the limits of active conservation capacity.

4. Joint-use capacity: This reservoir storage capacity is allocated for flood control during certain periods of the year and active conservation during the remainder of the year. Reservoir water surfaces within the limits of the joint-use capacity occur with a frequency and duration established by the reservoir operating criteria.

5. Exclusive flood control capacity: This reservoir storage space is allocated solely for regulating flood inflows to the reservoir. Reservoir water surfaces within the limits of exclusive flood control capacity are strictly controlled and are within these limits only during the duration of flood events.

6. Surcharge capacity: This reservoir storage space is provided as temporary storage during passage of a flood through the reservoir. Water surfaces within the surcharge space depend upon the severity of flood events.

The area of the embankment slope between the bottom of active conservation capacity and the top of joint-use capacity has maximum exposure to wave action. This area has the greatest potential for being subjected to the most severe wave action; therefore, it requires the greatest slope protection. For reservoirs that have significant change in fetch over the range of water surface elevations possible in this space, a reduction in riprap requirements may be possible for lower portions of the active conservation space.

For most embankment dams, it is often most economical to build the entire upstream riprap slope protection with the same design (rock size, gradation, thickness, etc.). However, there may be adequate reason to vary the design on certain portions of the embankment if some of the following conditions are met:

- The dam is very tall, very long, or both.
- Vertical height of flood storage capacity is significant.
- The reservoir elevation can vary significantly within the active conservation pool.
- Vegetation can be relied on as a viable means of slope protection.
- The dam alignment or slope angle varies.
- The capacity of the outlet works is great enough that the reservoir water surface can easily be controlled even during large floods.
- Appropriate-sized material is in short supply or very expensive.
- The embankment is constructed out of relatively erosion resistant materials.
- The predominant wind direction is away from the dam.
- There are other factors that would reduce the erosion potential of the dam in some locations.

The difficulty of specifying and constructing an embankment dam with more than one riprap design or gradation may preclude such considerations. When conditions warrant a change in slope protection design for various portions of the embankment slope, the selected design wind can be varied to account for the probability of the wind occurring when the reservoir water surface is within certain limits, such as flood control or surcharge space.

Slope protection is generally not required within the elevation limits of dead storage and inactive conservation capacity because water surfaces are usually above those elevations during normal operation of the reservoir. However, for reservoirs where water surfaces within these limits can occur for an extended period of time during construction, first filling, or operation; consideration should be given to providing designed slope protection.

7.2.4 Embankment Slope

The embankment slope is the only embankment design parameter used in computing riprap size requirements with Reclamation's riprap stability equations (equations 2, 6 and 7). These riprap stability equations are applicable for embankment slopes from about 2:1 to 5:1 (H:V) because these were the slopes modeled in deriving the relationship. Slopes flatter than about 8:1 are sufficiently flat such that slope protection is either not necessary or minimal, depending on the erosion resistance of the material that comprises the slope surface. Slopes steeper than 2:1 are typically constructed of rockfill, which may provide the necessary slope protection on its own. However, rockfill materials may not be ideally suited for embankment slope protection because they typically contain significant sand and gravel particle sizes between the larger rock fragments, which can be easily scoured by wave action. If the coarser rockfill is not concentrated on outer parts of the slopes, the embankment may still require a designed slope protection consisting of riprap and bedding.

7.2.5 Rock Quality/Shape

Rock for riprap should be hard, dense, durable, and able to resist long exposure to weathering. Preventing the unacceptable deterioration of rock requires both quantitative and qualitative design measures. The suitability of rock quality for riprap is typically determined by laboratory testing and petrographic examination. Many physical properties are determined through laboratory tests, including:

- Specific gravity (ASTM C127, USBR 4127): Specific gravity is a measure of rock density. Values greater than 2.60 generally indicate sound quality rock that would be stable in-place, while values less than 2.60 indicate less durable rock with a higher potential for displacement by wave action. However, rock with a specific gravity considerably less than 2.60 has been successfully used for riprap, especially when other measures of rock quality are not deficient.

- Absorption (ASTM C127, USBR 4127): Absorption is a measure of rock porosity. Test results greater than 2 percent may indicate poor quality rock with excessive voids or fracture systems. Such rock could be susceptible to deterioration from freeze-thaw, wet-dry, or wave action.

- Sodium sulfate soundness (ASTM C88, ASTM D5240, USBR 4088): Sodium sulfate soundness is an indicator of structural soundness of the rock. Test results showing greater than 10-percent loss may indicate low weathering resistance due to excessive voids and fractures, which would be susceptible to freeze-thaw. Typically, there is a good correlation between sodium sulfate soundness and freeze-thaw testing results.

- Los Angeles abrasion (ASTM C131, ASTM C535, USBR 4131): The Los Angeles abrasion test results are an indicator of hardness and structural soundness. The test measures rock resistance to degradation by surface abrasion and impact. Test results greater than 10 percent for 100 revolutions and 40 percent for 500 revolutions indicate a rock likely to deteriorate from wave action. Note that high-quality, coarse-grained granitic rock typically sustains high losses from this test, even though it may be of adequate quality for riprap.

- Freeze-thaw durability (ASTM D5312, USBR 4666): Freeze-thaw durability testing indicates structural weaknesses and is a measure of durability for various field exposure conditions as freezing, thawing, wetting, drying, and wave action. Because it can be used as a general indicator of durability, freeze-thaw test results are applicable even in areas not experiencing freeze-thaw.

Geologic investigations and/or a geologic survey of joint or defect spacings of the in situ rock can provide valuable information about the rock fragment sizes and shapes that can be produced. The geologic origin of the rock will affect the unit weight, strength, and durability. Most igneous rock, most metamorphic rock, many limestones, and some sandstones make suitable riprap. Limestones and sandstones that have shale seams, or that are thinly bedded, are undesirable. Additional properties should be evaluated, including the fragment size, grain size, structure, degree of jointing, faulting, permeability, and shape of the rock.

The shape of rocks can be a reflection of the physical properties of the rock. Rock shape can also influence riprap design considerations, such as the thickness and stability of the riprap layer and its ability to resist erosion.

The shapes of rock fragments (figure 7.2.5-1) can be described as:

- Tabular (also referred to as elongated): Fragments have a length-to-width ratio greater than 2.5:1 and are relatively “rectangular” or “platy” in shape with relatively sharp edges.

- Equant: Fragments are typically described as “equidimensional,” “cubic,” or “blocky” and have relatively sharp edges.

- Irregular: Fragments have various length, width, and height dimensions and relatively sharp edges.

- Semi-round : Fragments may be similar in shape to irregular or tabular fragments, but they have softer/more-rounded edges.

- Very round: Fragments are somewhat spherical, or similar in shape to an equant fragment but with very round edges.

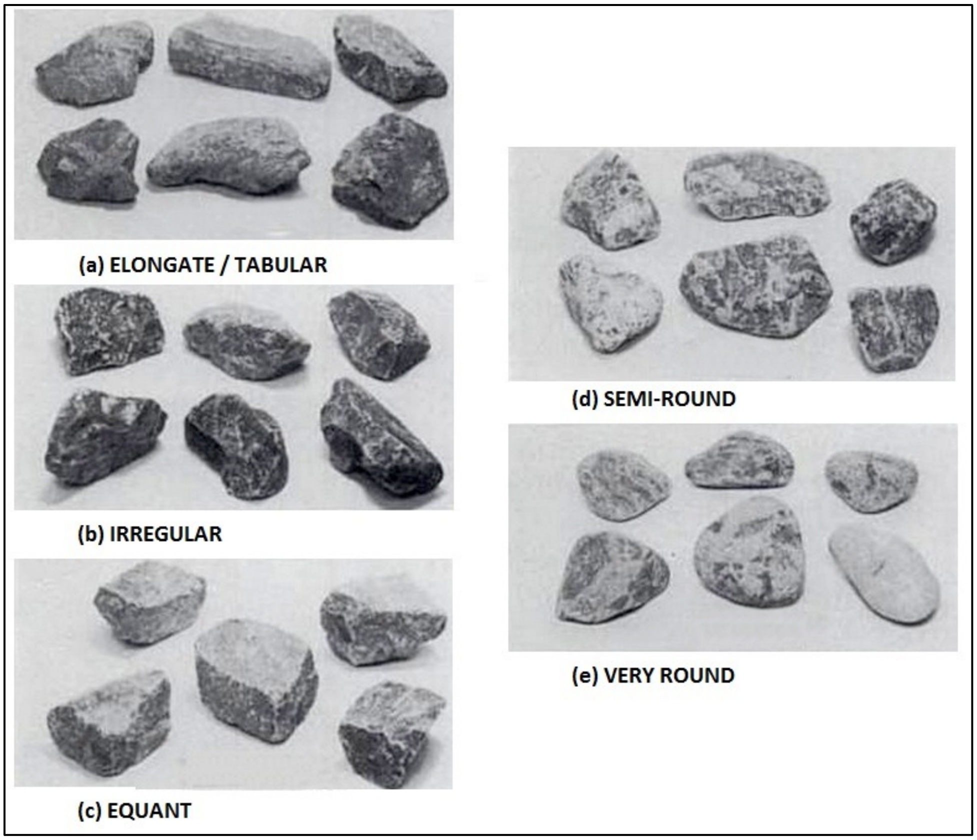


Figure 7.2.5-1. Visual comparison of block shapes (photo by H.R. Wallingford) [4].

Some of the effects that rock shape have on rock properties and riprap design considerations are listed below:

- Strength: Equant shapes are stronger and least problematic during handling and placement.
- Thickness: Different riprap shapes may necessitate different riprap layer thicknesses; riprap layer thickness derived according to this chapter assumes equant shapes. If tabular rock is used for riprap, larger riprap layer thicknesses are required.
- Porosity: Rounded rocks typically fit together more tightly to reduce void spaces.
- Static hydraulic stability: Tests have shown that tabular rocks are more stable than equant rocks and much more stable than round rocks.

Rock shape can also be described using a ratio between the length and width of the rock fragment. This allows designers to specify acceptable shapes numerically. It is commonly required that less than 30 percent of the rock fragments be tabular or elongated (fragments with a length:width ratio greater than 2.5) because these fragments tend to protrude out of the riprap layer, as well as tend to break into smaller fragments during handling.

Petrographic examinations also can provide an assessment of the grain shape, structure, bedding, degree of jointing, weathering, absorption, hardness, porosity, and permeability. Petrographic analysis involves looking at an extremely thin section of the rock sample to determine types and percentages of minerals, texture, structure, grain size, cementing material, and rock classification.

The physical properties, in conjunction with petrographic evaluation, are used to appraise the physical and chemical quality of the rock. No single test has proven superior to evaluate rock quality. The results of any single test should not be used as the sole justification for acceptance or rejection of a potential riprap source. Whenever possible, laboratory test results should be compared to actual performance of similar rock types used for riprap on dams.

Procedures for investigating potential riprap sources are outlined in the *Earth Manual* [5], as well as in Reclamation's *Engineering Geology Field Manual* [6]. Specific investigation requirements are site dependent; however, in general, all viable sources should be identified, investigated, sampled, and tested according to Designation USBR 6025-09 [7], which is included as appendix B to this Design Standard chapter. The American Society for Testing and Materials (ASTM) Designation D 4992-07 [22] also describes the practice of evaluating rock for riprap. Records of riprap performance on existing dams are available and should be reviewed when considering potential rock sources [8], [9]. Consideration of cost must be made if local sources of good quality rock are not available. Soil-cement may be more economical if good quality rock is unavailable within a reasonable haul distance (see section 7.5).

7.2.6 Other Considerations

Other situations that may influence design include items such as potential for ice or debris damage, extreme freeze-thaw conditions, availability of riprap-quality rock, and remoteness of the reservoir site (infrequent inspections). These, as well as other conditions that may be unique to a particular site, should guide the designer's judgment when selecting design parameters and establishing the necessary rock quality requirements for the riprap design.

7.3 Design Procedures

The scope of a riprap design includes: selecting a design wind, computing the design wave heights, computing the sizes of the material range, and determining the acceptable gradation band for both riprap and bedding layers.

7.3.1 General Stability Equation

The major forces to be resisted by riprap are those produced by wind-generated waves and gravity. Various researchers have developed relationships to express the forces exerted by the waves and the resisting forces offered by the riprap. The forces acting on the riprap are expressed in terms of the velocity of flowing water, gravity, characteristic dimensions of the riprap, and coefficients representing the effects of drag, mass, and hydrostatic pressures. Resisting forces offered by the riprap are expressed in terms of riprap volume and its buoyant weight. The acting and resisting forces are sensitive to the embankment slope. The basic stability equation, derived by equating the acting and resisting forces on a riprap element, is presented as follows:

$$W_r = \frac{\gamma_r \, H^{a}}{K \, (G_s - 1)^3 (cot \propto)^b} \qquad (2)$$

Where:

W_r = Weight of individual rock fragment necessary to resist wave action (pounds)
γ_r = Unit weight of rock pieces (pounds per cubic foot)
G_s = Specific gravity of rock
$\propto$ = Slope angle measured from horizontal (degrees)
H = Design wave height (feet)
K = Experimentally determined coefficient
a, b = Experimentally determined exponents

Values for K, a, and b have been determined empirically from observations and wave studies performed in tank models. Some authors have recommended different values for these variables for "tolerable damage" and "zero damage" design scenarios [10], [11]. Additional information on these design scenarios is provided in section 7.3.5 and appendix A-1, and the various values are provided in appendix A-2. Reclamation has adopted values originally presented by the USACE in 1975. These values are presented in table 7.3.1-1.

Table 7.3.1-1. Variations in the general form of the stability equation

Source	Coefficients			Remarks
	a	b	K	
USACE (1975) [11]	3	0.67	3.62	Average zero damage level for the worst wave conditions
	3	1.00	4.37	Average limit of tolerable damage for the worst wave conditions

7.3.2 Reservoir Fetch

The fetch length is calculated to account for the size and shape of the reservoir when estimating the design wave height. The method for determining fetch for inland reservoirs is presented in USACE's *Determining Sheltered Wave Characteristics* [23], as well as in Chapter 6, "Freeboard," of Reclamation's *Design Standard No. 13, Embankment Dams* [13]. This determination involves calculating the fetch for a reservoir level at the top of active conservation pool (section 7.2.3), or at the top of joint-use pool, if applicable. The lengths of nine radii (spaced at 3 degrees to cover a 24-degree arc) extending from a point on the dam face are then averaged. The center radius (of the nine) should be as perpendicular as possible to the dam centerline, while simultaneously maximizing the lengths of all of the radii. Several points along the dam should be evaluated to determine the point that produces the largest average radius. This value is then referred to as the "fetch." For an example of the implementation of this method, see figure C.1 in appendix C. It should be noted that this method is different from previous methods used to determine an "effective fetch."

7.3.3 Design Winds

A design wind velocity *(VMPH)* must be selected in order to compute the design wave height *(H).* When selecting a design wind velocity, it is advisable to use a wind database that is site specific, arranged in a probabilistic way, with a relatively long period of record. Reclamation uses wind data compiled in 1980 by the Battelle Memorial Institute, Pacific Northwest Laboratory, under contracts with the U.S. Department of Energy [12]. This wind data includes multiple wind stations within each of the contiguous 48 States. Wind velocities and directions were typically recorded hourly at these stations over a period of several years. At some wind stations, the data was processed ("digitized" and "summarized"), while at other stations it was not processed.

To select a design wind, the wind station(s) nearest to the dam site (preferably with similar elevation and vegetation) must be selected as the representative location. Reclamation is then able to relate the historical wind velocities recorded at the site to an hourly probability of exceedance for wind events. This is typically done using Reclamation's Probabilistic Freeboard and Riprap Analysis (PFARA) program. PFARA requires the designer to input the representative wind station (which must have processed data), the fetch length of the reservoir, and a maximum wind velocity (set to 100 mi/h by default). Reclamation's *Design Standards No. 13, Embankment Dams*, Chapter 6, "Freeboard" includes further information about how to use this program [13].

In the absence of the Battelle wind data or Reclamation's PFARA program, wind data collected hourly from a representative station can be ranked and statistically converted to develop this same relationship. To select the appropriate wind velocity and nonexceedance probability, the sensitivity of the nonexceedance probability should be examined relative to the selection of the wind velocity. For a selected set of wind velocities (for example, 50, 55, 60, 65, and 70 mi/h), the probability of not being exceeded (nonexceedance probability, P_{NE_L}) within a given design time period (L) is computed by equation 3:

$$P_{NE_L} = (1 - P_{W_H})^{8760L} \qquad (3)$$

Where:

P_{NE_L}	=	Probability of nonexceedance over design time period (L)
P_{W_H}	=	Hourly exceedance probability of the design wind event
L	=	Design time period (years)

A 100-year design time period is assumed for most embankment dams (which may loosely be associated with the remaining life of the structure), although economic factors can influence the decision to use a different design time period (e.g., a longer time period if riprap is difficult to obtain).

A plot of the nonexceedance probability on the vertical axis versus wind velocity on the horizontal axis will typically show that the nonexceedence probability tapers off above a certain wind velocity (represented by the curve approaching a horizontal orientation). This tapering of the curve indicates that there is little additional benefit to designing for a larger nonexceedance probability (i.e., as design wind velocity increases, the increase in nonexceedance probability reduces). Because of this, the design wind velocity is usually selected as a velocity just above the bend in this curve (e.g., see appendix C, figure C.3). However, if this design wind velocity does not provide a nonexceedance probability of at least 90 percent, a larger design wind velocity should be selected that will result in a nonexceedance probability of at least 90 percent (over the design time period).

7.3.4 Design Wave Height

Wind-generated waves are not uniform in height; rather, they consist of a distribution of waves with various heights. This distribution of waves can be assumed to follow a Rayleigh-type distribution, which allows the designer to calculate the wave height for various percentiles based on the value of the significant wave height (H_s). The significant wave height is defined as the average of the largest 33 percent of waves within a wave series. Since equation 2 was first adopted for use in riprap design, and prior to the 2013 revision to this chapter, Reclamation used H_s to represent the design wave height, H, in equation 2.

In 2008, the USACE updated their *Coastal Engineering Manual*, EM-1110-2-1100, to use a modified equation for calculating H_s [3]:

$$H_s = 0.0245\, F^{1/2}\, VMPH\, (1.1 + 0.0156\, VMPH)^{1/2} \quad (4)$$

Where:

H_s	=	The significant wave height (feet)
$VMPH$	=	Design wind velocity over water (mi/h)
F	=	Fetch (mi)

This modification results in a design wave height that is about 25 percent smaller than the design wave produced using the USACE's previous equation for significant wave height, H_s. This, in turn, results in smaller riprap when used as the design wave height within equation 2. Because of this, it was decided, during the 2013 update to this chapter, to gather additional information to determine if using smaller riprap would have been acceptable or if it would negatively affect riprap performance.

Research was conducted to study the history of riprap sizing and performance within Reclamation (see appendix D). The study compared a previous equation for calculating H_s in earlier versions of this chapter to the updated equation (equation 4) for sizing riprap at various dams. These values were then input into equation 2 to calculate the median rock weight, W_{50}. The resulting rock sizes were compared to the rock sizes actually used (as estimated from specifications) on these Reclamation embankment dams. When comparing riprap sizes required from computations to actual sizes and performance of riprap on the dams, the study showed that the 10-percent wave height (H_{10}), based on the H_s derived from equation 4, results in riprap sizes that perform well without unnecessary conservatism and undue cost. This is in agreement with the USACE approach to the design of armor protection for critical revetment structures [3]. The calculation of H_{10} is based on the assumption of a Rayleigh wave distribution within the wave series:

$$H_{10} = 1.27 \text{ x } H_s \quad (5)$$

Where:

H_{10}	=	Average height of the largest 10 percent of waves within a wave series (feet)

Thus, H_{10} derived from equations 4 and 5 above is to be used as the design wave height in equation 2, as well as the equations that follow in this chapter, for computing a rock weight (W_{50}) in the design of riprap for the upstream slope protection of embankment dams.

7.3.5 Riprap Weights and Thickness

To determine riprap size, Reclamation uses equation 2 to calculate W_{50}, with H_{10} to represent *H*, and the values presented in table 7.3.1-1, where applicable.

For cases where **tolerable damage** is selected for design, W_{50} is calculated as:

$$W_{50} = \frac{\gamma_r \, {H_{10}}^3}{4.37 \, (G_s - 1)^3 (cot \propto)} \qquad (6)$$

For cases where **zero damage** is selected for design, W_{50} is calculated as:

$$W_{50} = \frac{\gamma_r \, {H_{10}}^3}{3.62 \, (G_s - 1)^3 (cot \propto)^{0.667}} \qquad (7)$$

The computed riprap weights can vary substantially depending on whether the tolerable damage or zero damage equation is used. It is recommended that the tolerable damage equation be used when the design wind velocity is selected as described in section 7.3.3 (having a minimum nonexceedance probability of 90 percent). More conservatism against damage for high-risk, high-hazard structures can be obtained by increasing the rock sizes from those calculated by the tolerable damage equation (not to exceed sizes calculated by the zero damage equation); however, the need for additional conservatism should be a case by case consideration. It should be noted that using the zero damage equations nearly doubles the riprap weight requirements for most design conditions. Less conservatism (i.e., riprap sizes closer to tolerable damage) may be warranted if damage to the riprap would not cause dam failure and periodic repair of damaged riprap is economically justified. (See appendix A for more detailed definitions of tolerable and zero damage.)

The W_{50} values calculated from equations 6 and 7 are subject to minimum and maximum weight limitations. The maximum W_{50} for dams is generally 2,000 pounds. Based on the research presented in appendix D, this W_{50} rock size would have been adequate to avoid riprap failure by erosion for all of the historical cases studied, while affording a reasonable level of economy. The minimum W_{50} to protect a typical Reclamation dam should not be less than 160 pounds.

To convert from the representative (W_{50}) weight of riprap to the representative rock volume, (V_{50}), a standard shape is assumed for the rock fragment. The volume computed by equation 8 is of a shape that is assumed to be equant (i.e., approximately between a sphere and the volume of a cube). From this equation, the riprap rock diameter can also be approximated. Based on this assumption, the representative volume of riprap can be calculated as:

$$V_{50} = W_{50}/\gamma_r = 0.75(D_{50})^3 \quad (8)$$

Where:

V_{50} = Representative volume of the rock where 50 percent is smaller (cubic feet)

D_{50} = Representative diameter of the rock where 50 percent is smaller (feet)

Reclamation has found a 3-foot thickness (normal to the slope) of dumped riprap to be generally economical and satisfactory for many of its major dams. Lesser thicknesses have been used on low dams or dike sections where the expected wave action is less severe. Lesser thicknesses have also been specified for the upper slopes of dams where reservoirs are largely allocated to flood control. Greater thicknesses have been specified in cases where rock having a low specific gravity (G_s less than 2.5) was used, or where the riprap was very large (e.g., D_{50} > 18 inches). A minimum thickness of a riprap layer can be computed as:

$$T \geq 2\, D_{50} \quad (9)$$

Where:

T = Riprap layer thickness normal to the slope (units same as D_{50})

Riprap thickness is typically specified in 12-inch increments for construction but can also be specified in 6-inch increments, if preferred.

7.3.6 Riprap Gradation

A riprap gradation is specified based on the W_{50} value calculated from either equation 6 or equation 7. The resulting gradation should result in a well-graded material from the maximum to the minimum size. The maximum and minimum weights of the riprap gradation (in pounds) are calculated as:

$$W_{max} = 4\ W_{50} \quad (10)$$

$$W_{min} = W_{50} / 8 \quad (11)$$

Where:

W_{max} = 100 percent of the rock in the riprap gradation is smaller

W_{min} = Approximately 5 to 20 percent of the material in the riprap gradation is smaller

Acceptable riprap gradation bands (consisting of both a coarse-limit curve and a fine-limit curve) can be plotted (figure 7.3.6-1) based on the results of equations 10 and 11, using the guidance provided in the following sections of this chapter. The "20-percent band" is recommended, but guidance for constructing a "35-percent band" is also provided to improved constructability if the availability of properly sized material is a concern. A blank riprap gradation chart is also provided in figure 7.3.6-2 to aid the designer in riprap design and banding of the riprap material.

7.3.6.1 The "20-Percent Band"

The values derived for W_{max}, W_{50} and W_{min} are used to create a band of riprap to be specified for construction. The initial band created in the design process is one with 20-percent vertical separation between the upper (fine) and lower (coarse) size limits. This "20-Percent Band" is the minimum width of a band to be specified for the gradation of riprap. Such a band is wide enough to be constructible (from a standpoint of material availability), yet it is narrow enough to reduce the possibility of gap-graded material or segregation of the riprap during placement. Table 7.3.6.1-1 can be used to produce an initial "20-percent band" width for the riprap gradation.

Table 7.3.6.1-1. Values used to define the coarse- and fine-limit curves for the initial "20-percent band" riprap gradation

20-percent band coarse-limit curve	
Weight of rock fragment	**% finer by weight**
W_{max}	100
$0.5\,W_{\text{max}}$	70
W_{50}	35
W_{min}	0
20-percent band fine-limit curve	
Weight of rock fragment	**% finer by weight**
$0.5\,W_{\text{max}}$	90
W_{50}	55
W_{min}	20

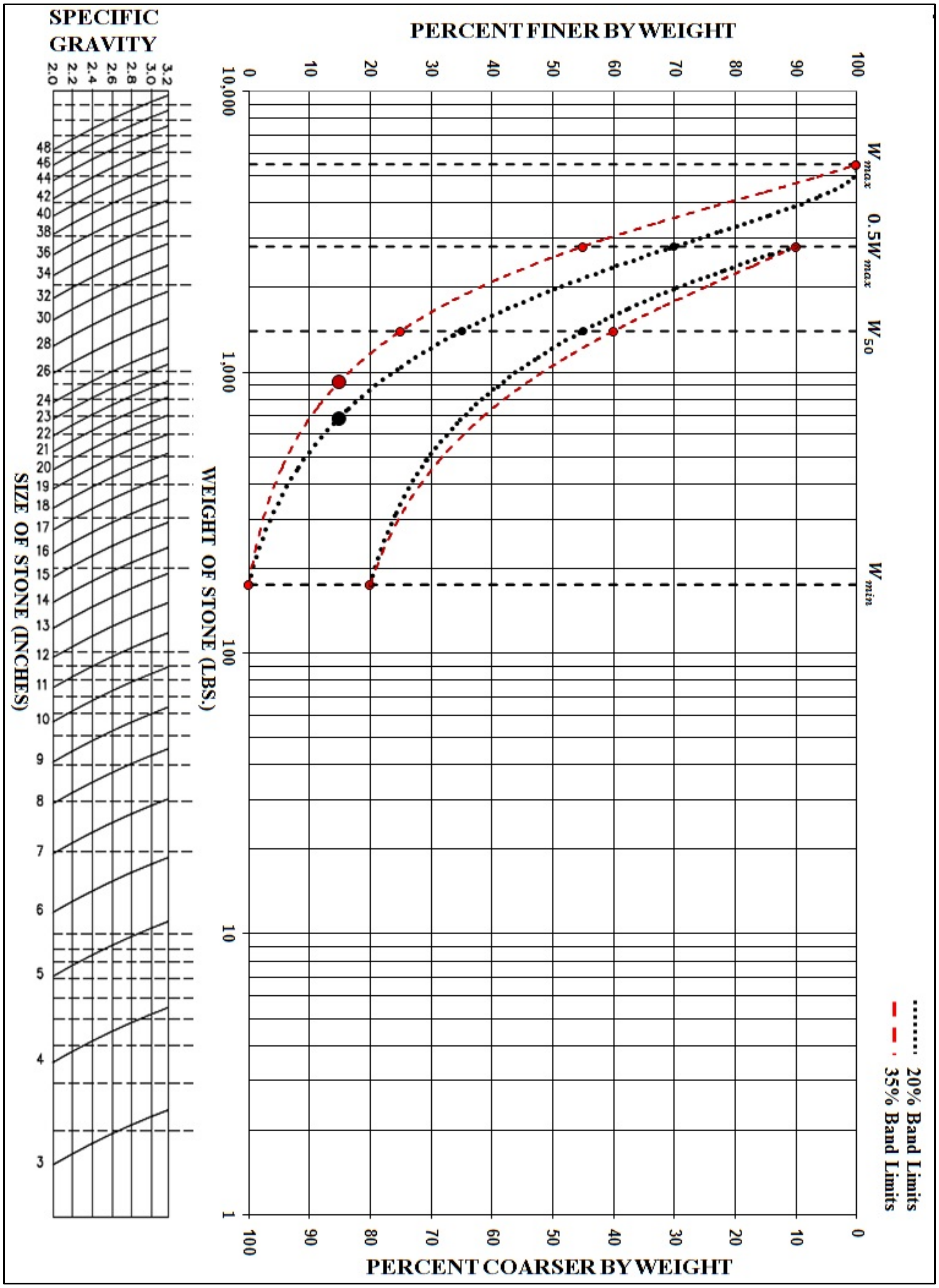


Figure 7.3.6-1. Example riprap gradations (20-percent and 35-percent bands).

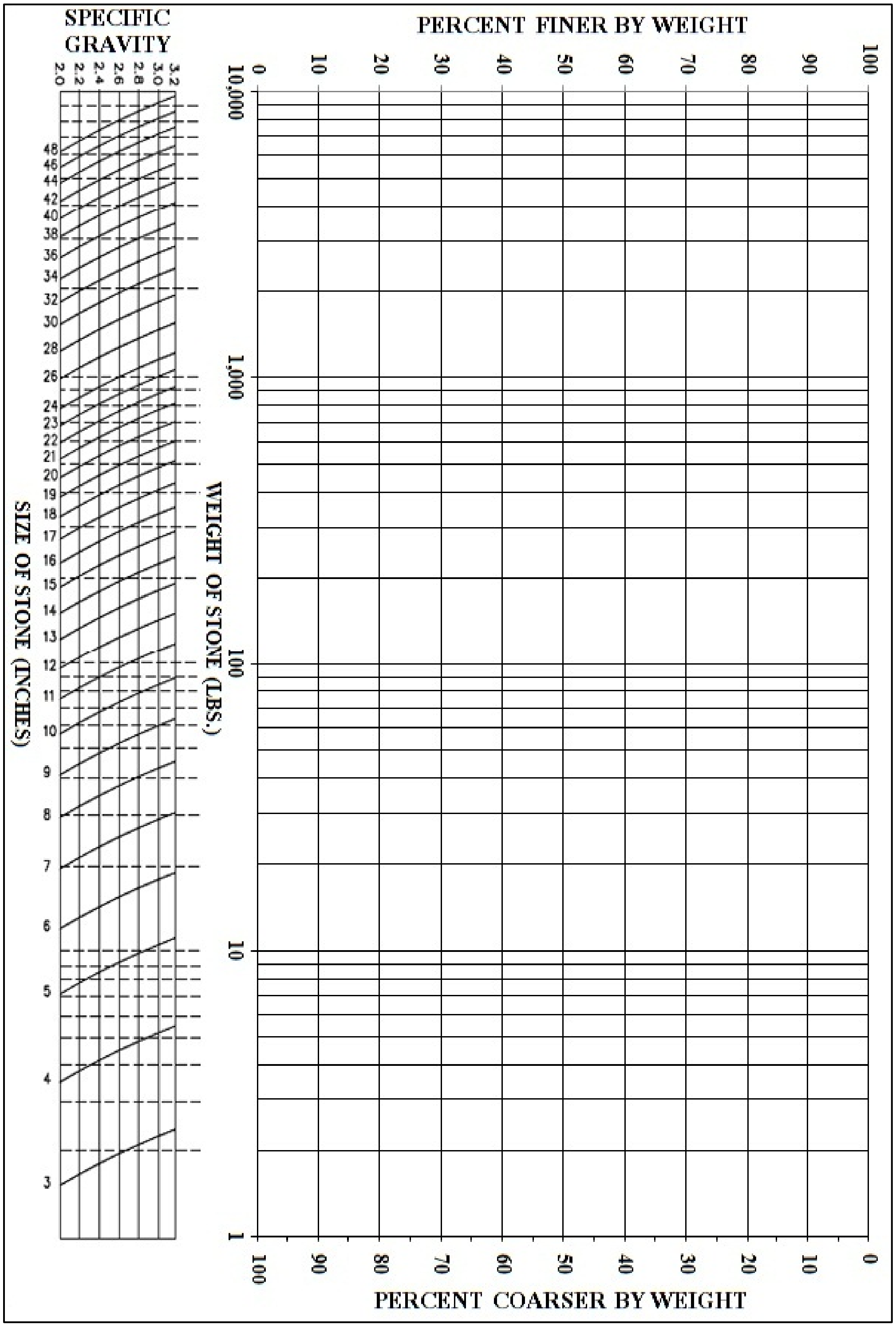


Figure 7.3.6-2. Blank riprap gradation, by weight (pounds). Equant shape assumed.

The ranges used were selected to provide 20 percent vertical spacing between the coarse- and fine-limit curves. The W_{50} size is adjusted to fall between 35 and 55 percent, and is therefore not centered at 50 percent. This lowers the center of the band, increasing the percentage of particles larger than the W_{50} size. The horizontal dashed line at "20-percent-finer" (for sizes smaller than W_{min}) allows the finer-portion of the gradation to tail-off as may be needed for constructability. Materials within this region may improve stability of the riprap by partially filling void space between the larger rock fragments. A gap-graded distribution of particles within a band just 20 percent wide is still possible and should not be allowed, although it is unlikely to affect stability.

Constructing the gradation bands using the method described above allows the designer to more easily specify the allowable gradations. Three to four size bands are typically used to specify a gradation band as presented in table 7.3.6.1-2 below.

Table 7.3.6.1-2. Example riprap gradation specification table (by percent passing) for a W_{50} of 1,400 pounds (maintaining the initial 20-percent band

Design parameter	Size (pounds)	Percent finer by weight
W_{max}	5,600	100
0.5 W_{max}	2,800	70 to 90
W_{50}	1,400	35 to 55
W_{min}	175	0 to 20

7.3.6.2 The "35-Percent Band"

Certain adjustments can be made when defining the final riprap gradation curves as long as sound engineering judgment is used. Adjustments are often made to widen the initial band to improve constructability or to match the rock sizes that are readily available from a quarry, borrow area, or commercial source. When modifying the riprap gradation band, the curves should not be separated (vertically) by more than 35 percent (see figure 7.3.6-1) to help avoid gap gradation and segregation during placement.

A "35-percent band" can be constructed (see Figure 7.3.6-1) using table 7.3.6.2-1.

Table 7.3.6.2-1. Values used, in general, to define the coarse- and fine-limit curves for a "35-percent band" width

35-percent band coarse-limit curve	
Weight of rock fragment	**% finer by weight**
$W_{\max}$	100
$0.5\,W_{\max}$	55
W_{50}	25
$W_{\min}$	0
35-percent band fine-limit curve	
Weight of rock fragment	**% finer by weight**
$0.5 \text{ x } W_{\max}$	90
W_{50}	60
$W_{\min}$	20

The associated size bands would be specified as shown in table 7.3.6.2-2 below.

Table 7.3.6.2-2. Example riprap specification table (percent finer by weight) for a W_{50} of 1,400 pounds

Design parameter	Size (pounds)	% finer by weight
W_{max}	5,600	100
0.5 W_{max}	2,800	55 to 90
W_{50}	1,400	25 to 60
W_{min}	175	0 to 20

7.3.6.3 Additional Considerations

The 20-percent band widths and 35-percent band widths are expected to provide adequately sized riprap for slope protection at typical Reclamation dams. Riprap gradation specified for embankment dam upstream slope protection should not be narrower than the 20-percent band and not wider than the 35-percent band. Alternative bands for riprap sizing are available for other applications. ASTM has published riprap gradation bands for nine varying sizes, as presented in Designation D 6092-97 [14]. Three of these gradation bands (R-1500, R-750, and R-300) have riprap sizes (1,000, 425, and 200 pounds, respectively) that may be appropriate as slope protection for some Reclamation dams as long as they meet the W_{50} size and gradation requirements presented in the previous sections of this chapter. The other ASTM riprap gradation bands are for smaller riprap. They are better suited for other erosion protection applications such as a second layer of riprap, a bedding layer, or erosion protection within a channel. It is important to point out that the separation between the coarse and fine limit curves exceeds

35 percent for most of the ASTM gradation bands, especially at the coarser end of the bands. Riprap constructed from these gradations may, therefore, be subject to segregation during placement.

Internal instability is typically not a concern within properly designed and constructed riprap due to the high percentage of large rock fragments and grain sizes. The larger rock fragments make up a majority of the “skeleton” (or “structure”) of the riprap zone and are able to provide stability through contact with each other. Any finer material that is able to move or wash through the larger fragments is typically insufficient to cause instability within the material. Instability is more likely to occur if the material immediately beneath the riprap is able to internally erode through the riprap layer. To address this issue, one or more layers of bedding material are placed under the riprap. These layers are designed to be filter compatible with adjacent materials to prevent internal erosion.

7.3.7 Bedding Requirements

The bedding material should be designed to meet three primary criteria: (1) it must not be so broadly graded as to be susceptible to internal instability; (2) it must be coarse enough to prevent it from eroding through the riprap; and (3) it must be fine enough to retain the underlying embankment material. The process for designing the bedding layer(s) to meet these requirements is defined below. It is noted that the bedding design is based largely on Reclamation’s *Design Standards No. 13, Embankment Dams*, Chapter 5, “Protective Filters” [15], which requires that material sizes are defined by diameter, rather than by weight. To convert the riprap weights above to equivalent diameter values, equation 8 should be used. Figure 7.3.7-1 can be used to assist with design of the bedding layer(s).

7.3.7.1 Internal Stability Criteria

When the designed riprap gradation is much coarser than the gradation of the embankment material, a single bedding material would need to be very broadly graded in order to comply with each of the last two bedding criteria stated in paragraph 7.3.7. However, if the bedding material is too broadly-graded, it will be susceptible to internal instability, and will not comply with the first criteria stated in paragraph 7.3.7 (and will likely require a second layer of bedding, as will be described later in this chapter, in paragraph 7.3.7.5). According *to Design Standards No. 13, Embankment Dams*, Chapter 5, “Protective Filters,” a material is considered internally unstable when it is plotted within Sherard’s unstable band or when its gradation curve is flatter/less steep than the “4x” line (figure 7.3.7.1-1). For the purpose of this chapter, a bedding material can be considered internally stable when its coefficient of uniformity, C_u, has a value less than 10 [3]:

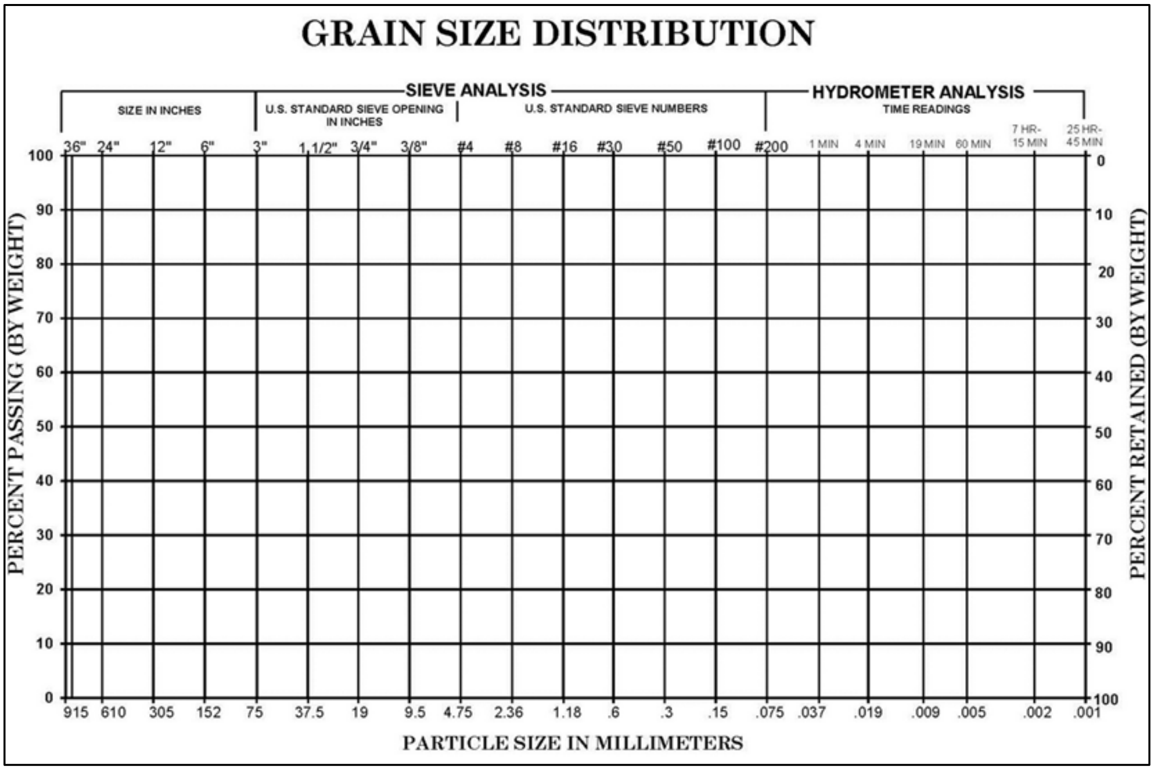


Figure 7.3.7-1. Blank gradation chart (by particle diameter) for riprap and bedding material design.

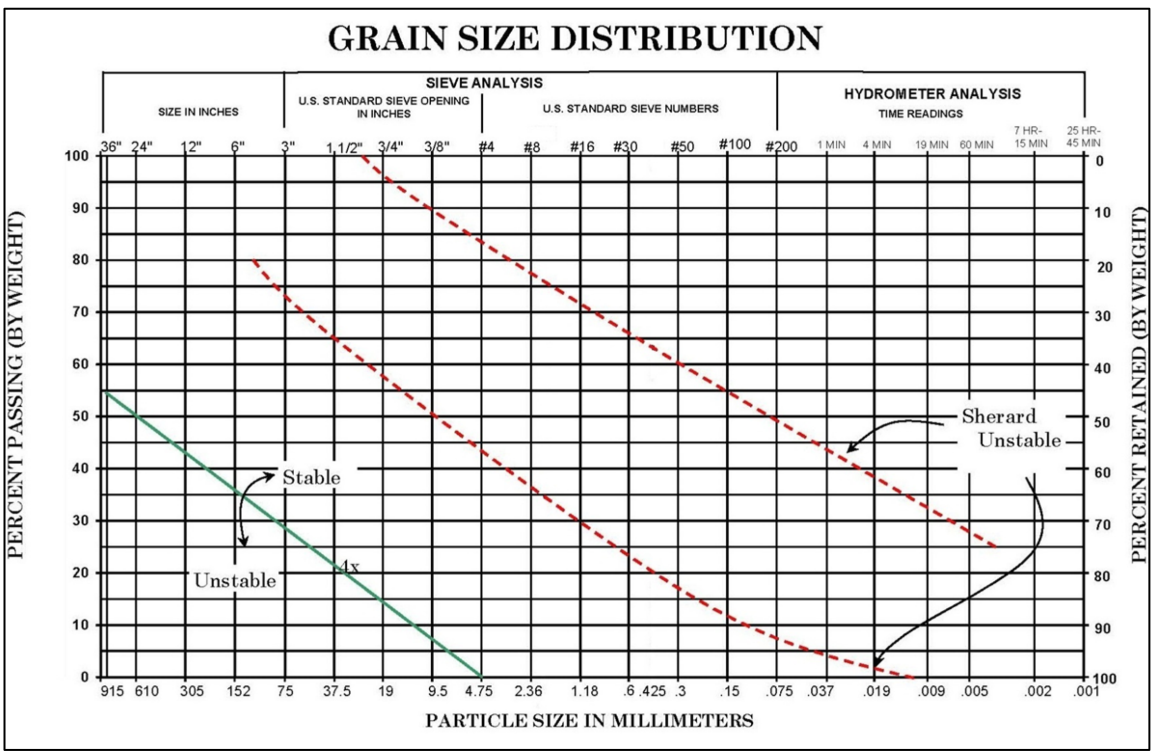


Figure 7.3.7.1-1. Bedding material instability chart; material may be internally unstable if it lies within Sherard's unstable bands or is flatter than the 4X line [15].

$$C_u < 10, \qquad C_u = \frac{D_{60\ B_{Coarse\ limit}}}{D_{10\ B_{Fine\ limit}}} \tag{12}$$

Where:

$D_{60\ B_{Coarse\ limit}}$ = The 60-percent-passing size of the coarse-limit curve of the design bedding gradation band

$D_{10\ B_{Fine\ limit}}$ = The 10-percent-passing size of the fine-limit curve of the design bedding gradation band

The process for defining the coarse- and fine-limit gradation curves is included in the design procedure in section 7.3.7.4.

7.3.7.2 Retention of Bedding Material by Riprap

To keep the bedding material from eroding through the riprap, the bedding material is designed to meet the filter criteria presented in *Design Standards No. 13, Embankment Dams*, Chapter 5, "Protective Filters." The photograph in figure 7.3.7.2-1 shows bedding that is compatible with the overlying riprap. The criterion used to ensure that bedding material is retained by the riprap is:

$$D_{85\ Min} > \frac{D_{15\ R_{Coarse\ limit}}}{5} \tag{13}$$

Where:

$D_{85\ Min}$ = The minimum 85-percent-passing size of bedding material that will ensure that the bedding material is coarse enough to be retained by the riprap

$D_{15\ R_{Coarse\ limit}}$ = The 15-percent-passing size of the coarse-limit curve of the design riprap gradation band. This value is calculated from $W_{15\ R_{Coarse\ limit}}$ using equation 8

The factor of 5 in the denominator of equation 13 was selected (instead of 4 as would be required per chapter 5 [15] for retention of "Base Soil Category 4" materials) to allow for a slightly smaller bedding gradation that is still considered filter compatible with the riprap according to Reclamation's "no erosion" filter criteria. This adjustment is reasonable considering the very coarse nature of the bedding and riprap, which renders erosion of the bedding through the riprap to be more unlikely. Also, these zones are well engineered, and it is likely that their sizes are sufficiently controlled and their placements are adequately inspected during construction. When evaluating the compatibility of existing riprap with its bedding or another material underlying and adjacent to the riprap, the gradation of the underlying material may be compared to Fell's "excessive erosion" boundary [16]. This boundary can be computed with equation 13, except that a factor of 9 is used in the denominator. This assumes that “some erosion” of the underlying material will occur into or through the riprap because the underlying material would be about half the size of bedding designed using the unchanged equation 13 (i.e., shown above, with a factor of 5 in the denominator). “Some erosion” is not recommended for the design of new or modified riprap and bedding.

Figure 7.3.7.2-1. Riprap and bedding in construction.

7.3.7.3 Retention of Embankment Material

The designed bedding material gradation must also be fine enough to provide for the retention of the embankment material beneath it. This is especially important if the underlying embankment material is the primary impervious core of the dam, has low plasticity, or is easily erodible. To ensure that the bedding material is fine enough, a 15th percentile size limit is defined for the bedding:

$$D_{15\,Max} < 5D_{85\,E\,Fine\,Limit} \tag{14}$$

Where:

$D_{15\,Max}$ = The maximum 15-percent passing size of bedding material that will ensure that the bedding material is fine enough to be able to retain the embankment material

$D_{85\ E_{Fine\ Limit}}$ = The 85-percent passing size of the most finely graded sample(s) of embankment material. **If the embankment materials are broadly graded and contain particles greater than the No. 4 sieve size, this value should be calculated by regrading the embankment material to ignore larger particle sizes (in accordance with *Design Standards No. 13, Embankment Dams,* Chapter 5, "Protective Filters," figure 5.4.2-3 [15]).**

If the embankment material immediately beneath the bottom bedding layer is a "Base Soil Category 1" material (i.e., the embankment material has more than 85 percent finer than the No. 200 sieve size [0.075 millimeters] after regrading, if necessary), the coefficient in equation 14 can be increased from a value of 5 to a value of 9.

Figure 7.3.7.3-1 presents an example of the use of $D_{15\ Max}$ and $D_{85\ \mathrm{E}\ \mathrm{Fine\ limit}}$ based on the example riprap gradation from figure 7.3.6-1 (35-percent band limits), and two samples of embankment material.

7.3.7.4 Defining the Bedding Gradation Band

Coarse- and fine-limit curves are constructed to define the bedding gradation in the following manner:

1. $D_{85\ Min}$ should be used to define the 85th percentile point on the fine-limit curve and the 60th percentile point on the coarse-limit curve:

$$D_{85_{Min}} = D_{85\ B1_{Fine\ limit}} = D_{60\ B1_{Coarse\ limit}} \tag{15}$$

   Where:

   $D_{85\ B1_{Fine\ limit}}$ = The 85-percent-passing size of the fine-limit curve of the first layer of bedding material

   $D_{60\ B1_{Coarse\ Limit}}$ = The 60-percent-passing size of the coarse-limit curve of the first layer of bedding material

2. To ensure that the bedding's coefficient of uniformity, C_u, will be less than 10, $D_{10\ B1_{Fine\ limit}}$ should be calculated:

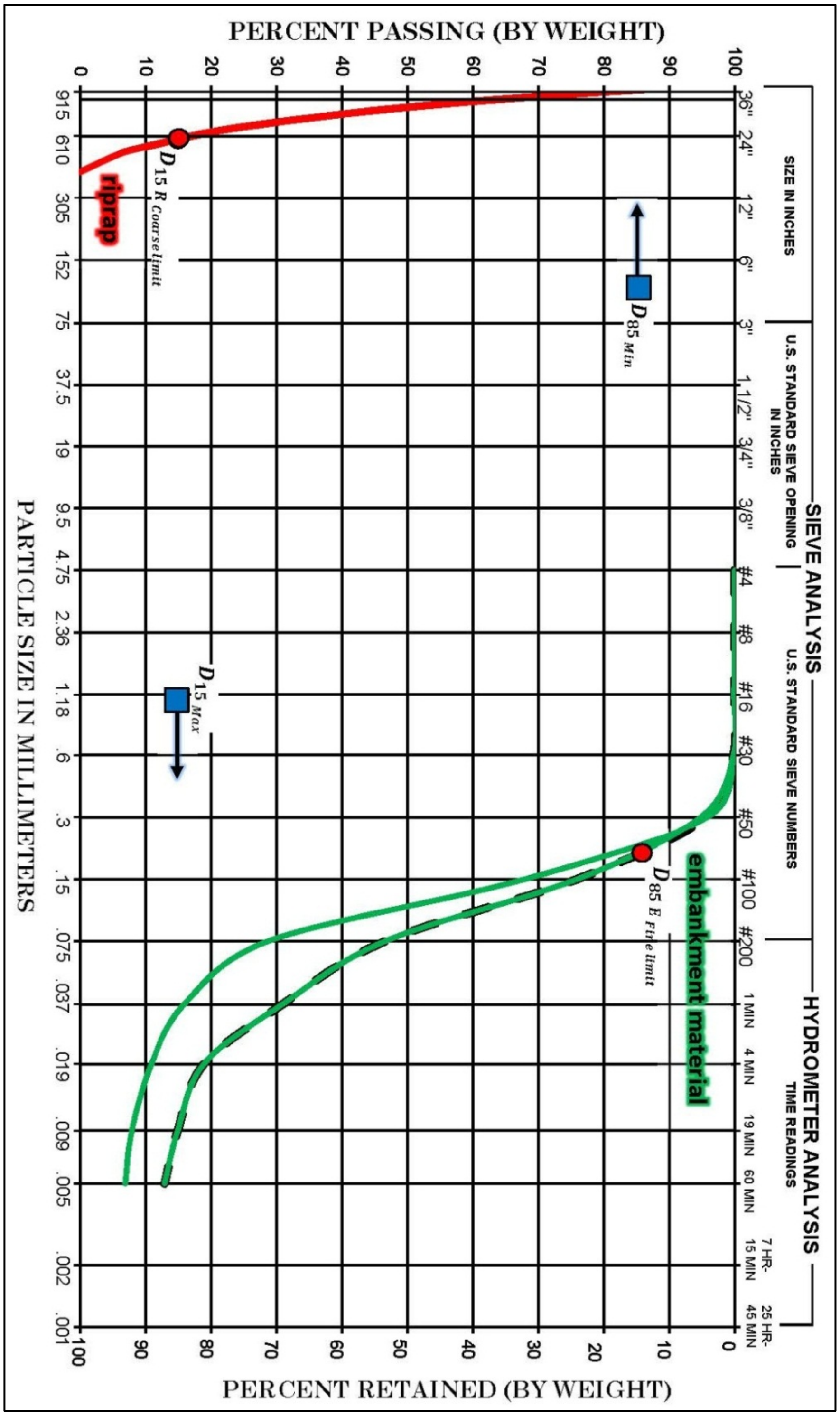


Figure 7.3.7.3-1. Bedding sizes required for particle retention $D_{15\ Max}$ and $D_{85\ E\ Fine\ limit}$ depicted by blue squares.

$$D_{10\ B1_{Fine\ limit}} = \frac{D_{60\ B1_{Coarse\ limit}}}{10} \tag{16}$$

Where:

$D_{10\ B1_{Fine\ limit}}$ = The 10-percent passing size of the fine-limit curve of the first layer of bedding material

3. A straight line is drawn between the $D_{85\ B1_{Fine\ limit}}$ and $D_{10\ B1_{Fine\ limit}}$ points to define the central portion of the fine-limit curve. The top of this line should be extended to intersect the 100-percent passing line. The bottom of this line should be curved to allow the bedding to contain some finer materials (see figure 7.3.7.5-3, which appears later in this chapter, or appendix C, figure C.6).

4. To define the coarse-limit curve, a straight line is drawn parallel to the straight portion of the fine-limit curve. This line should pass through the point, $D_{60\ B1_{Coarse\ limit}}$, and can be extended at the top towards the 100-percent-passing line, and at the bottom towards the 0-percent-passing line.

Table 7.3.7.4-1 presents a summary of the points used for this method.

Table 7.3.7.4-1. Points used to define bedding gradation

Particle size (X-axis)	Percent passing (Y-axis)	Bedding band curve
$D_{85\ B1_{Fine\ limit}}$	85	Fine-limit curve
$D_{10\ B1_{Fine\ limit}}$	10	Fine-limit curve
$D_{60\ B1_{Coarse\ limit}}$	60	Coarse-limit curve

Minor modifications can be made to the gradation band as needed. Modifications that can be considered include:

- Curvature: Adding slight curvature to the coarse- and fine-limit curves (figure C.7)
- Widening: Widening the vertical distance between the coarse- and fine-limit curves (to a maximum of 35 percent)
- Narrowing: Decreasing the vertical distance between the coarse- and fine-limit curves (to a minimum of 20 percent)

- Steepening: Steepening the coarse- and fine-limit curves, which can be accompanied by a widening of the band
- Flattening: Flattening the coarse- and fine-limit curves, which is often accompanied by a narrowing of the band to meet C_u criteria

When any modifications are made, the gradation must be checked to ensure conformity to the criteria presented in equations 12, 13, and 14.

7.3.7.5 Using a Second Bedding Layer

If the coarse-limit curve of the bedding gradation designed above lies to the right of (is smaller than) the $D_{15_{Max}}$ point, the bedding material will be adequate to retain the embankment material. However, multiple bedding layers may be needed (figures 7.3.7.5-1 and 7.3.7.5-2) if the coarse-limit curve lies to the left of (is larger than) the $D_{15_{Max}}$ point, because the bedding material may not otherwise be able to retain the embankment material (figure 7.3.7.5-3).

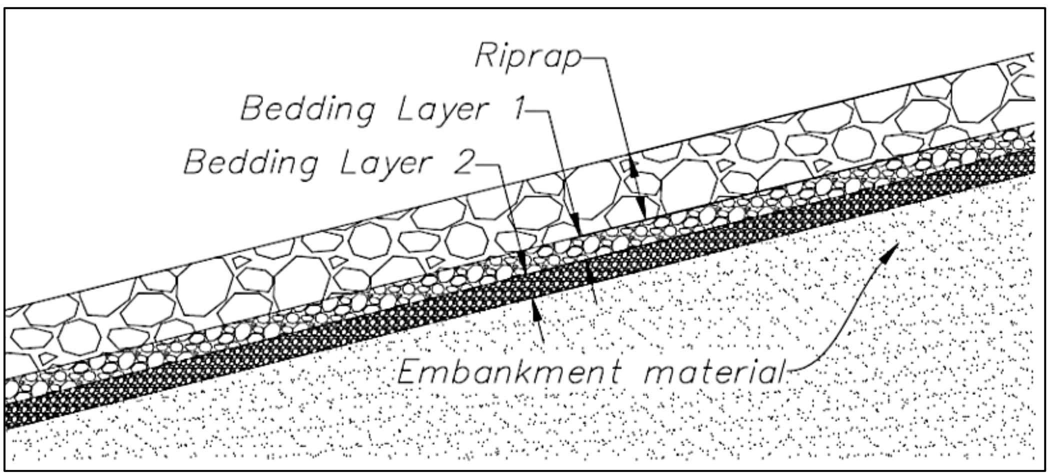


Figure 7.3.7.5-1. Bedding material instability.

The first bedding layer is defined using the method presented in section 7.3.7.4. The second bedding layer is designed relative to the first bedding layer in a similar manner (figure 7.3.7.5-3).

Figure 7.3.7.5-2. Photo presenting use of two bedding layers.

The 15-percent-passing size of the coarse-limit curve of the first bedding layer, $D_{15\ B1_{Coarse\ limit}}$, is determined visually from the coarse-limit curve constructed in section 7.3.7.4:

1. The 15-percent-passing size of the coarse-limit curve of the first bedding layer, $D_{15\ B1_{Coarse\ limit}}$, is determined visually from the coarse-limit curve constructed in section 7.3.7.4.

2. $D_{85\ B2_{Fine\ limit}}$ is determined from $D_{15\ B1_{Coarse\ limit}}$ as:

$$D_{85\ B2_{Fine\ Limit}} \geq \frac{D_{15\ B1_{Coarse\ Limit}}}{5} \qquad (17)$$

Where:

$D_{85\ B2_{Fine\ limit}}$ = The 85-percent-passing size of the fine-limit curve of the second bedding layer.

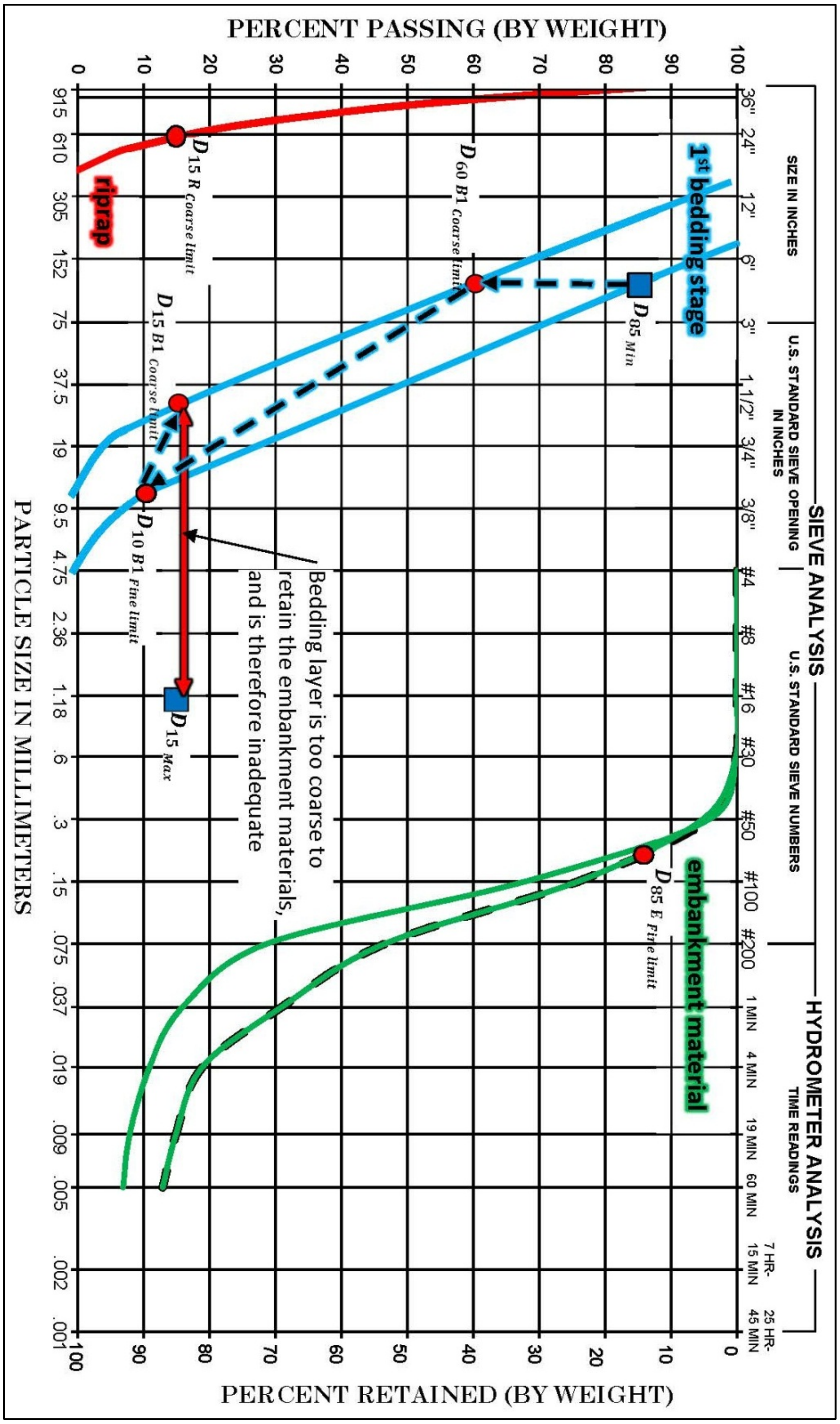


Figure 7.3.7.5-3. First bedding layer is inadequate because $D_{15\ B1_{Coarse-limit}}$ is greater than $D_{15\ _{Max}}$. The blue dashed arrows indicate the order in which the points are calculated when constructing the bedding gradation band (section 7.3.7.4).

3. To ensure that the bedding's coefficient of uniformity, C_u, will be less than 10, $D_{10\ B2\ _{Fine\ limit}}$ should be calculated to define the 10-percent-passing size of the fine-limit curve:

$$D_{10\ B2\ _{Fine\ limit}} = \frac{D_{60\ B2\ _{Coarse\ limit}}}{10} \tag{18}$$

Where:

$D_{10\ B2\ _{Fine\ limit}}$ = The 10-percent-passing size of the fine-limit curve of the second bedding layer.

4. A straight line is drawn between the $D_{85\ B2\ _{Fine\ limit}}$ and $D_{10\ B2\ _{Fine\ limit}}$ points to define the central portion of the fine-limit curve. The top of this line should be extended to intersect the 100-percent-passing line. The bottom of this line should be curved to allow the bedding to contain some finer materials (see appendix C, figure C.6).

5. To define the coarse-limit curve, a straight line is drawn parallel to the straight portion of the fine-limit curve. This line should pass through the point, $D_{60\ B2\ _{Coarse\ limit}}$, and can be extended at the top towards the 100-percent-passing line, and at the bottom towards the 0-percent-passing line.

6. The last step is to ensure that the second bedding layer will retain the embankment materials. $D_{15\ B2_{Coarse\ Limit}}$ is determined visually from the coarse-curve of the second bedding layer, constructed in step 5. This value should be finer than the $D_{15_{Max}}$ (from equation 14), which was derived at the beginning of section 7.3.7.3:

$$D_{15\ B2\ _{Coarse\ Limit}} < D_{15_{Max}} \tag{19}$$

Where:

$D_{15\ B2\ _{Fine\ limit}}$ = The 15-percent-passing size of the fine-limit curve of the second bedding layer.

The order of the steps presented above and from section 7.3.7.4 is visually presented in figure 7.3.7.5-4. If the criteria presented in sections 7.3.7.1 through 7.3.7.3 are still not satisfied using steps 1 through 6, the bedding gradations may be modified slightly to meet the criteria (figure 7.3.7.5-5) as discussed in section 7.3.7.4. Alternatively, a third bedding layer may be used if it is more cost effective and still meets retention and stability criteria.

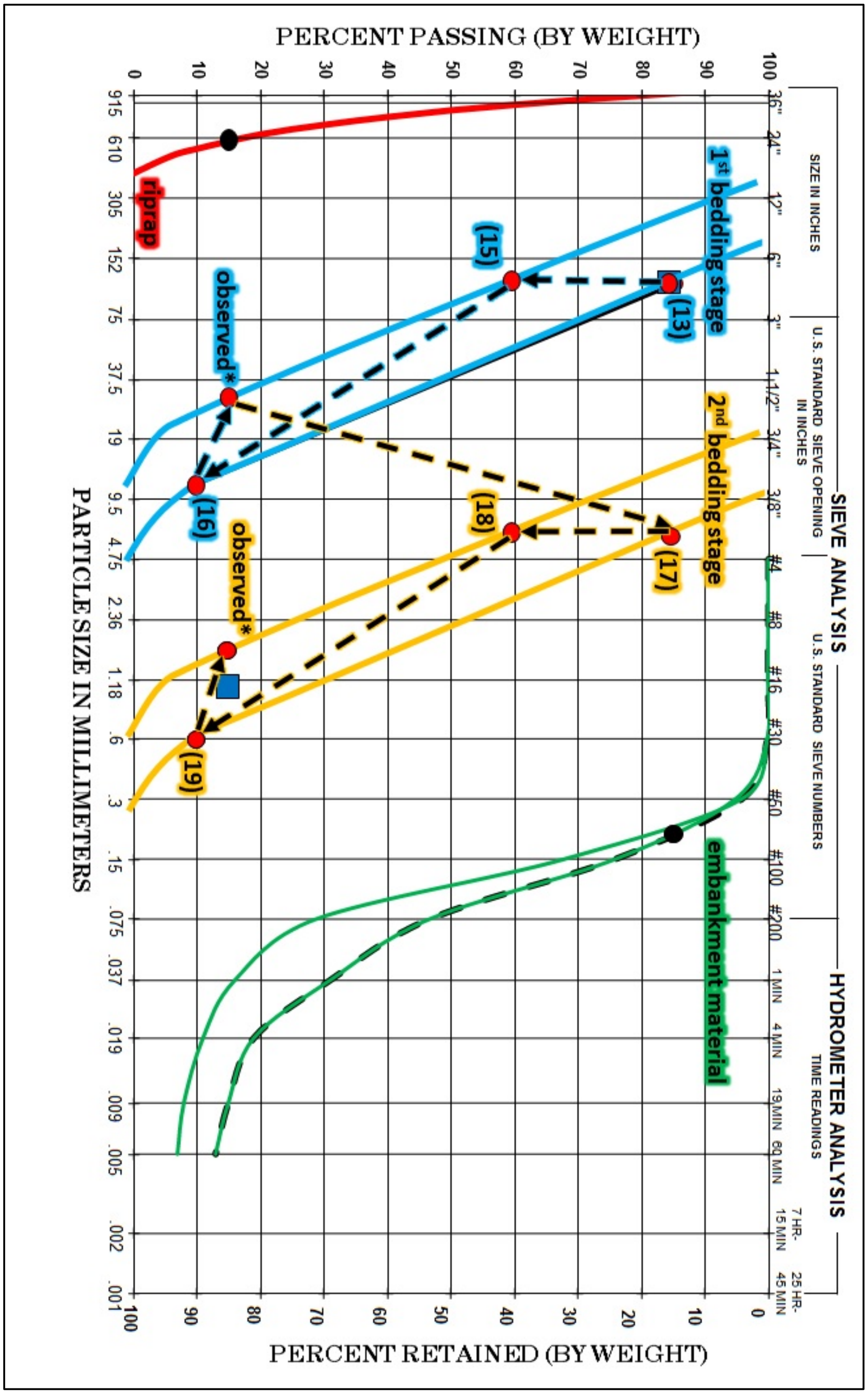


Figure 7.3.7.5-4. Steps used to define gradation bands for two layers of bedding. Blue arrows indicate steps used to define the first layer. Orange arrows indicate steps used to define the second layer. Numbers highlighted in blue indicate the equation used to determine the location of the point. The size of points with the "observed*" label are estimated from the gradation band after it is constructed.

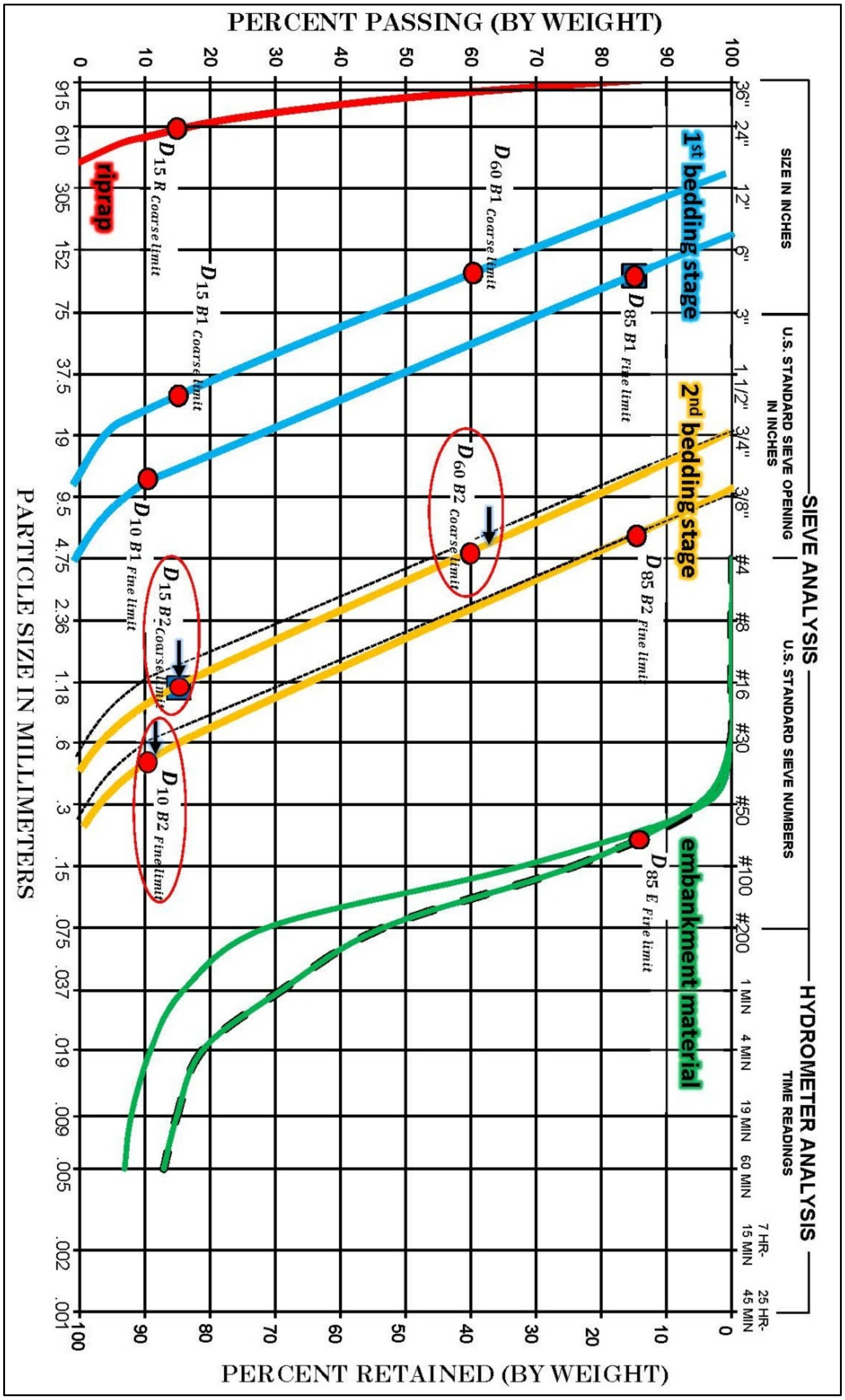


Figure 7.3.7.5-5. Modified second bedding layer. Circled points were translated right to meet $D_{15_{max}}$ criteria, resulting in a more broadly graded (flatter) gradation. Coarse- and fine-limit curves were moved closer together to meet stability criteria (C_u >10).

7.3.7.6 Bedding Layer Thickness

The thickness of the bedding layer(s) needs to be sufficient to provide filter protection and support for the riprap. Riprap particles will partially penetrate the bedding layer and will derive some stability from this. Table 7.3.7.6-1 provides minimum bedding thicknesses for several riprap thicknesses using the conventional design approach for bedding. If multiple bedding layers are designed, each layer should be designed with the thickness recommended from table 7.3.7.6-1.

Table 7.3.7.6-1. Thickness of riprap bedding

Thickness of riprap (inches)	Minimum bedding thickness (inches)
12-24	12
24-36	15
>36	18

7.3.8 Additional Riprap Design Considerations

Each design should produce a specification that defines material gradations and layer thicknesses to economically provide the riprap and bedding layers required to protect the embankment. If appropriate sources for riprap are known, have been tested, and are of acceptable quality, they should be identified in the specification. The specification should also include minimum rock quality requirements for riprap (such as specific gravity, sodium sulfate soundness, and Los Angeles (L.A.) abrasion if other sources may be used that have not been tested.

The top of dam (crest) elevation is usually selected much earlier in the design process than is the slope protection. When the slope protection design is selected, the top of the dam elevation should be reviewed to ensure that the run-up computations are consistent with the type of slope protection. The slope protection provided on the upstream slope near the dam crest must also be consistent with the design wave used to establish the top of dam elevation.

7.4 Construction

Test quarries (or test areas within a quarry or borrow area) may be specified if there is uncertainty in the ability of the rock sources to produce adequate quantities of appropriate rock sizes, shapes, or quality for the riprap slope protection.

Riprap must be placed carefully to avoid segregation (figure 7.4-1). Riprap does not need to be compacted, but it should be dumped or placed in a manner that ensures that the particles are uniformly distributed (reasonably well-graded) so that smaller particles fill the voids between the larger particles and result in well-keyed, dense, and uniform layers. Rearrangement (by hand or using construction equipment) to achieve an acceptable distribution of particles is usually required to achieve the above. ASTM Designation D 6825-02, “Standard Guide for Placement of Riprap Revetments” covers methods of riprap placement. ASTM Designation D 5519-94 (2001), “Standard Test Method for Particle Size Analysis of Natural and Man-Made Riprap Materials,” describes field test methods for measuring the onsite gradation of riprap. More information is available on the construction of riprap in *Design Standard No. 13, Embankment Dams*, Chapter 10, “Embankment Construction” [17], section 10.6.8.2.1.

Figure 7.4-1. Careful placement of riprap (note the small drop height.

7.5 Alternative Slope Protection Methods

The design of slope protection other than riprap is not covered in this design standard chapter; however, some discussion of alternatives to riprap is provided in the following paragraphs. Alternative slope protection designs that are functional and cost effective should be considered. Factors that influence the selection of alternative slope protection methods include, but are not limited to: (1) the potential for embankment damage, (2) the materials available from required excavations, (3) haul distances, and (4) the quality of rock from offsite quarries.

A viable alternative to the designed riprap layer may be a rockfill zone of greater thickness containing lower quality rock that does not meet the designed riprap gradation and material quality requirements.

When an upstream rockfill zone is used, rather than a designed riprap layer, the rock is generally dumped, spread, and then processed by using rock rakes to move the larger rock to the outer slope. The rockfill on the outer slope of an embankment dam that provides slope protection should meet all of the criteria stated in this chapter for riprap rock sizing and quality. Rockfill is also usually compacted. The smaller sizes that remain inside the zone of large material serve as a filtered bedding zone. The size of rock particles in the outer zone can be partially controlled by blasting techniques, handling of the rock, and by the tooth spacing on the rock rake. The outer zone of large stone should produce a thickness considerably greater than the required layer thickness for the designed riprap to account for the fact that the rock is of lesser quality or poorer gradation.

When natural rock of adequate quality is in short supply, another alternative to riprap is soil-cement (figure 7.5-1). The design of soil-cement is covered in *Design Standards No. 13, Embankment Dams*, Chapter 17, "Soil-Cement" [1]. Potential issues when using soil-cement include: poor bonding at lift lines, insufficient durability (especially with exposures to wind and ice in very cold climates), availability of cement, high cost of cement, inappropriate mix designs, adequacy of a suitable aggregate supply, brittleness, inadequate drainage, placement inefficiency, inadequate construction quality control, aesthetics, etc.

Figure 7.5-1. Typical aged soil-cement slope protection.

Sometimes grout is used to stabilize riprap as well. By filling the voids between the rock fragments, the rock fragments become interlocked and cemented together, providing increased stability (figure 7.5-2). Lean grout (flowable, high slump, controlled low-strength material (CLSM) [18]) is used to permit gravity flow of the grout into the voids surrounding the riprap particles. Grouted riprap also offers additional resistance to erosion and may allow a thinner layer of riprap. Usually, a significant amount of spading, probing, or hand tamping, known in the field as "cramming the grout," is required to maximize the depth of penetration of the grout into the riprap. Drainage beneath or through grouted riprap zones (by means of weep holes) is often required to avoid uplift or blowout concerns. Partially grouted riprap (PGR) or matrix riprap is a special kind of grouted riprap that is used often in Europe. In this construction technique, dumped riprap is partially grouted with the intent to primarily place the grout at the points of contact between stones but not fill the entire void space. Typically, the grout of this technique might fill about one-third to one-half of the total void space. The objectives of PGR are threefold:

1. To produce conglomerated riprap particles that are effectively much larger than the base size of the stones and are tightly interlocked with adjacent conglomerates of riprap.

2. To produce a riprap layer that remains flexible and able to adjust itself to future settlement and shifting of the underlying materials.

3. To produce a riprap layer that is porous and able to relieve any buildup of pore-water pressure that might occur beneath the riprap when flow takes place over or through the riprap.

When design wave heights exceed 6 or 7 feet, it may not be possible to obtain the very large rock particle sizes necessary from natural sources. In these cases, riprap units made of concrete are a possible alternative [19]. These slope protection units can be sized using a form of equation 2, and they can be constructed in various shapes (i.e., dolos, cube, tetrapod, etc.). It should be pointed out that it is often difficult to design adequate filter zones between these riprap units and embankment materials and that these are much more expensive than natural rock.

Concrete can also be used in the form of articulated concrete-blocks (ACB). However, the use of ACB's for embankment upstream slope protection is not common at Reclamation, and the appropriate design should be reviewed by a consultant familiar with ACB use.

Geotextiles have been used in place of riprap bedding (figure 7.5-3). There are, however, a number of issues to be addressed with this type of design, including: (1) stability along both the top and bottom surface of the geotextile, (2) filter compatibility of the geotextile with the underlying embankment materials,

(3) proper support for the geotextile, and (4) survivability. Survivability refers to the ability of the geotextile to avoid excessive damage when placed against a rough or angular subgrade or riprap materials, or upon impact of riprap during placement if drop heights are not minimized or carefully controlled. Geotextile design is covered in *Design Standards No. 13, Embankment Dams*, Chapter 19, “Geotextiles” [20].

Figure 7.5-2. Grouted riprap in drop structures downstream from Ridges Basin Dam.

Figure 7.5-3. Riprap being placed on a geotextile serving as bedding.

7.6 References

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[22] ASTM International. 2007. *Standard Practice for Evaluation of Rock to be Used for Erosion Control.* ASTM Standard D 4992-07, American Society for Testing of Materials, West Conshohocken, Pennsylvania.

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Appendix A

Appendix A-1

Definitions

20-percent band	Riprap gradation band with a minimum of 20-percent vertical separation between the fine-limit and coarse-limit curves to provide for a constructible material (in terms of material availability) and minimize the potential for segregated or gap graded riprap placements.
35-percent band	Riprap gradation band with a maximum of 35-percent vertical separation between the fine-limit and coarse-limit curves to increase constructability (in terms of material availability) while continuing to avoid segregated or gap graded riprap placements.
Bedding	Zone(s) serving as a filter between the embankment materials and the riprap designed to retain embankment material and be retained by the riprap.
Collapsing breaker	A breaking wave in an intermediate condition in which breaking occurs over the lower half of the wave, and an irregular turbulent water surface advances up the embankment.
Fetch	An average horizontal distance in the general direction (within 24 degrees) of the wind over water.
Nonexceedance probability	The probability of an event not being exceeded during a given design time period.
Plunging breaker	A breaking wave in which the wave crest curls over the face and falls onto the base with a high splash.
Probability of exceedance	The probability that an event of a given magnitude will be exceeded within a certain time period.
Riprap	A protective layer of durable rock fragments that is usually well graded within wide size limits and placed to prevent erosion, beaching, scour, or sloughing of an underlying slope; also the stone that is used.

Significant wave height	The average height of the highest one-third of the waves for a stated wave group.
Stone	An individual rock fragment.
Surging breaker	A breaking wave in which the wave crest remains unbroken while the base of the wave advances up the embankment.
Tolerable damage limit	Level of damage where a considerable amount of riprap displacement has occurred, but no bedding material has been lost and no embankment material has been pulled through the bedding or riprap layers. Periodic maintenance of the riprap is expected, and planning for this may include constructing stockpiles of riprap near the dam and arranging for the resources needed to place the material.
Wave height	The vertical distance between a wave crest and the preceding trough.
Wave length	The horizontal distance between similar points on successive waves.
Wave period	The time for two successive wave crests to pass a fixed point. The time for a wave crest to travel a distance equal to one wavelength.
Zero damage level	Condition where no damage occurs to the riprap layer, and very little, if any, movement of the riprap occurs.

Appendix A-2

Coefficients

For various coefficients used in the empirical riprap equations (e.g., equation 2 of this chapter)

Source	Coefficients			Remarks
	a	b	K	
Hudson and Jackson (1962) (U.S. Army Corps of Engineers Coastal Engineering Research Center, 1973)	3	1	2.2	K=2.2 for breaking waves
	3	1	2.5	K=2.5 for nonbreaking waves
Thomsen, Wohlt, and Harrison (1972)	3	0	14	K=14, slope of 1:2
	3	0	18	K=14, slope of 1:2.5
	3	0	27	K=14, slope of 1:3
	3	0	51	K=14, slope of 1:5
EM1110-2-2300 U.S. Army Corps of Engineers (1971)	2	1	1.36	
Technical Memo 51 U.S. Army Corps of Engineers (1975) [11][1]	3	0.67	3.62	Average zero damage level for the worst wave conditions
	3	1.00	4.37	Average limit of tolerable damage for the worst wave conditions
Beene and Ahrens (1973)	3	1	2.63	Zero damage level

[1] Adopted Reclamation method.

Appendix B

Procedure for Sampling and Quality Evaluation Testing of Rock for Riprap Slope Protection

Designation USBR 6025-09

Procedure for Sampling and Quality Evaluation Testing of Rock for Riprap Slope Protection

This procedure is under the jurisdiction of the Materials Engineering and Research Laboratory, code 86-68180, Technical Service Center, Denver, Colorado. The procedure is issued under the fixed designation USBR 6025. The number immediately following the designation indicates the first year of acceptance or the year of last revision.

1. 1. Scope

1.1 *Application.*-This designation covers the sampling and quality evaluation testing of rock from operating quarries, potential quarries, talus slopes, or stream-deposited boulders for slope protection (riprap).

1.2 *Additional Use.*-This procedure also provides useful information for:

- Control of operations at the source of supply
- Control of operations at the site of use
- Acceptance or rejection of materials

1.3 *Units.*-The values stated in SI/metric (inch-pound) units are to be regarded as standard.

1.4 *Caveats.*-This designation does not purport to address all the safety issues associated with its use and may involve use of hazardous materials, equipment, and operations. The user has the responsibility to establish and adopt appropriate safety and health practices. Also, the user must comply with prevalent regulatory codes while using this procedure.

2. Applicable Documents

2.1 USBR Procedures:

USBR 4075 - Sampling Aggregates

USBR 4088 - Soundness of Aggregates Using Sodium Sulfate

USBR 4127 - Specific Gravity and Absorption of Coarse Aggregate

USBR 4131 - Resistance to Degradation of Small Size, Coarse Aggregate by Abrasion and Impact in Los Angeles Machine

USBR 4295 - Petrographic Examination of Aggregate for Concrete

USBR 4666 - Resistance of Concrete to Rapid Freezing and Thawing

USBR 4702 - Reducing Field Samples of Aggregate to Testing Size

2.2 ASTM Documents:

ASTM C 294 - Standard Descriptive Nomenclature for Constituents of Natural Mineral Aggregates

ASTM D 4992 - Standard Practice for Evaluation of Rock to be Used for Erosion Control

ASTM D 5121 - Standard Practice for Preparation of Rock Slabs for Durability Testing

2.3 Other Documents:

Design Standards No. 13- Embankment Dams, Chapter 7 - Riprap Slope Protection - Bureau of Reclamation, 1992.

Report No. REC-ERC-73-4 - Riprap Slope Protection for Earth Dams: A Review of Practices and Procedures.

OSHA Regulations (29 CER, CH. XVII, 1926.900-.950, 1989), Blasting Safety.

Design of Small Dams, Bureau of Reclamation, 3rd Edition, 1987.

Engineering Geology Office Manual, Bureau of Reclamation, 1988.

Engineering Geology Field Manual, Bureau of Reclamation, 1989.

Construction Safety Standards, Bureau of Reclamation, 1987.

Petrographic Laboratory Analytical Techniques and Capabilities Reference, pp. 6-8, Bureau of Reclamation, September 1985 .

3. Summary of Method

This procedure describes the various states of riprap investigations. Representative rock samples obtained from quarries, borrow areas, or talus slopes are petrographically classified and physical properties (including freeze-thaw durability> are determined.

Laboratory test data are used to evaluate rock quality sad suitability for potential riprap slope protection placements in critical structure zones subject to severe wave action and environmental exposure conditions

4. Significance and Use

4.1 *Slope Protection.*-This practice provides recommendations for investigation, sampling, and quality evaluation testing of riprap rock fragments for use as slope protection. Production sources should produce rock fragments in suitable sizes for the required usage. The fragments should be sufficiently hard, dense, and durable to withstand processes in procurement, transportation, placement, weathering, and the physical forces of nature such as wind and wave action, freezing and thawing, wetting and drying, as well as heating and cooling. Investigations must identify a sufficient quantity of material of required quality.

4.2 *Embankment Dams.*-Most embankment dams built by Reclamation contain one or more zones that require the production of rock. The rock is used as riprap for protection against erosion, or as rockfill or filter zones that strengthen or drain the embankment, thereby increasing its degree of stability. Riprap blankets are also commonly required below spillway and outlet works stilling basins and for canal and channel protection.

4.3 *Preparation.*-Production of such rocks generally requires drilling, blasting, and processing to obtain the required sizes.

4.4 *Riprap.*-Igneous, metamorphic, and sedimentary rocks can be used for the production of riprap.

5. Apparatus

5.1 *Excavating Equipment.*-Equipment such as bulldozers, backhoes, draglines, bucket augers, core drills, and jackhammers.

5.2 *Blasting Equipment*.-Dynamite, blasting caps, and drills for providing holes for setting blasting charges.

5.3 *Production evaluation*.-Survey equipment and truck weigh scales for production evaluation.

5.4 *Saw*.- A diamond, slab, or other saw of suitable size and quality to prepare cubical rock specimens from the sample.

5.5 *Miscellaneous Materials*.-Bags and pallets for transporting and handling samples.

6. Precautions

6.1 *Hazardous Materials*.-This test procedure may involve hazardous materials, operations, and equipment and does not claim to address all safety problems associated with its use. The user has the responsibility to consult and establish appropriate safety and health practices and determine applicability of regulatory limitations prior to use.

6.2 *Qualified Personnel*.-Personnel shall be well versed in handling the above equipment. Only qualified and authorized persons shall be permitted to handle and use explosives.

6.3 *Safety Standards*.-Blasting safety must be executed in accordance with Reclamation Construction Safety Standards and the OSHA regulations (29 CFR, CH.XVII, 1926.900- .950, 1989) whichever is more stringent.

7. Source Investigation Stages

7.1 *General*-The complexity of investigations to determine suitable sources of riprap materials will be governed by project development stage and design requirements of the project features. Normally, project development occurs in four stages: reconnaissance, feasibility, specifications, and construction.

7.1.1 *Reconnaissance*.-Initial or preliminary exploration involves field surface reconnaissance using topographic, geologic, and agricultural soil maps and aerial photographs with supplemental information provided by records of known developed sources of material. A study of maps and aerial photographs may reveal possible sources of material. Contours are often an indication of the type of material; sharp breaks usually indicate hard rock, and slopes below cliffs often have talus deposits. During field reconnaissance, the countryside should be examined for exposed rock outcrops or cliffs. Road cuts and ditches may also reveal useful deposits. Data obtained should define the major advantages or disadvantages of potential materials sources within reasonable haul distance to the job site. Reporting accumulated data and information at this stage of investigation is accomplished by construction materials reports to the Technical Service Center.

7.1.2 *Feasibility*.-Information accumulated during this stage is needed to prepare preliminary designs and cost estimates. Sufficient information concerning potential sources should be gathered to determine whether the Government should acquire the source or if the rock should be furnished by the contractor. Selection of sources should be limited to those which may eventually be cited in specifications. Core drilling or blast tests may be required to confirm fragment size and quantity of material available in the sources. The potential material sources are examined to determine size and character, and particularly to observe joint and fracture spacing, resistance to weathering, and variability of the rock. The spacing of joints, fractures, schistosity, lineations, bedding, and other planes of weakness may control the size of rock fragments obtainable from the deposit. Observation of weathering resistance of rock *in situ* will provide a good indication of its durability. Particular attention should be given to location and distribution of unsound seams or strat which must be avoided or wasted during quarrying operations. A general location map and report describing the potential sources and containing estimates of available quantities, overburden, haul roads, and accessibility are prepared. Representative samples of riprap material from the most promising potential sources are required to be submitted to the Materials Engineering and Research Laboratories in Denver or other approved laboratory for quality evaluation tests. The extent and detail of information necessary at this stage is described in section 7.

7. 1.3 *Specifications.*-Investigations at this stage furnish design data and information required for specifications preparation. Exploration requests issued by the Technical Service Center will define requirements for riprap materials investigations. Sources indicated by feasibility investigation data to be of suitable quality for project feature work are surveyed and investigated to establish the quantity of material available and determine its uniformity.

7.1.3.1 Core drilling may be required, if dictated by geologic conditions. Such core drilling should be done on a grid system, if appropriate, and should include both vertical and angled holes as directed by the geologist or materials engineer. Blast testing should also be done at this time if not performed previously. Blast testing data shall be submitted to the Technical Service Center in the form of construction reports suitable for reference by the specifications. Sampling and testing should also be completed during this stage.

7.1.3.2 If additional deposits are considered at this stage, they must be investigated as thoroughly as the originally considered source or sources.

7.1.4 *Construction.*-Investigations during the construction stage are sometimes required to provide field and design personnel with additional detailed information for proper source development. This information should be obtained sufficiently ahead of quarrying or excavation operations to provide for proper processing and placing of material. If unforeseen changes occur in quality of material being removed from the source, sampling and quality evaluation testing of the rock may be required to confirm material suitability or delineate unsuitable rock areas.

8. Source Information

8 1 *Background.*-Reporting information and data accumulated during any investigation stage is most important. Although detailed information requirements increase with each successive stage, adequate information must be available by the feasibility stage to develop realistic cost estimates and properly select sources for possible use.

Required data obtained earlier than needed should be submitted when available and not withheld. For feasibility studies, the designers should have sufficient information to supplement laboratory test data to determine whether the Government should acquire the source, whether the rock should be furnished by the contractor, or whether other types of embankment protection should be considered. A suggested outline for riprap reports for rock obtained from an undeveloped quarry is:

a. Ownership

b. Location, indicated by map, with reference to the U.S. Public Land Survey legal description (section, township, range, and meridian). If, as will be the case in unsurveyed areas, the legal description is unavailable, the latitudinal and longitudinal coordinates (degrees, minutes, and seconds) should be obtained.

c. General description

d. Geologic type arid classification

e. Joint spacing and fracture systems

f. Bedding and planes of stratification

g. Manner and sizes in which rock may break on blasting as affected by jointing, bedding, or internal stresses

h. Shape and angularity of rock fragments

i. Hardness and density of rock

j. Degree of weathering

k. Any abnormal properties or conditions not covered above

l. Thickness, extent, estimated volume, and average depth of deposit type, extent, and thickness of overburden

m. Accessibility (roads affording access to highways or railroad, giving distance, load limitations, required maintenance, whether privately owned, and other pertinent information)

n. Photographs and any other information which may be useful or necessary

8.2 *Quarry*.-If commercial quarry deposits are considered, the following information should be obtained and included in the report:

a. Name and address of plant operator; if quarry is not in operation, a statement about ownership or control

b. Location of plant and quarry

c. Age of plant (if inactive, approximate date when operations ceased)

d. Transportation facilities and difficulties

e. Deposit extent, plant and stockpile capacity

f. Plant description (type and condition of equipment for excavating, transporting, crushing, classifying and loading, and restrictions, if any)

g. Approximate percentages of various sizes of material produced by the plant

h. Location of scales for weighing shipments

i. Approximate prices of materials at the plant

j. Principal users of plant output

k. Service history of material produced l. Any other pertinent information

8.3 *Nonquarry*.-When rock deposits other than quarries are considered for riprap use, the rock properties and deposit should be described in the same manner as for quarry rock where applicable and, in addition, the deposit description should indicate shape, average size, and variation in sizes of the rock.

8.4 *Data Sheet.*-A typical source information data sheet is shown on figures 1 and 2.

9. Sampling

9.1 *Representation.*-Sampling, often a weak link in the chain of investigative procedures, is equally important as testing, and the sampler shall use every precaution to obtain samples that will show the nature and condition of the materials which the samples represent. Thus, sampling must be carefully performed by qualified, experienced personnel.

9.2 *Reports.*-Sampling is initiated at the specifications development phase of the project. Sampling is requested by exploration or design data requests, which should delineate size and location requirements for the riprap source. Detailed reports of investigations are submitted to the Technical Service Center as part of design data or Construction Materials reports.

9.3 *Size.*-The sample size should be at east 275 kg (600 lbm) and represent proportionally the quality range from poor to medium to best as found at the source. If the material quality is quite variable, it may be preferable to obtain three samples which represent, respectively, the poorest, medium, and best quality material available. The minimum size of individual fragments selected should be at least 0.014 m^3 (1/2 ft^3) in volume, if possible. An estimate of the relative percentages of each material quality should be made and included as information relating to the source. Samples from undeveloped sources must be very carefully chosen so that the material selected will, as far as possible, be typical of the deposit and include any significant rock-type variations.

9.3.1 Representative samples may be difficult to obtain. Overburden may limit the area from which material can be taken and obscure the true character of a large part of the deposit. Surface outcrops will often be more weathered than the ‘interior of the deposit. Samples obtained from loose rock fragments on the ground or collected from weathered outer surfaces of rock outcrops are seldom representative. Fresh material may be obtained by breaking away the outer surfaces, or by trenching, blasting, or core drilling. In stratified deposits such as limestones or sandstones, vertical and horizontal uniformity must be evaluated, as strata often differ in character and quality.

9.3.2 The dip of stratified formations must also be considered. Strata inclination with respect to surface slope will expose different strata at the surface in different parts of the area. Attention should be directed to the possibility of zones or layers of undesirable material. Clay or shale seams may be so large or prevalent as to require selective quarrying or excessive wasting of undesirable material.

9.4 Shipping Samples:

9.4.1 Samples of rock fragments can be shipped by conventional transport such as motor freight. Large rock fragments should be securely banded to shipping pallets. Smaller fragments should be transported in bags or containers to preclude loss, contamination, or damage from mishandling during shipment.

9.4.2 Shipping containers for rock fragments shall have suitable individual identification attached and enclosed. A data sheet outlining details of the shipped sample should be included. It is often desirable to identify individual rock fragments by painted numbers or similar markings.

10. Procedure

10.1*Tests*.-Quality evaluation tests performed in the Technical Service Center laboratories on representative samples submitted from the field include detailed petrographic examination, determination of physical properties, and rapid freeze-thaw durability tests. These tests serve as a guide for determining if the material can be considered acceptable for use as riprap or rockfill material

10.2 *Petrographic Examination*.- Laboratory petrographic examination procedures for riprap/rockfill materials are not detailed, but USBR 4295 (although developed for concrete aggregate) may serve as a guide. Decisions concerning specific procedural methods and specimen preparation depend upon the nature of the rock, the intended usage of the rock, and the petrographer's judgment.

102.1 The rock pieces comprising the sample are visually examined and different rock facies and rock types, if present, are segregated for individual evaluation. The size range and characteristic fragment shapes are noted. The rock pieces are studied to evaluate if fragment shape and/or size is determined by discontinuities such as joints, fractures, bedding planes, or shear zones. Surface weathering and secondary deposits of alkali salts or clay are noted. Fracture or vein systems are described as well as the ease with which fractures or veins can be opened. Hardness, toughness or brittleness, and visible voids or pore characteristics and their variations are noted, The texture, internal structure, grain size, and mineralogy of the various facies and rock types are determined. Special attention is given to internal voids and fractures and to the type and amount of cementing material in sedimentary rocks. Thin section analyses, sometimes supplemented by X-ray diffraction analysis, are made as required.

10.3 *Freeze-Thaw Test Specimen Preparation*-For freeze-thaw durability testing, 73-mm (2 7/8-in) cubes are sawed from rock fragments selected by visual inspection to represent the poorest, medium, and best quality rock for each rock facies or type. Because the rock pieces could exhibit significant physical or structural features (e.g., joints, fractures, bedding planes), the number of cubes obtained for testing will vary from sample to sample. Prior to freeze-thaw testing, 'before test" photographs are taken and oven-dry cube masses are determined. Before testing, the cubes are immersed in water for 72 hours and specific gravities (bulk oven-dry, bulk saturated-surface-dry, and apparent) and absorptions are determined by USBR 4127. The cubes are reimmersed in water to maintain a saturated condition for freeze-thaw testing.

10.4 *Freeze-Thaw Test Performance*.- Rapid freezing and thawing durability tests (USBR 4666) are performed on all riprap samples, including those from areas not subject to freeze-thaw environments. The test detects structural weaknesses and is a good indicator of potential rock durability.

10.4.1 After saturated-surface- day cube masses are determined, the cubes are inserted in 76-mm (3-in) square rubber sheaths and sufficient water is added to cover the specimens. The rubber sheaths containing the specimens are placed in automatically controlled freezing and thawing cabinets, where the cubes are subjected to rapidly repeated eyelet of freezing and thawing in water. Each cycle consists of 1½ hours freezing at -12 °C (10 °F) and 1½ hours thawing at 21 °C (70 °F). During the test, cube mass loss determinations are made at periodic intervals and the appearance and manner of cube deterioration is noted. Termination of the test is 250 cycles or when the rock splits or fails (see section 10.4.2).

10.4.2 The criterion for rock failure is 25 percent loss of cube mass calculated from the difference in mass between the largest cube fragment remaining after testing and the initial cube mass. Cube specimen failure modes (e.g., splitting, disaggregation, popouts, exfoliation) are noted and "after test" cube photographs are taken.
Apparent and actual mass loss values are calculated when a cube specimen fails along preexisting fractures, joints, bedding planes, or stylolites into a few large fragments. Apparent mass loss is calculated as described above, using the mass of the largest remaining fragment. Actual mass loss is calculated from the difference between the combined masses of all fragments remaining after testing and the initial cube mass.

10.5 *Physical Properties Sample Preparation and Testing* -Material remaining after petrographic examination of the rock sample (excluding any pieces selected for more detailed petrographic analysis and freeze-thaw durability tests) is crushed into 37.5- to 75-mm, 19.0- to 37.5-mm, 9.5- to 19.0- mm, 4.75-109,5-mm (1½- to 3-in. 3/4 to 1½-in, 3/8-to 3/4-in, and No. 4 to 3/8-in) size fractions. Representative samples of each size fraction are obtained for physical properties tests (USBR 4702). Physical properties tests performed on the various size fractions of crushed material are:
(a) bulk saturated-surface-dry specific gravity and absorption, USBR 4127;
(b) Los Angeles abrasion, USBR 4131; and (c) sodium sulfate soundness, USBR 4088. Typical laboratory work forms appear on figures 3 and 4.

Note 1.-Representative samples are also obtained for petrographic examination if the material is to be evaluated for use as crushed concrete aggregate.

11. Riprap Quality Evaluation Report

11.1 *Rock Type.*-Rock for riprap should be hard, dense, durable, resistant to abrasion, and free from discontinuities that will tend to increase destruction or displacement by wave action or exposure to various environmental conditions such as wetting and drying, heating and cooling, and freezing and thawing. Structural design requirements vary and each site presents unique problems. To allow designers to work within these structural and environmental parameters, the standard Reclamation riprap quality evaluation for slope protection is based upon material requirements for placements in critical zones, frequently inundated for long periods of time with fluctuating water levels, and subject to heavy wave action and severe environmental exposure conditions. Economic factors are also considered in selection of riprap material sources.

11.2 *Test Significance.*-Riprap quality evaluation reports are based on physical properties test data, freeze-thaw durability, and petrographic examination. In Reclamation's experience, no single specific test has proven to be of significantly greater importance in evaluating rock quality for riprap usage than any other single test. Petrographic analysis (although a subjective evaluation) and freeze-thaw durability tests generally provide the most reliable and consistent measure of riprap quality. Each potential riprap material is judged independently with all available test data considered. The significance of test data is discussed, if appropriate, because some materials are suitable for slope protection even though the test data indicate the rock to be of marginal or poor quality. If applicable, recommendations are presented for improving and extending the life and durability of a riprap blanket.

11.3 *Report Form.*-A typical riprap quality evaluation report form is shown on figure 5.

Form No. Bureau of Reclamation	ROCK SOURCE INFORMATION	Designation USBR 6025

TYPE of DEPOSIT
QUARRY: ☐ Undeveloped; ☐ Commercial;
☐ Talus Slope; ☐ Stream Bed; ☐ Borrow Area; ☐ Other (Describe)

OWNER (Name/Address)

PLANT OPERATOR (Name/Address)

PLANT LOCATION

PLANT DESCRIPTION: Age (If inactive, approximate date when operations ceased); Type and Condition of Equipment for Excavation, Transportation, Crushing, Classifying, Loading and Restrictions (if any).

ACCESSIBILITY/TRANSPORTATION FACILITIES

QUARRY EXTENT/PLANT and STOCKPILE CAPACITY

PERCENTAGES of MATERIAL SIZES PRODUCED/MATERIAL PRICES

LOCATION OF WEIGH SCALES

USERS of PLANT

MATERIAL SERVICE HISTORY

Figure 6025 - 1

Feature	Project	Specifications

☐ Aggregate ☐ Riprap ☐ Other: ______________________

TEST: Freeze and Thaw Durability

☐ Petrographic
☐ Routine Aggregate ☐ Concrete
☐ Routine Riprap ☐ Riprap
☐ Other: ______________________

Sample. No. ____________
Date Received ____________
Processed By ____________
Tested By ____________
Tested By ____________
Computed By ____________
Checked By ____________

Sample Source

GRAVEL or RIPRAP

Grading – USBR 4136					24-Hour Specific Gravity and Absorption – USBR 4127						
					Test Sample Mass				B-A	$\left(\frac{B-A}{A}\right)(100)$	$\left(\frac{B}{B-C}\right)$
Nominal Size Fraction		Mass Retained	Percent Retained		B SSD Mass In Air, grams	C SSD Mass In Water, grams	B-C Displaced Mass of Water grams	A Mass of Ovendry Sample in Air, grams	Absorption Mass of Water, grams	Absorption Percent	SSD Bulk Specific Gravity
Inches or No.	Mm	lbm kg	Indiv.	Cumul							
6+	150+										
3 to 6	75 to 150										
1 ½ to 3	37.5 to 75										
¾ to 1 ½	19.0 to 37.5										
3/8 to ¾	9.5 to 19.0										
No.4 to 3/8	4.75 to 9.5										
Total Gravel Mass			-	-							
FM (Fineness Modulus)		-	-								
Sand Mass			-	-							
Total Sample Mass			-	-							
Percent Sand		-		-							

	Average	Weighted	No. 4 to 1 ½ inches (4.75 to 37.5 mm) Average	Weighted
Specific Gravity	______	______	______	______
Absorption, %	______	______	______	______

Los Angeles Abrasion – USBR 4131 ☐ Grading A B C D -USBR 4535 ☐ Grading 1 2 3

		Mass, grams	Revolutions	Mass Retained No. 12 (1.70 mm), grams	Mass Loss, grams	Percent Loss
USBR 4131	Test Sample		100			
	Abrasive Charge		500			
USBR 4535	Test Sample		200			
	Abrasive Charge		1000			

	Grading (As Received) USBR 4136								Grading (Washed) USBR 4136							
	Sample No. 1			Sample No. 2			Average									
	Mass Ret., grams	% Retained		Mass Ret., grams	% Retained		% Retained		Mass Ret., grams	% Retained		Mass Ret., grams	% Retained		% Retained	
		Cum.	Indiv.		Cum.	Indiv.	Cum.	Indiv.		Cum.	Indiv.		Cum.	Indiv.	Cum.	Indiv.
*No.4 (4.75 mm)																
No. 8 (2.36 mm)																
No. 16 (1.18 mm)																
No. 30 (600 µm)																
No. 50 (300 µm)																
No. 100 (150 µm)																
No. 200 (75 µm)																
Pan																
FM	-			-					-			-				
Washed Mass	**		-	**												

* Indicates oversize
**Indicates mass for USBR 4117

COLOR ☐ As Received ☐ Washed — Organic Impurities – USBR 4040

As Received	Clear	1	2	3 (Std.)	4	5
Washed	Clear	1	2	3 (Std.)	4	5

Material Passing No. 200 (75 µm) Sieve USBR 4117

Test Sample Mass
Dry (B) =
Washed (C) =
Minus No. 200 (75µm)
(B-C) =
Passing No. 200 (75µm)
$\frac{B-C}{B}(100)$ = __%

24-Hour Specific Gravity and Absorption – USBR 4128

Sample ☐ As Received ☐ Washed

Specific Gravity

Jar No. ____ Water Temp. = ____ °F (°C)
SSD Sample Mass (B) =
Jar Calib. Mass (E) =
Total Mass (B+E) =
Jar Sampl, Water (F) =
Displacement (B+E-F) =
Specific Gravity
$\left(\frac{B}{B+E-F}\right)$ =

Absorption

Sample Mass
SSD (B) =
Dry (A) =
Absorption,
Water (B-A) =
Absorption
$\left(\frac{B-A}{A}\right)$ (100) = ________ %

Remarks:

Remarks:

Figure 6025 – 2 (Sheet 1 of 2)

Sodium Sulfate Soundness – USBR 4088

Bowl No. Start Date Results Date

Solution ☐Fresh ☐Reused Cycles ☐5 (Std.) ☐Other

Sieve Size	Grading Standard		Grading Other	Sample Mass Before Test	Sample Mass After Test	Sample Mass Loss Actual %	Sample Mass Loss Wgt'd %
Sand							
No.8 (2.36 mm)	20						
No.16 (1.18 mm)	20						
No.30 (600 µm)	30						
No.50 (300 µm)	30						
Total Weighted	100			-	-	-	
Gravel - Riprap							
2 ½ inch (63 mm)							
1 ½ inch (37.5 mm)							
¾ inch (19.0 mm)	50						
3/8 inch (9.5 mm)	30	60					
No. 4 (4.75 mm)	20	40					
Total Weighted	100	100					

QUALITY EXAMINATION – COARSE SIZES

Sieve Size	Total Particles	Splitting No.	Splitting %	Crumbling No.	Crumbling %	Cracking No.	Cracking %	Flaking No.	Flaking %
2 ½ inch (63 mm)									
1 ½ inch (37.5 mm)									
¾ inch (19.0 mm)									

Comments:

Low Density Pieces – USBR 4123

Size / Mass	1½-3 inch (37.5-75mm)	¾-1½ inch (19.0-37.5mm)	3/8-¾ inch (9.5-19.0mm)	No.4-3/8 inch (4.75-9.0mm)	Sand +No. 30 (600 µm)
Original Sample					
Float					
% Float					

Heavy Liquid: Specific Gravity =

Clay Lumps (CL) and Friable Particles (FP) – USBR 4142

Gravel Grading					-
Size / Mass	1½-3 inch (37.5-75mm)	¾-1½ inch (19.0-37.5mm)	3/8-¾ inch (9.5-19.0mm)	No.4-3/8 inch (4.75-9.0mm)	Sand +No. 16 (1.18 mm)
Original Sample					
Sample After Test					
Plus No. 200 (75 µm) *					
Minus No. 200 (75 µm) *					
CL/FP					
% CL/FP					
%FP					
% CL					
Weighted %CL/FP					-
*FP	Gravel CL/FP				
**CL	Total Weighted Percent =				-

Moisture Content of Aggregate – USBR 4566

Size / Mass	1½-3 inch (37.5-75mm)	¾-1½ inch (19.0-37.5mm)	3/8-¾ inch (9.5-19.0mm)	No.4-3/8 inch (4.75-9.0mm)	Sand
Original Sample					
Oven-Dry Sample					
Water					
Content, % Total					
Content, % Surf.					

Physical Properties, Standard Concrete Freeze-Thaw Durability Mix – USBR 4666

Gravel – 30-Minute Specific Gravity and Absorption – USBR 4127

Nominal Size Fraction Inches	mm	B SSD Mass in Air, grams	C SSD Mass in Water, grams	B-C Displaced Mass of Water, grams	A Oven-Dry Mass, Grams	B-A Absorption Mass of Water, Grams	$\frac{(B-A)}{A}(100)$ Absorption, Percent	$\frac{B}{(B-C)}$ SSD Bulk Specific Gravity
3/8–¾	9.5-19.0							
No.4-3/8	4.75-9.5							

	Average	Weighted
Specific Gravity	______	______
Absorption	______	______

Standard Grading – USBR 4666

Gravel Size Fraction	%	Sand Sieve Size	%
3/8 – ¾ inch (9.5-19.0mm)	60	No. 8 (2.36 mm)	15
		No. 16 (1.18 mm)	15
No.4-3/8 inch (4.75-9.5mm)	40	No. 30 (600 µm)	25
		No. 50 (300 µm)	24
Total	100	No. 100 (150 µm)	16
		Pan	5
		Total	100
		FM = 2.74	

SAND

Material Passing No. 200 (75 µm) Sieve USBR 4117

Test Sample Mass
Dry (B) =
Washed (C) =
Minus No. 200 (75µm) (B-C) =
Passing No. 200 (75µm) $\frac{B-C}{B}(100) =$ __%

30-Minute Specific Gravity and Absorption – USBR 4128

Specific Gravity

Jar No. _____ Water Temp. =
SSD Sample Mass (B) =
Jar Calib. Mass (E) =
Total Mass (B+E) =
Jar Sampl, Water (F) =
Displacement (B+E-F) =
Specific Gravity $\left(\frac{B}{B+E-F}\right) =$

Absorption

Sample Mass
SSD (B) =
Dry (A) =
Absorption, Water (B-A) =
Absorption $\left(\frac{B-A}{A}\right)(100) =$ ______ %

Net Absorption (at time of mix), percent

% Net Abs. = % Abs. - % RM (Residual Moisture)

Size Fraction	% Abs.	% RM	% Net Abs.
3/8 – ¾ inch (9.5 – 19.0 mm)			
No.4- 3/8 inch (4.75 – 9.5 mm)			
Weighted Gravel			
Sand (FM = 2.74)			

Freeze-Thaw Specimens – Date Cast

Strength, lbf/in² (MPa)	Mass Loss, percent	Cycles

Remarks:

Figure 6025 – 2 (Sheet 2 of 2)

Project	Ownership:	Compiled by Date
Feature	Location:	Checked by Date
Date Letter Transmitted	Section________ Township________	Reviewed by Date
Branch File No. C-	Range Meridian	Submitted by Date

QUALITY EVALUATION

☐ Concrete Aggregate ☐ Riprap ☐ Filter Material

State ______ Region ______ Source No. ______ Latitude ______ Longitude ______
Sample No. M- ______ Date Received ______ Material ______ Max. Size Sampled ______ inches (mm)
Visual Estimate of Plus ______ -inch (mm) ______
Source Name ______ Overburden ______ Volume ______ yd^3 (m^3)
Remarks:

TEST RESULTS

Sieve Analysis – USBR 4117 and 4136				
Sieve Size, No., inch, or mm	Cumulative Percent Retained			
	Gravel, As Rec'd	Sand, Unwashed	Sand, Washed	
G R A V E L				
S A N D				
Fineness Modulus				
Percent Sand				
Percent Fines				

Washed Sand: ☐ Plain Water ☐ Ovendried ☐ Wetting Agent ______ ☐ Rapid Drying

Nominal Sieve Size Fractions No., inches, or mm							Fine Agg.	Washed Fine Agg.
Organic Impurities USBR 4040	-	-	-	-	-	-		
Low Density Pieces Specific Gravity – USBR 4123								
Specific Gravity USBR 4127, 4128								
Absorption, percent USBR 4127, 4128								
Clay Lumps and Friable Particles, percent – USBR 4142								
Sodium Sulfate Soundness ☐ USBR 4088 ☐ ASTM C88 Solution: ☐ Fresh ☐ Reused No. of cycles ______								

Effect of Organic Impurities on Strength of Mortar – USBR 4087

Grading: ☐ Standard ☐ Other — Average Strength Ratio of Fine Aggregate for Untreated to Treated Condition

Compressive Strength, lbf /in² (kPa)	____Day	
	7-Day	
	____Day	
	28-Day	

Los Angeles Abrasion

USBR 4131					USBR 4535		
Grading	A	B	C	D	Grading 1	2	3
100 Rev							
500 Rev							

Remarks:

Potential Alkali Reactivity of Cement-Aggregate Combinations – USBR 4227

	Sand				Gravel				Smpl No. M-	Type or Class	% K_2O	% Na_2O	% Na_2O Equiv
	100	100	50	25	100	100	50	25					
Test Agg., %													
Neutral Agg., %													
	Low Alkali	High Alkali			Low Alkali	High Alkali							
Cement No. 1													
Cement No. 2													
Pozzolan													
Expansion, % Avg. of 4													
____ months													
6 months													
12 months													
____ months													

Resistance of Concrete to Rapid Freezing and Thawing – USBR 4666

Concrete: ☐ Cylinder ☐ Core Size: ______ Riprap Size:

Fresh					Hardened					Riprap		
$\frac{W}{C+P}$	Slump, inches mm	Meter Air Content, %	Density lbm/yd³ kg/m³	Water lbm/yd³ kg/m³	Density lbm/yd³ kg/m³	Air Content %	28-Day Comp.Str. lbf/in2 kPa	Mass Loss, %	No. of Cycles	Density lbm/yd3 kg/m3	Mass Loss, %	No. of Cycles

INFORMATION SHOWN ON THIS DATA SHEET REGARDING COMMERCIAL PRODUCTS MAY NOT BE USED FOR ADVERTISING OR PROMOTIONAL PURPOSES, AND IS NOT TO BE CONSTRUED AS AN ENDORSEMENT OF ANY PRODUCT BY THE BUREAU OF RECLAMATION. APPROVAL OF DEPOSITS BY THE CONTRACTING OFFICER SHALL NOT BE CONSTRUED AS CONSTITUTING THE APPROVAL OF ALL OR ANY SPECIFIC MATERIALS FROM THE DEPOSIT.

Figure 6025 – 3 (Sheet 1 of 2)

Petrographic Summary – USBR 4295	Memo. No.	Date__________	By______________

Figure 6025 – 3 (Sheet 2 of 2)

	Ownership:	Compiled by Date
Feature	Location:	Checked by Date
Date Letter Transmitted	Section_____Township____________	Reviewed by Date
Branch File No. C-	Range_____Meridian____________	Submitted by Date

MISCELLANEOUS PHYSICAL PROPERTIES OF MINERAL AGGREGATE

☐ Concrete Aggregate ☐ Filter Material ☐ Subbase Course ☐ Base Course ☐ Asphaltic Concrete Aggregate ☐ Other
State_______________ Region____________ Source No._________ Latitude_________________ Longitude_________________
Sample No. M-________ Date Received_____________ Material ___________________ Max. Size Sampled ____________ in(mm)
Visual Estimate of Plus ______ -inch (mm) ____
Source Name ________________________ Overburden _____________________________ Volume ____________________ yd3 (m3)
Remarks:

TEST RESULTS

Sieve Analysis of Fine and Coarse Aggregates – USBR 4.136
Materials Finer Than No. 200 (75 µm) Sieve in Mineral Aggregates by Washing- USBR 4117
Washed Sample: inch(mm) Thru No. 200 (75 µm) ☐ Plain Water ☐ Wetting Agent

Cumulative Percent ☐ Retained ☐ Passing

Ovendried Rapid Drying Sample Description	MSA Inches mm						No. 4 4.75mm	No. 8 2.36mm	No. 10 2.00mm	No. 16 1.18mm	No. 30 600 µm	No. 50 300µm	No. 100 150µm	No. 200 75µm	Pan

_______% Sand _______% Silt Fineness Modulus: Coarse______ Fine: Washed __________ Unwashed _________

Remarks:

Flat and Elongated Particles in Aggregates - USBR 4903

Length-to-Width or Width-to- Thickness Ratio = _____	Gravel (Weighted Averages)				Sand (Weighted Averages) No. 4 (4.75 mm) to No. ____ (____ mm)			
	Particle Mass	Particle Count	Total Weighted Average		Particle Mass	Particle Count	Total Weighted Average	
Flat, %								
Elongated, %								
Flat and Elongated, %								
Total Flat and/or Elongated, %								
Crushed Particles in Agg. –USBR 4904	_____ inch (mm) to No. 4 (4.75 mm)				No. 4 (4.75 mm) to No. ____ (____ mm)			
Single Face Fracture, %								
Multiple Face Fracture, %								
Total Fractured Aggregates, %								

Sand Equivalent Value of Soils and Fine Aggregate - ASTM D2419

$$\text{Sand Equivalent, \%} = \frac{\text{Sand Reading}}{\text{Clay Reading}}(100)$$

1	2	3	Average	1	2	3	Average

Degradation of Fine Aggregate Due to Attrition - ASTM C-9, Proposal PI9R
Grading: ☐ Standard ☐ Specifications Mass of Impeller, lbm (kg): Before____________________ After ____________________
Fineness Modulus: Before After Minus No. 200 (75 µm): After %
Remarks:

Figure 6025 – 4

Technical Service Center Civil Engineering Services Materials Engineering and Research Lab	UNITED STATES DEPARTMENT OF THE INTERIOR BUREAU OF RECLAMATION	Sheet No. of Branch File No. C- Compiled by Checked by Reviewed by Submitted by
	RIPRAP - ROCKFILL QUALITY EVALUATION	

STATE	REGION	SOURCE NO.	LAT.	LONG.
SAMPLE NO. M-	MATERIAL		Date REC'D	
DEPOSIT NAME			OVERBURDEN	
OWNERSHIP			VOLUME	
LOCATION				
	SEC.	T.	R.	MERIDIAN
FEATURE				
PROJECT			DATE REF. LTR.	
REMARKS				
FIELD GEOLOGY NOTES:				

IMPORTANT NOTICE

INFORMATION CONTAINED IN THIS DATA SHEET REGARDING COMMERCIAL PROOUCTS MAY NOT BE USED FOR ADVERTISING OR PROMOTIONAL PURPOSES AND IS NOT TO BE CONSTRUED AS AN ENDORSEMENT OF ANY PROJECT BY THE BUREAU OF RECLAMATION. APPROVAL OF DEPOSITS BY THE CONTRACTING OFFICER SHALL NOT BE CONSTRUED AS CONSTITUTING THE APPROVAL OF ALL OR ANY SPECIFIC MATERIALS FROM THE DEPOSIT.

LABORATORY TEST RESULTS

	75-37.5 mm (3-1.5in)	36.5-19.0 mm (1.5-0.75in)	19.0-9.5 mm (.75-.375in)	9.5-4.75 mm (.375–No.4)	Average
Specific Gravity, Bulk SSD USBR 4127					
Absorption. % USBR 4127					
Na2SO4 Soundness, 5 cycles, Wgt'd % Loss USBR 4088					

Los Angeles Abrasion	USBR 4131					USBR 4535			
Sample Grading	----	A	B	C	D		1	2	3
% Loss	100 rev					200 rev			
% Loss	500 rev					1000 rev			

Freeze-Thaw Cube Durability USBR 4666

Number of Test Cubes	Absorption. % USBR 4127	Specific Gravity USBR 4127			Mass Loss %	Freeze-Thaw cycles
		SSD Bulk	Oven-dry Bulk	Apparent		

Cube Failure Mode:

PetrographicSummary USBR6025 MemoNo: Date By:

Figure 6025 – 5

Appendix C

Sample Riprap Analysis

Introduction

This report presents an example of riprap that was designed using Reclamation's 2013-update to Chapter 7: Riprap Slope Protection of Design Standard No. 13 [1].

The design presented within this appendix was based on an existing dam. However, it has been made into a generic example for publishing purposes, and is herein referred to as "Dam A". Dam A is a homogeneous earth fill embankment dam located in eastern Arizona. The crest length is approximately 6,800 feet, the crest width is approximately 40 feet, and the maximum height is approximately 200 feet. The new riprap slope protection has been designed to replace the existing slope protection that is inadequate and deteriorating and being displaced.

The upstream face of the embankment where slope protection is to be placed is sloped at 3.5H:1V. This appendix serves as the documentation for the design of riprap that will be replaced along the upstream face of this section of the embankment for slope protection.

Design Details

Design of the riprap slope protection was based on Reclamation's Design Standard No. 13, Chapter No. 7 [1] which was updated in 2013. According to the riprap design standard, riprap design can be done by one of two general methods: 1) the tolerable damage method which produces smaller riprap sizes and assumes that some repairs might be needed during the life of the dam; and 2) the zero damage method which produces larger riprap and assumes zero damage through the life of the project. Both methods calculate the median weight of riprap (W_{50}) as a function of several factors, including the design wave height, rock density, and the slope of the embankment. From W_{50}, the rest of the gradation can be determined, as explained later.

For Dam A, it was assumed that using a larger riprap size to limit maintenance would be preferable over using a smaller size that would occasionally require maintenance. This is because there is a significant amount of rock available from the riprap borrow area and resources for maintenance are very limited. For this reason, the design was based on the zero damage method. Using this method, the median weight of riprap (W_{50}) was calculated as:

$$W_{50} = \frac{\gamma_r {H_{10}}^3}{3.62(G_s - 1)^3\,(\cot\alpha)^{.667}} \qquad (7)\,[1]$$

[1] Equation numbers in this appendix reference equation numbers from the main text of this chapter.

Where:

W_{50} = Weight of the median-sized rock in the riprap (lb)
γ_r = Specific unit weight of the rock units (lb/ft^3)
H_{10} = Average height of the largest 10-percent of waves expected (ft)
G_s = Specific gravity of the rock
α = Slope angle of the embankment measured from horizontal

Some of the above parameters were known at the site of Dam A, including α (computed for the 3.5H:1V slope). G_s was assumed[2] to be 2.7, resulting in a γ_r value of 168.5 lb/ft^3 (62.4 lb/ft^3 * G_s). H_{10} was computed based on the significant wave height (H_s), which was calculated from Equation 4 below.

Design Wave Height

As mentioned, H_{10} was computed from H_s, which is a function of the fetch length (F) and the design wind speed ($VMPH$). H_s represents the average of the highest one-third waves expected, and was calculated as:

$$H_s = 0.0245 * F^{0.5} * VMPH(1.1 + 0.0156 * VMPH)^{0.5} \quad (4)$$

Where:

H_s = Height of the significant wave (ft)
$VMPH$ = Design wind velocity (miles per hour, mph)
F = Fetch length (miles)

Computation of Fetch, F

The fetch length was determined using the method recommended in Section 7.3.2; averaging the nine longest radii (spaced 3 degrees apart) extending from several points on the upstream face of the dam. This was done assuming the reservoir to be at normal operating level. At Dam A, F was calculated to be 3.4 miles (figure C.1).

Selection of a Representative Wind Station

A wind station was chosen for use in Reclamation's PFARA program, based on the guidance of Section 7.3.3. The wind station at Winslow, Arizona was selected based on its proximity to the dam-site (eastern Arizona, see Figure C.2) and

[2] For a new dam or a major modification, the source of rock would be well known and tested, so assumptions would not ordinarily be necessary.

other key similarities (elevation, vegetation, etc.). This selection was made by referencing the wind station maps (see Figure C.1) available in the Wind Energy Resource Atlases, published by Battelle Pacific Northwest Laboratory [2]. The wind station identification number was found from a table (Table C.1) which accompanies the maps.

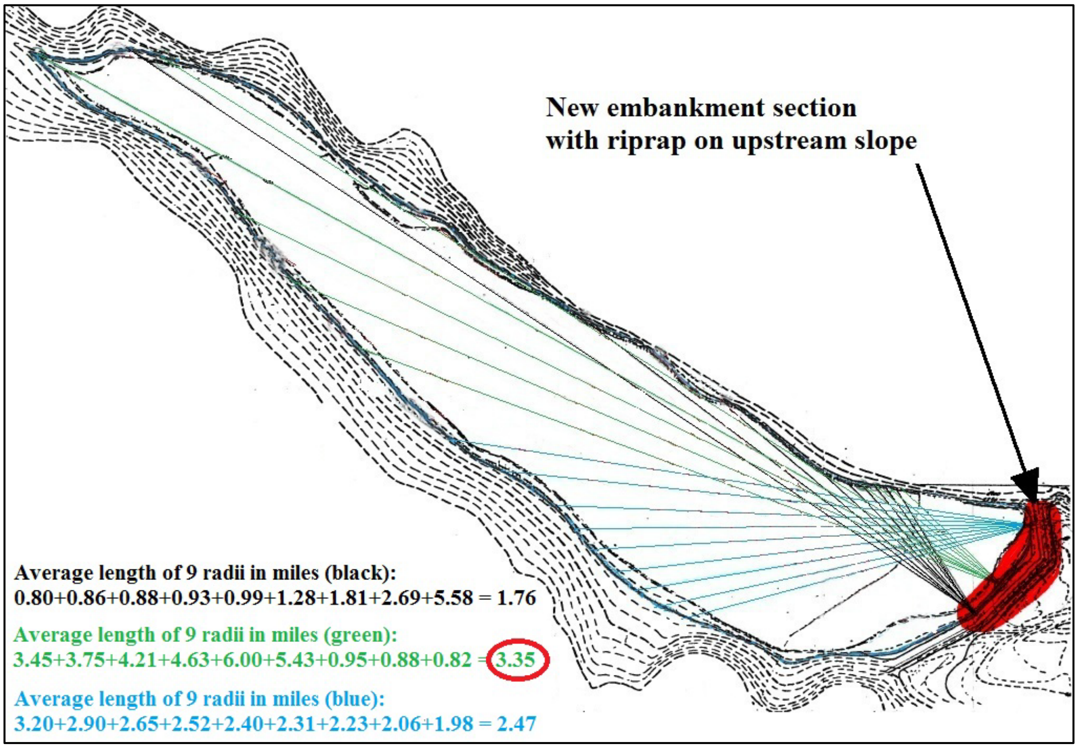

Figure C.1. Fetch calculation at Dam A using the method described in section 7.3.2.

Computation of Design Wind Speed, VMPH

VMPH was calculated using the method presented in Section 7.3.3. A 90-percent nonexceedance probability (over a 100-year time period) was used to select a design wind velocity. To produce a "wind velocity-vs-nonexceedance probability" chart (Figure C.3), several key factors were required to be input within Reclamation's PFARA program:

- Representative wind station(s) -"Winslow, Arizona", with wind station ID AZ23194.
- A "maximum wind velocity" - 100 miles per hour (mph) was selected by default.
- Fetch length - determined to be 3.3 miles, as described above.

Although the wind at the site may not blow directly (orthogonally) into the dam, the design wind was assumed to blow directly into the dam to account for the worst-case scenario. At Dam A, the design wind velocity, *VMPH*, was calculated to be 79.1 mph (Figure C.3). This value was conservatively rounded up to 80 mph for use in design.

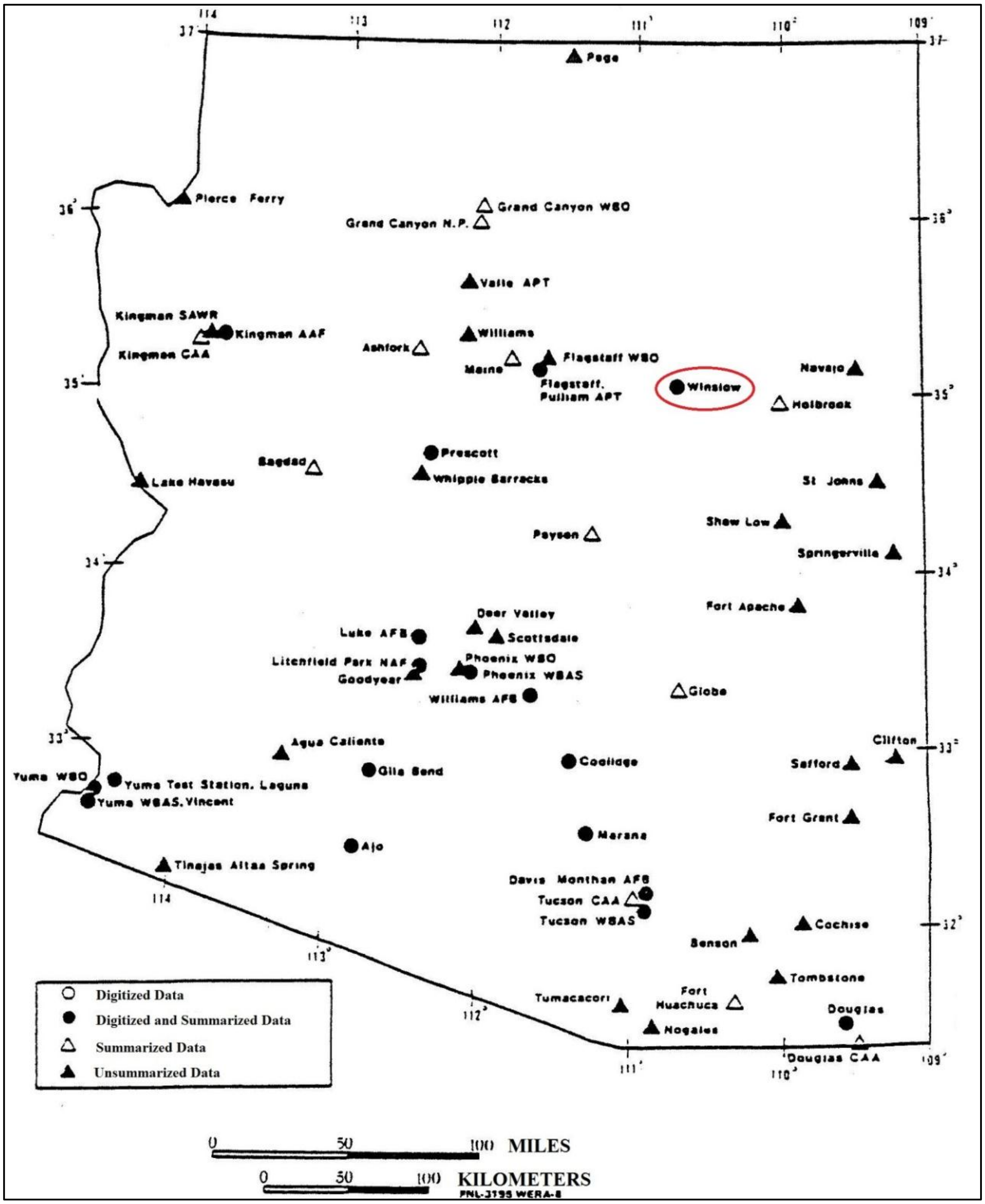

Figure C.2. Wind station locations in Arizona as presented in Wind Energy Resource Atlases, published by Battelle Pacific Northwest Laboratory [2].

Table C.1. Example wind station table, as presented in *Wind Energy Resource Atlases*, published by Battelle Pacific Northwest Laboratory [2]

Station ID No.	Station name	No. of observations	Station ID No.	Station name	No. of observations
	ARIZONA			CALIFORNIA - Continued	
AZ03103	Flagstaff	27,768	CA23192	Silver Lake	15,298
AZ03124	Fort Huach	147,164	CA23195	Chula Vista	55,411
AZ03125	Yurna	69,980	CA23199	El Centro	69,959
AZ03148	Gila Bend	5,839	CA23202	Fairfield	191,322
AZ23104	Chandler	122,676	CA23203	Merced/Cas	165,611
AZ23109	Tucson/Dav	163,557	CA23206	Sacramento	157,184
AZ23111	Phoenix/Lu	164,158	CA23208	Sacramento	174,568
AZ23160	Tucson/mt	87,984	CA23211	San Rafael	192,781
AZ23168	Gila Bend	54,036	CA23225	Blue Canyon	92,883
AZ23183	Phoenfx/Sk	91,217	CA23226	Dormer Sum	27,413
AZ23184	Prescott	149,037	CA23230	Oakland	130,006
AZ23194	Winslow	65,628	CA23232	Sacramento	97,868
AZ23195	Yuma/int	120,209	CA23233	Salinas	122,243
AZ93026	Douglas	54,047	CA23234	San Francisco	103,720
AZ93105	Phoenix/Li	71,472	CA23236	Santa Marl	59,594
AZ93139	Payson	26,138	CA23237	Stockton	54,031

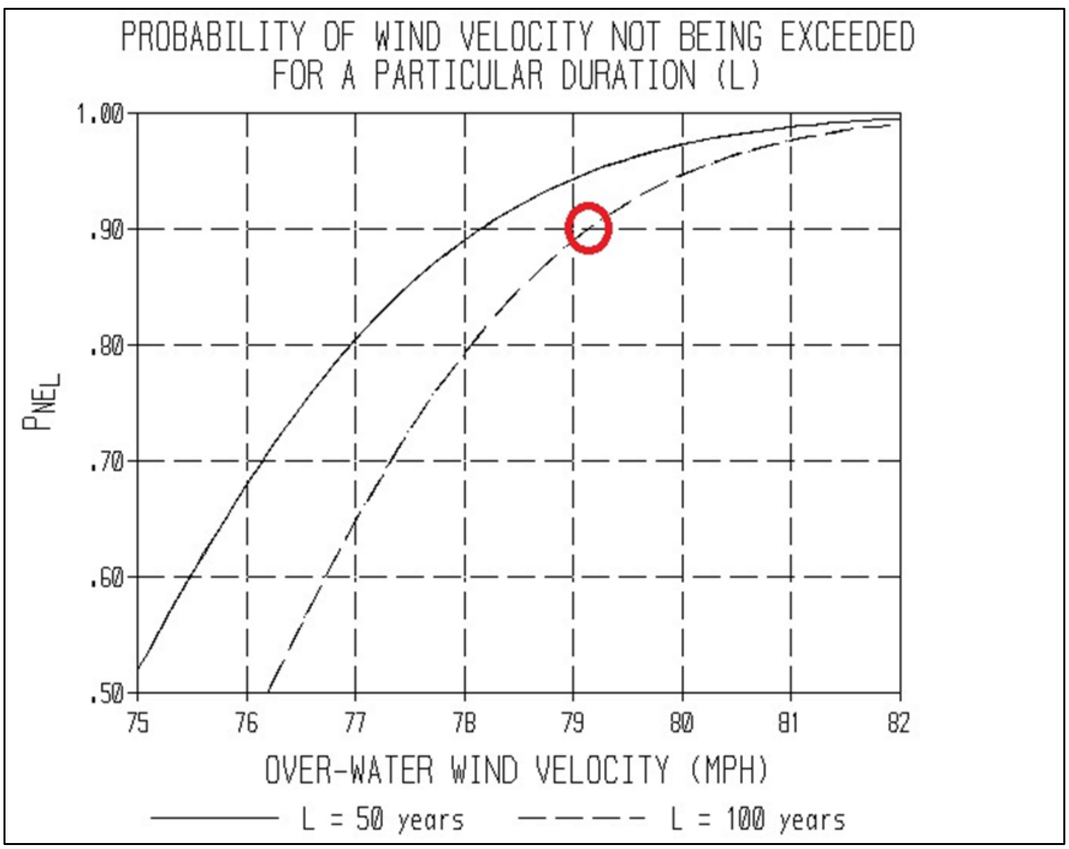

Figure C.3. Design wind velocity versus probability of nonexceedence chart for Dam A.

Computation of H_{10}

H_{10} was calculated using Equation 5 from the 2013 update of Reclamation's Design Standards, Embankment Dams, Chapter 7: Riprap Slope Protection [1]:

$$H_{10} = 1.27 * H_S \quad (5)$$

Based on the *F* and *VMPH* values calculated previously, H_{10} was calculated to be 6.98 feet.

Computation of Median Riprap Weight, W_{50}

W_{50} was calculated using Equation 7. G_s was assumed to be 2.7, making γ_r = 168.5 lb/ft^3. Based on these values, W_{50} was calculated to be 1,398 lbs. For ease of calculations, W_{50} was rounded up to 1,400 lb in determining the rest of the gradation boundary limits. It should be noted that this value conforms with Reclamation's recommended riprap size guidelines, as it is greater than the recommended minimum W_{50} size (160 lb) and smaller than the recommended maximum W_{50} size (2,000 lb).

Minimum and Maximum Riprap Sizes

The maximum and minimum weights for the riprap at Dam A were calculated from W_{50} using the following equations [5]:

$$W_{max} = 4 * W_{50} \quad (10)$$

and

$$W_{min} = \frac{W_{50}}{8} \quad (11)$$

For a W_{50} size of 1,400 lb, W_{max} is calculated to be 5,600 lb and W_{min} is calculated to be 175 lbs. From these values, estimates of volume and diameter were calculated using the following equation:

$$V = 0.75 * {D_n}^3 = \frac{W_n}{\gamma_r} \quad (8)$$

Where:

V = Volume of rock (ft^3)
D_n = Diameter of the n-percent-passing size (ft)
W_n = Weight of the n-percent-passing size (lb)

Equation 8 assumes the typical shape of a riprap stone to be somewhere between a sphere and a cube). Using Equation 8, the design W_{50} value of 1,400 lb is expected to coincide to a rock with a diameter of 2.2 ft and a volume of 8.3 ft^3. The W_{min} value of 175 lb coincides with a diameter of 1.11 ft and a volume of 1.0 ft^3, and a W_{max} value of 5,600 lb coincides with a diameter of 3.54 ft and a volume of 33.2 ft3 (Table C.2).

Riprap Gradation

At Dam A there are no rock sources nearby that could easily serve as riprap materials. The "35-Percent Band" will therefore be used to define the riprap gradation, as it allows for the greatest range of rock fragment sizes to be used as riprap, increasing the constructability of the riprap gradation. The "35-Percent Band" method will specify the riprap gradation using W_{50}, W_{min}, and W_{max} (Section 7.3.6).

The curves constructed from Table C.3 were converted to a single table (Table C.4) to present the gradation specification in tabular form, as is normally done.

Table C.2. Conversion between weight, diameter, and volume for calculated riprap sizes

	Weight (lb)	Diameter (ft)	Volume (ft^3)
W_{min}	175	1.1	1.0
W_{50}	1,400	2.2	8.3
W_{max}	5,600	3.5	33.2

Table C.3. Points plotted to construct "35-percent band" riprap gradation

35-percent band coarse-limit curve	
W value	**Percent finer by weight**
W_{max}	100
$0.5\,W_{\mathrm{max}}$	55
W_{50}	25
W_{min}	0
35-percent band fine-limit curve	
W value	**Percent finer by weight**
$0.5\,W_{\mathrm{max}}$	90
W_{50}	60
W_{min}	20

Table C.4. Final riprap specification for Dam A

Design parameter	Size (lbs)	Percent finer by weight
W_{max}	5,600	100
$0.5W_{max}$	2,800	55 to 90
W_{50}	1,400	25 to 60
W_{min}	175	0 to 20

Riprap Thickness

The thickness of the required riprap layer (perpendicular to the slope) was calculated from Equation 9:

$$T \geq 2\,D_{50} \qquad (9)$$

Where:

T = Thickness of the riprap layer perpendicular to the slope

For a D_{50} of 2.2 ft. (from Table C.2), the required thickness of the riprap is 4.4 ft. For ease of construction, the thickness of the riprap was specified to be 54 inches (4.5 feet).

Bedding Gradation

The bedding material should be sized in accordance with Section 7.3.7 to prevent internal instability, internal erosion of the bedding through the riprap, or internal erosion of the embankment material through the bedding [1].

Embankment Material Retention Requirement

The bedding material has to be fine enough to retain the silty sand embankment material. To account for this, the bedding material has a maximum size 15-percent-passing size, which was calculated from Equation 14:

$$D_{15\,Max} < 5\,D_{85\,E\,Fine\,limit} \qquad (14)$$

Where:

$D_{85\,E\,Fine\,limit}$ = The 85-percent-passing size of the finest gradation of sampled embankment material

$D_{15\,Max}$ = The 15-percent-passing size of bedding material that will ensure that the bedding material is fine enough to be able to retain the embankment material

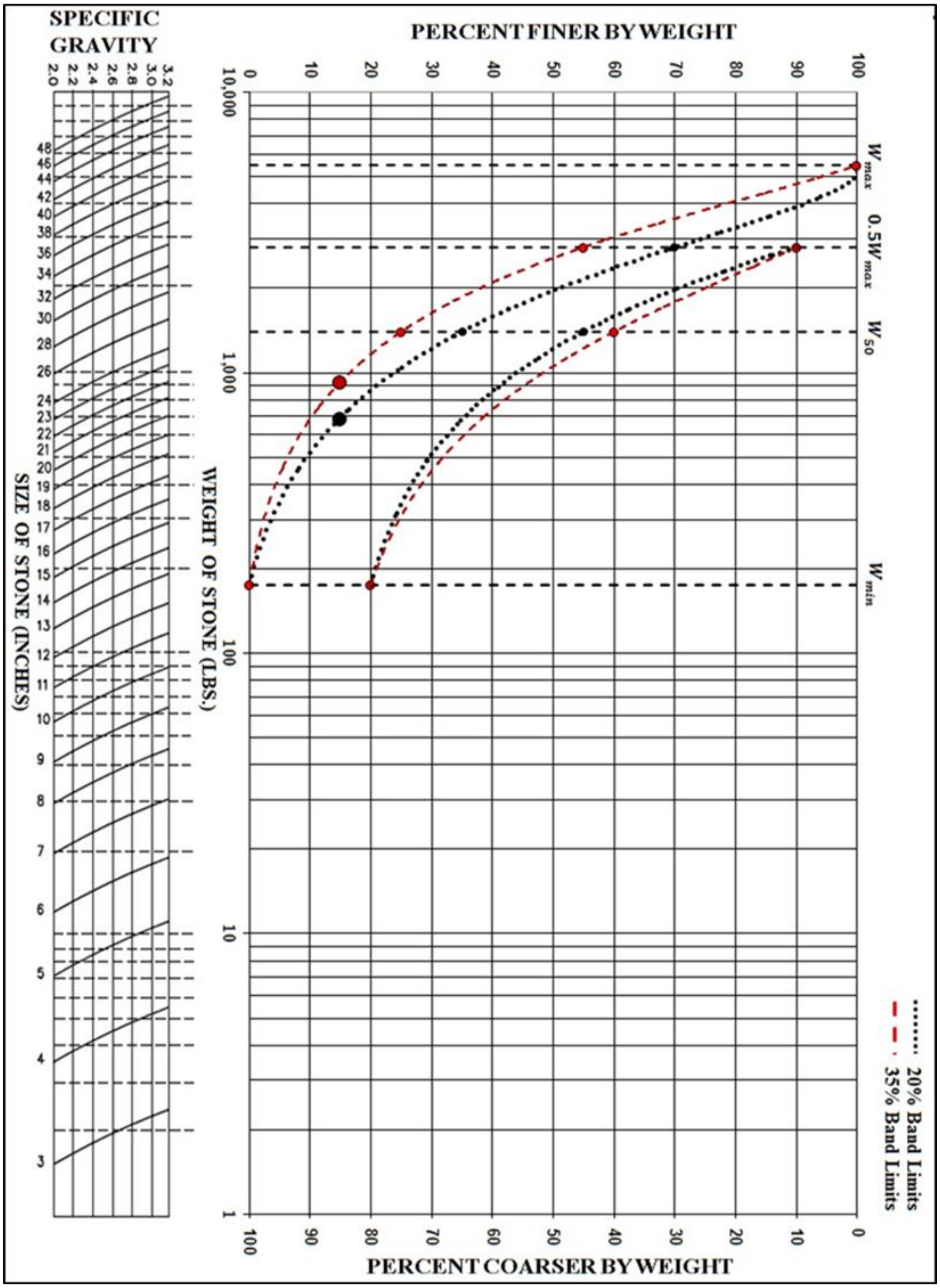

Figure C.4. Design riprap gradation band. $D_{15\,R_{Coarse\ limit}}$ was estimated from coarse-limit curve of 35-percent band to have a value of 900 lbs.

At Dam A, gradations of sampled embankment material (Figure C.5) showed the material to be a silty sand with 28 to 46 percent fines. Based on the finer of the two gradation samples, $D_{85\ E_{Fine\ limit}}$ was taken as 0.22 mm. From Equation 14, $D_{15\ Max}$ was therefore calculated to be 1.10 mm.

Bedding Material Retention Requirement

The bedding material must be coarse enough to prevent it from eroding through the riprap. To meet this requirement, the bedding material must meet the criteria of Equation 13:

$$D_{85\ Min} > \frac{D_{15\ R_{Coarse\ limit}}}{5} \qquad (13)$$

Where:

$D_{85\ Min}$	=	The minimum 85-percent-passing size of bedding material that will ensure that the bedding material is coarse enough to be retained by the riprap
$D_{15\ R_{Coarse\ limit}}$	=	The 15-percent-passing size of the coarse-limit curve of the design riprap gradation band

From Figure C.4, the $D_{15\ R_{Coarse\ limit}}$ can be approximated as about 900 lbs. Using Equation 7, this is equivalent to a rock fragment with a diameter of 586 mm. From Equation 13, $D_{85\ Min}$ is calculated as 117 mm.

Constructing the Bedding Gradation Band

An initial bedding gradation band was constructed based on the guidance of Sections 7.3.7.4 and 7.3.7.5:

- $D_{85\ B1_{Fine\ limit}}$ was set as 117 mm, equal to $D_{85\ Min}$
- $D_{60\ B1_{Coarse\ limit}}$ was set as 117 mm, equal to $D_{85\ Min}$
- $D_{10\ B1_{Fine\ limit}}$ was calculated from Equation 16 as 11.7 mm
- A straight line was drawn between $D_{85\ B1_{Fine\ limit}}$ and $D_{10\ B1_{Fine\ limit}}$
- Another straight line was drawn parallel to the previous one, and was located to pass through the point $D_{60\ B1_{Coarse\ limit}}$

This gradation band is presented in Figure C.6 as "1st bedding stage". It can be seen that the coarse-limit curve lies significantly left of the $D_{15\ Max}$ limit, signifying that the proposed bedding gradation would not be adequate to retain the underlying embankment material. An attempt to modify the gradation band by moving the coarse-limit curve to the right of $D_{15\,Max}$ results in a C_u value significantly greater than 10 (thin, dashed lines).

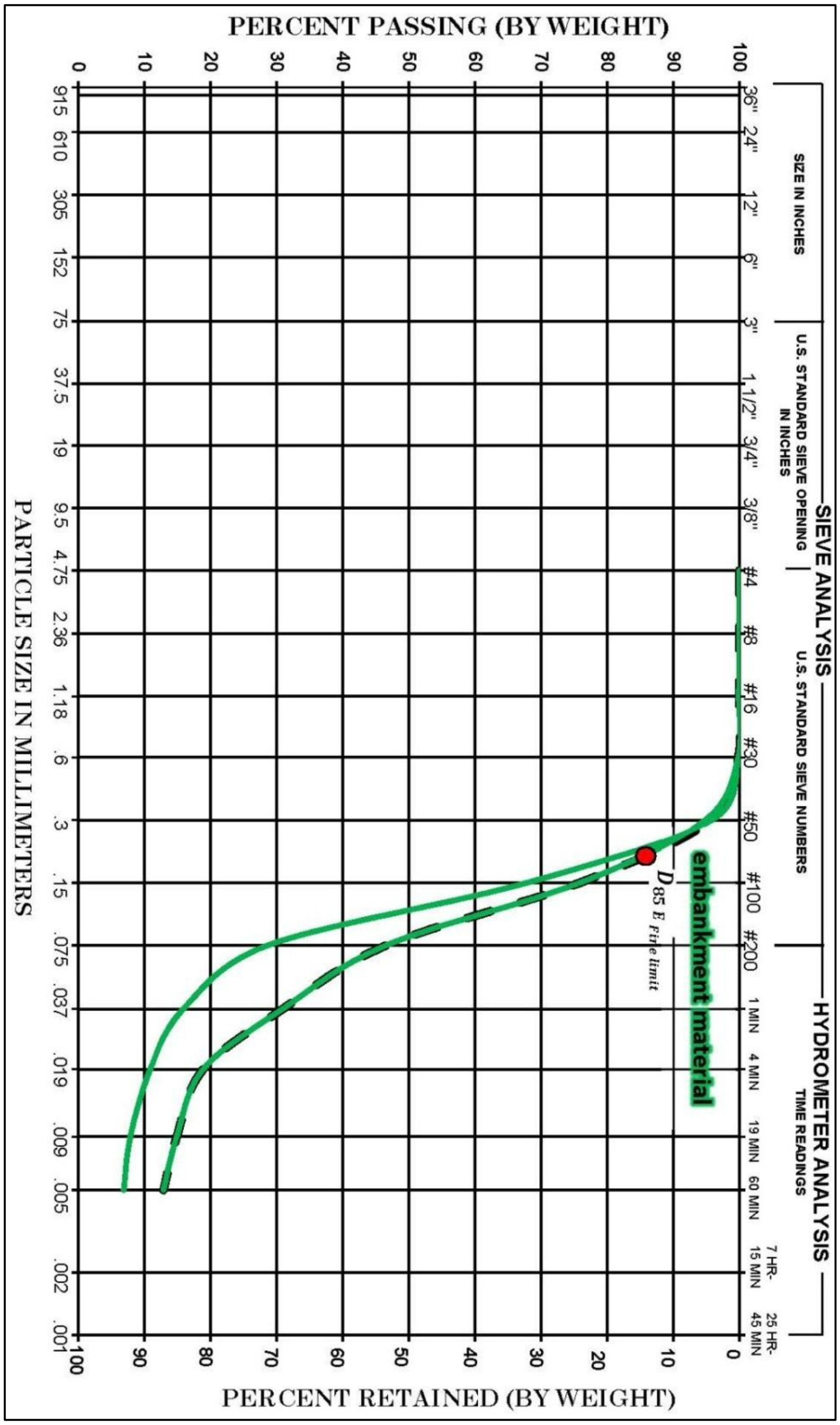

Figure C.5. Gradations of embankment material samples at Dam A.

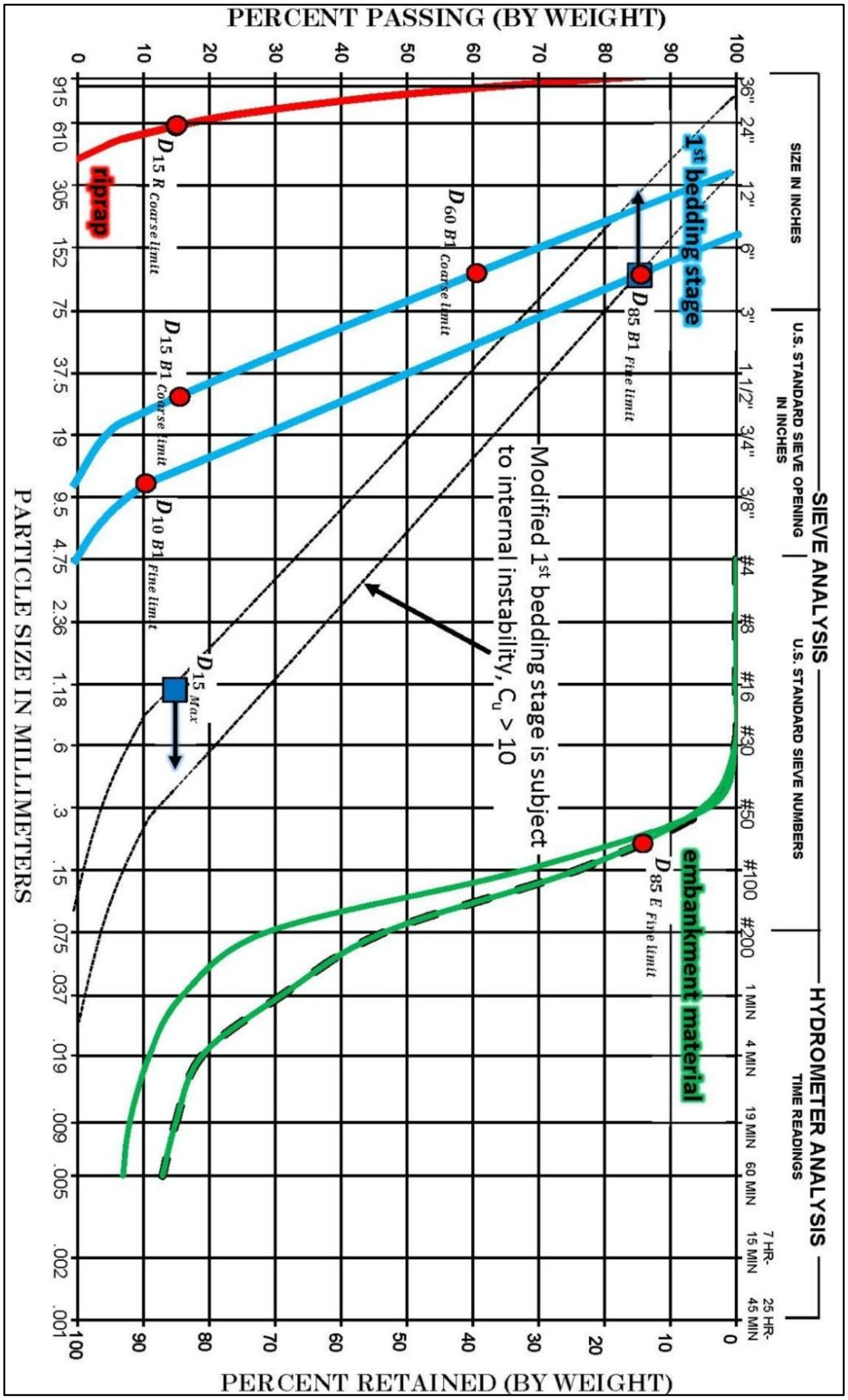

Figure C.6. Preliminary bedding gradation (blue) does not meet D_(〖15〗_Max) requirement; modified bedding gradation (dashed) does not meet internal stability requirements.

Requirement for Multiple Bedding Stages

Instead of trying to meet required criteria by modifying the gradation of first bedding stage, a second stage of bedding material was used. The initial gradation band was left unmodified to serve as the first bedding stage.

The second bedding stage was designed using the method described in Section 7.3.7.5. $D_{85\ B2\ Fine\ Limit}$ was first calculated from Equation 17:

$$D_{85\ B2\ Fine\ Limit} \geq \frac{D_{15\ B1\ Coarse\ Limit}}{5} \quad (17)$$

Where:

$D_{85\ B2\ Fine\ Limit}$	=	The 85-percent-passing size of the fine-limit curve of the second stage of bedding material
$D_{15\ B1\ Coarse\ Limit}$	=	The 15-percent-passing size of the coarse-limit curve of the first stage bedding material

$D_{15\ B1\ Coarse\ Limit}$ was estimated from the gradation of the first bedding stage as 30 mm. $D_{85\ B2\ Fine\ Limit}$ was then calculated to be 6 mm. The remainder of the second bedding stage gradation band was then defined as follows:

- $D_{60\ B2\ Coarse\ Limit}$ was calculated to be 6 mm from Equation 17
- $D_{10\ B2\ Fine\ Limit}$ was calculated to be 0.6 mm from Equation 18
- A straight line was drawn between $D_{85\ B2\ Fine\ limit}$ and $D_{10\ B2\ Fine\ limit}$
- Another straight line was drawn parallel to the previous one, and was located to pass through the point $D_{60\ B2\ Coarse\ limit}$

The coarse-limit curve of this gradation band (thin black lines, Figure C.7) was also found to lie to the left of the $D_{15\ Max}$ point. It was therefore considered too coarse to meet the criteria required to retain the finer embankment material. However, by slightly modifying the gradation of the second bedding stage (orange lines, Figure C.7), it was able to comply with the required criteria. The coarse- and fine-limit curves were slightly flattened to meet the particle filter criteria requirements (Equations 13 and 17). The value of C_u remained below 10 (and therefore met internal stability criteria) after slightly raising the coarse-limit curve to be closer to the fine-limit curve. Despite bringing the curves closer together, they were still separated by 20-percent vertically to allow for constructability.

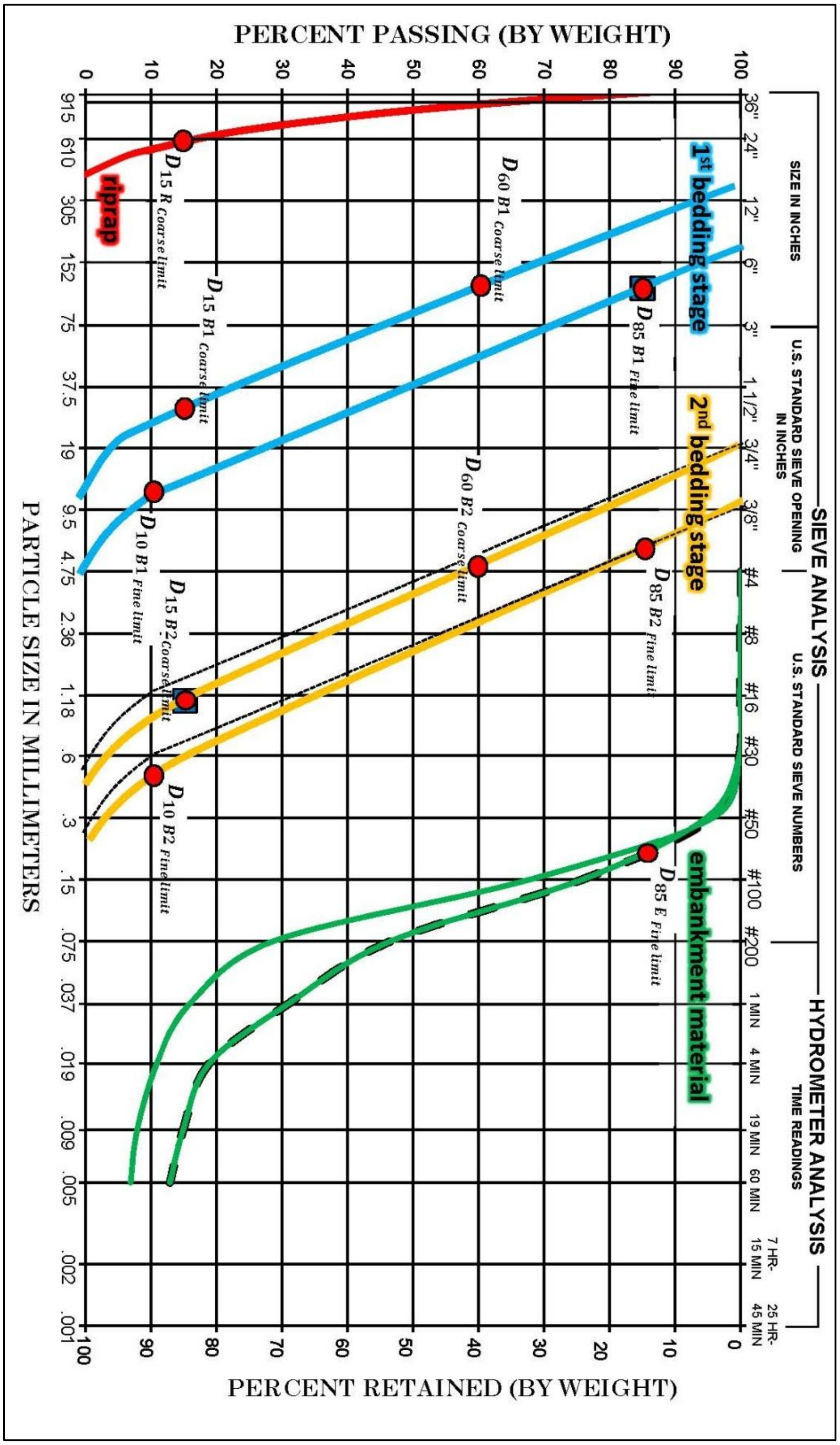

Figure C.7. Final gradation curves for first (blue) and second (orange) bedding stages.

Tabular Bedding Gradations for Specifications

The bedding gradation curves presented in Figure C.7 were converted to tabular form (Table C.5) to present in the specifications.

Table C.5. Final bedding gradation specification for Dam A

First bedding stage		
Diameter (mm)	**Diameter (in)**	**Percent-passing (%)**
350	13.8	100
117	4.6	60 to 85
30	1.2	15 to 40
11	0.4	0 to 10
Second bedding stage		
Diameter (mm)	**Diameter (in)**	**Percent-passing (%)**
19	0.7	100
6	0.2	65 to 85
1.1	0.04	15 to 35
0.5	0.5	0 to 10

Bedding Thickness

The thickness of the bedding layers was derived from the thickness of the riprap layer (Table 7.3.7.6-1). Since the riprap at Dam A was designed to have a thickness of 54 inches, each of the two bedding stages was designed to have a thickness of 18 inches (1.5 feet).

Summary

Riprap and bedding were designed based on Reclamation's updated Design Standard No. 13, Chapter 7: Riprap Slope Protection [1]. Riprap was designed according to the zero damage criteria for an assumed design life of 100 years. The zero damage design was followed and marginally adjusted to allow for a constructible and conservative gradation.

Two bedding layers were designed for placement beneath the riprap to prevent internal instability, erosion of the embankment material through the bedding, and erosion of the bedding materials through the riprap.

Final specifications for the riprap and bedding layers are presented in Table C.6. The values were rounded slightly from values presented earlier to enhance constructability.

Table C.6. Final riprap and bedding size specifications for Dam A

Riprap		Bedding Stage 1		Bedding Stage 2	
Thickness:	**54 inches**	**Thickness:**	**18 inches**	**Thickness:**	**18 inches**
Size (weight)	**% finer**	**Size (dia.)**	**% passing**	**Size (dia.)**	**% passing**
5,600 lb	100	15 in	100	0.75 in	100
1,400 lb	35 to 55	4.5 in	60 to 85	0.25 in	65 to 85
175 lb	0 to 20	1.25 in	15 to 40	0.04 in (#16 sieve)	15 to 35
		0.5 in	0 to 20	0.425 in (#40 sieve)	0 to 10

References

[1] Embankment Dams Design Standards No. 13, Chapter 7, Riprap Slope Protection (DRAFT), Bureau of Reclamation, Denver, CO, January 2013..

[2] "Battelle Pacific Northwest Laboratory Under Contract No. DE-AC06-76RLO 1830" for the U.S. Department of Energy, 1980.

[3] "Large Wave Tank Tests of Riprap Stability," Technical Memorandum No. 51, U.S. Army Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir VA, May 1975.

[4] "Design of Riprap Revetments for Protection Against Wave Attack," Ahrens, J.P. 1981 CERC TP-81-5, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS..

[5] "ASTM Standard C33, 2008, "Standard Specification for Concrete Aggregates," ASTM International, West Conshohocken, PA, 2008.

[6] "Design Standard No. 13, Chapter 5 - Protective Filters".

Appendix D

A Brief History of Riprap Sizing within Reclamation

Contents

Addendums

Addendum

INTRODUCTION

Riprap has long been used by the United States Bureau of Reclamation (Reclamation) for slope protection on reservoir-impounding embankments. Several factors are typically analyzed to determine if a rock source will produce quality riprap: density, durability, size, gradation, etc. While each of these factors can affect the performance of riprap, this report specifically looks at how the size of riprap affects its performance.

The criteria used to specify riprap size has varied significantly during Reclamation's history. Dams constructed during the 1940s and 1950s were often designed using generic riprap size requirements based on past successes, material availability or both. Modern riprap specifications are typically more unique to each dam, and are based on physical factors such as reservoir fetch length, historical wind speeds, and embankment geometry.

PURPOSE

The purpose of this report is to investigate how riprap performance compares to riprap size for Reclamation facilities. The information from this investigation will be used to optimize riprap design that is portrayed in Reclamation's Design Standard No. 13, Chapter 7 [3]. The design parameter which is the focus of this work is the wave height. Recent changes to equations for estimating wave height used by the U.S. Army Corps of Engineers (USACE) have resulted in changes to riprap size specifications. The size of riprap used within the inventory of Reclamation's dams has also changed over time, allowing a comparison of size with performance. This report looks at the recent changes, and compares them to historical riprap sizes (and their performance) to determine if the updated wave height equations are underconservative, adequate, or overconservative in riprap design.

BACKGROUND – HISTORICAL RIPRAP SIZING

In 1967, Reclamation's Elbert E. Esmiol documented riprap performance for 149 existing embankments in a report titled "Rock as Upstream Slope Protection for Earth Dams – 149 Case Histories" [1]. This report is herein referred to as "149 Case Histories." This study compiled various components of riprap specifications, such as source rock type, bedding, specific gravity, construction method, etc. It also classified riprap performance from each case as excellent, good, satisfactory, or failure. Riprap failures were further categorized by type of failure: change of shape (subsidence, settlement, sloughing), erosion (abrasion, beaching, washing of fines, displacement, plucking of stones, slumping), rock fragment breakdown (weathering, disintegration, decomposition), removal of stones, nonuniform placement, or a combination of these types.

Although the compiled specifications included a variety of riprap sizes, it was observed that most of the riprap specifications were derived from one of the generic riprap specifications shown in Table D.1; about half of the riprap specifications exactly matched one of the generic specifications, while many of the rest had been modified slightly. These generic specifications were often used for several years before being replaced by an updated specification. A trend was observed between the subsequent generic specifications. In general, riprap size has increased with time.

Table D.1. Typical riprap descriptions observed from 149 case histories

Typical era(1)	Label(2)	Nominal thickness (in)	Specification description	Est. avg. size(3) (ft^3)	Est. avg. size(4) (lb)
1935-1941	C	N/A	Largest rock to be no larger than 0.5 CY. Average size to be 1 CF	1.0	165
1940-1956	A	N/A	Reasonably well graded from 0.5 CY to 0.5 CF. Not more than 25% to be smaller than 0.5 CF. At least 30% larger than 3 CF.	1.8	297
1935-1964	B	N/A	Reasonably well graded from 0.5 CY to 0.5 CF	3.5	577.5
1956-1964	D	24	Greater than 75% of riprap to have volume between 0.5 CF and 0.5 CY. Less than 25% of riprap to have volume less than 0.5 CF.	5.3	874.5
1956-1964	E	36	Greater than 25% of riprap to have volume between 0.5 CY and 1.0 CY. 45 to 75% of riprap between 0.5 CY and 0.5 CF. Less than 25% of riprap to have volume less than 0.5 CF.	8.2	1353.0

In 1956, riprap specifications began to include more details specific to the gradation. This trend was carried into Reclamation's *Design of Small Dams* (Table D.2), which presented typical gradation examples to be used for riprap design [2]. As can be seen in Table D.2, Design of Small Dams used a reservoir's fetch length as a primary factor for determining riprap size.

Table D.2. Riprap specification examples as found in *Design of Small Dams*

Specifications suggested by *Design of Small Dams* for dams with 3H:1V slopes								
Design of Small Dams – 1st Ed. (1960)	**Fetch (miles)**	**Nominal thickness (in)**	**Max size (lb)**	**25% greater than (lb)**	**45 to 75% greater than (lb)**	**25% less than (lb)**	**Estimated avg. size[3] (ft^3)**	**Est. avg. size[4] (lb)**
	< 1	18	1,000	300	10-300	10	1.0	165
	2.5	24	1,500	600	30-600	30	1.6	264
	5	30	2,500	1,000	50-1,000	50	2.7	445.5
	10	36	5,000	2,000	100-2,000	1000	5.5	907.5
Design of Small Dams – 2nd (1973), 3rd (1987), 4th (2004)	**Fetch (miles)**	**Nominal thickness (in)**	**Max size (lb)**	**40 to 50% greater than (lb)**	**50 to 60% greater than (lb)**	**0 to 10% less than (lb)**	**Est. avg. size[3] (ft^3)**	**Est. avg. size[4] (lb)**
	< 2.5	30	2,500	1,250	75-1,250	75	4.2	693
	> 2.5	36	4,500	2,250	100-2,250	100	7.5	1,237.5

[1] Based on review of "Rock as Upstream Slope Protection for Earth Dams."
[2] Designated label for the purpose of this study.
[3] Average size was calculated based on assumptions. See Addendum D-2 for assumed values.
[4] Average size was calculated from the average volume, assuming rock density to be 165 lb/ft^3.

Deterministic Riprap Sizing Criteria

Reclamation began using a modern deterministic riprap design method starting around 1975. This method used the median weight of the riprap (W_{50}) to determine the rest of the gradation. W_{50} was found as a function of several factors, including rock density, fetch length, historical wind speeds at the site of the reservoir, and the slope of the embankment:

$$W_{50,Hs,old} = \frac{\gamma_r {H_s}^3}{K(G_s - 1)^3 (\cot\alpha)^b} \qquad \text{Equation 1}$$

Where:

W_{50} = Median weight of riprap (lb)
γ_r = Unit weight of rock used for riprap (lb/ft^3)
H_s = Significant wave height (ft)
G_s = Specific gravity of rock
α = Upstream slope angle measured from horizontal
K = Stability factor (3.62 for zero damage, 4.37 for tolerable damage)
b = Empirical coefficient (0.67 for zero damage, 1.0 for tolerable damage)

A gradation was specified based on the median weight of the riprap (W_{50}); the maximum riprap size (W_{100}) was calculated as 4 times W_{50}, and the minimum riprap size (W_5) is calculated as W_{50} divided by 8.

As discussed in Chapter 7 of Reclamation's Design Standard No. 13 [3], other factors also influence riprap performance and should be accounted for by the engineer. Reclamation has investigated whether these factors should be included within design equations. However, these factors have never been included in the design equations due to the successful performance of riprap using Equation 1.

Computation of Characteristic Wave Height – Original Method

Reclamation's method uses the significant wave height (H_s) within equation 1. H_s is defined as the average height of the largest 33% of waves typically expected within a series of waves. H_s was originally calculated as:

$$H_{s,old} = 0.0177 * F^{0.6} * VMPH^{1.23} \quad \text{Equation 2}$$

where F represents the fetch length in miles, and $VMPH$ represents the design wind velocity in miles per hour. This equation was published in 1977 by the U.S. Army Corps of Engineers (USACE). Reclamation's riprap design standard suggests that $VMPH$ have a 90% probability of non-exceedance over the life of the structure, assumed to be a 100-year time period. More information about how to use equation 2 is available in Reclamation's riprap design standard [3].

Method Change #1

In 1984, the USACE replaced H_s with H_{10} in the calculation of W_{50}, resulting in a larger design wave. H_{10} represents the average height of the largest 10% of waves within a series, and can be calculated (assuming a Rayleigh distribution) as:

$$H_{10,old} = 1.27 * H_{s,old} \quad \text{Equation 3}$$

The decision to use a larger H value is particularly significant because the H term is cubed in the determination of W_{50}:

$$W_{50,H10,old} = \frac{\gamma_r {H_{10}}^3}{K(G_s-1)^3 (\cot\alpha)^b} \quad \text{Equation 4}$$

This results in $W_{50,\mathrm{H10,old}}$ being 205% greater than $W_{50,\mathrm{Hs,old}}$ (1.27 cubed, multiplied by 100). Due to the over-conservatism of this modification, Reclamation did not change its method at the time.

Method Change #2

In 2008, the USACE modified the equation used for calculating H_s [6]:

$$H_{s,new} = 0.0245 * F^{0.5} * VMPH(1.1 + 0.0156 * VMPH)^{0.5} \quad \text{Equation 5}$$

Equation 5 increases the influence of F and decreases the influence of $VMPH$, compared to Equation 2. The resulting decrease in $H_{s,new}$ varies exponentially with F; i.e. $H_{s,new}$ decreases significantly when F is large, but only slightly when F is small.

To exemplify this, several hypothetical cases were calculated:

Table D.3. Hypothetical Cases

F **(miles)**	***VMPH*** **(mph)**	**$H_{s,old}$ (Equation 2) (ft)**	**$H_{s,new}$ (Equation 5) (ft)**	**% change**
10.0	90	17.85	11.57	-38%
1.0	60	2.72	2.10	-23%
0.1	90	1.13	1.10	-2%

It should be noted that USACE's adoption of Equation 5 affected the calculation of H_{10} and W_{50}:

$$H_{10,new} = 1.27 * H_{s,new} \qquad \text{Equation 6}$$

$$W_{50,H10,new} = \frac{\gamma_r {H_{10,new}}^3}{K(G_s - 1)^3 (\cot \alpha)^b} \qquad \text{Equation 7}$$

Because Equation 5 results in smaller values for H_s, Equation 7 generally reduces the over-conservatism introduced when H_{10} was adopted in 1984 (Equation 4). Prior to this Design Standard revision, Reclamation had not adopted Equation 7 for sizing riprap. However, Equation 5 *has* been adopted for freeboard analysis and is adopted in this revision of the Embankment Dams Design Standard riprap chapter, as well.

An additional equation for calculating W_{50} has also been suggested, representing if Equation 5 was adopted, but not Equation 6:

$$W_{50,Hs,new} = \frac{\gamma_r {H_{s,new}}^3}{K(G_s - 1)^3 (\cot \alpha)^b} \qquad \text{Equation 8}$$

The following sections compare the W_{50} values produced by Equations 1, 4, 7, and 8. Furthermore, they provide guidance on which method should be used in Reclamation's riprap standard methods.

Effect of Adopting $W_{50,H10,new}$ (Equation 7)

While $W_{50,Hs,old}$ (Equation 1) is currently used for riprap design within Reclamation, $W_{50,H10,new}$ (Equation 7) is being considered to bring Reclamation's standard up-to-date with research conducted by USACE. If Equation 7 is adopted, W_{50} sizes would be increased when $F<0.8$ miles, and decreased when $F>0.8$ miles. However, for some cases (F approximately 0.5 to 1.2 miles), W_{50}

would remain relatively the same (within 10%). The hypothetical cases presented earlier are again used to exemplify how W_{50} would vary:

Table D.4. Variance of $W_{50,H10,new}$ within hypothetical cases

F (miles)	*VMPH* (mph)	$W_{50,Hs,old}$ (Equation 1) (lb)	$W_{50,H10,new}$ (Equation 7) (lb)	% change
10.0	90	70,467	34,080	-52%
1.0	60	250	234	-6%
0.1	90	18	34	+93%

Additional cases are presented in Addendum D-1.

Adequacy of New Riprap Criteria

Equation 7 produces a W_{50} size that is larger for dams with short fetch distances, and smaller for dams with long fetch distances. If adopted, most riprap designs would be less conservative, since most dams have a fetch length greater than 1 mile. To ensure that the decreased riprap sizes would be adequate, design riprap sizes ($W_{50,Hs,old}$, $W_{50,H10,old}$, $W_{50,Hs,new}$, and $W_{50,H10,new}$) were compared to actual riprap sizes constructed ($W_{50,Actual}$), as observed in the Esmiol's "149 Case Histories."

$W_{50,Actual}$ values were estimated based on the riprap specifications presented in "149 Case Histories" (Addendum D-2). Since riprap performance was recorded for the 149 dams presented, a riprap performance could be compared to $W_{50,Actual}$ size. Riprap performance could also be compared to design riprap sizes by assuming that design W_{50} sizes perform similar to riprap with equivalent $W_{50,Actual}$ sizes.

$W_{50,Actual}$ values were only estimated for dams with riprap performance categorized as "excellent" or "failure due to erosion" (D.5). To compare design riprap sizes to $W_{50,Actual}$ sizes, design riprap sizes were also calculated for these dams. To determine these values, F, *VMPH*, specific gravity (G_S), and upstream embankment slope (S_E) were needed. *F* and *VMPH* values were estimated using Google Maps and PFARA software, respectively. G_S and S_E were often included within the specifications. When they were not, G_S was assumed to be 2.65, and S_E was assumed to be 3. Design riprap values were then calculated using Equations 1, 4, 7, and 8.

Riprap that Failed

Riprap cases that failed due to erosion or movement of the riprap particles were generally found to have $W_{50,actual}$ sizes significantly less than what most of the design methods would have required (Figure D.1). The exception to this is for dams with small fetch distances and small design wind speeds (cases F1 through F4). For these dams, the design methods typically required W_{50} sizes less than 500 lb.

It can be seen that $W_{50,H10,old}$ requires a riprap size significantly greater than Reclamation's current standard ($W_{50,Hs,old}$). $W_{50,Hs,new}$ sometimes requires a riprap size greater than $W_{50,actual}$, but in many cases did not. It is therefore not expected to be a reliable design criterion. Riprap designed to meet $W_{50,H10,old}$ criteria would be significantly larger than both the $W_{50,actual}$ sizes, as well as any other design criterion. While it would not be expected to fail, it is not very economical due to its very large size and is likely to be far too conservative.

The current design requirement using ($W_{50,Hs,old}$) would have required riprap sizes reasonably larger than the $W_{50,actual}$ sizes (except for cases F1 through F4). It could therefore be expected to perform adequately. $W_{50,H10,new}$ was typically larger than $W_{50,actual}$ by a reasonable margin (except for cases F1 through F4) and like the current requirement, it could be expected to perform adequately.

Riprap that Performed Excellently

Some of the riprap cases evaluated were found to have used riprap that was significantly overdesigned (Figure D.2); $W_{50,actual}$ was found to exceed the selected design W_{50} sizes.

However, some cases had $W_{50,actual}$ sizes less than the current design requirements ($W_{50,Hs,old}$), including most of the cases for dams with long fetch lengths (Figure D.3). For these cases, increasing the W_{50} design size would be providing unnecessary overconservatism. Using the $W_{50,H10,old}$ requirement is an example of this, as it would be severely overconservative and inefficient.

Additional information regarding the comparison of riprap requirements, including which dams were included (and the riprap requirements specified at each dam), can be found in Addendum D-2.

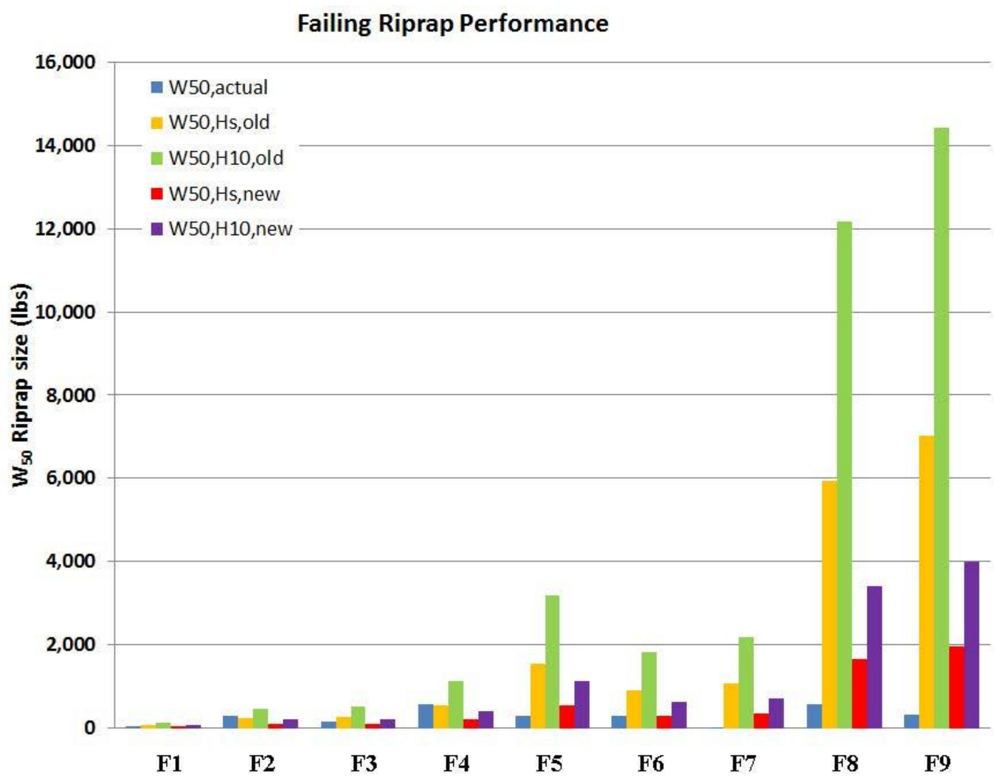

Figure D.1. W_{50} **sizes of riprap "failures" due to erosion.**

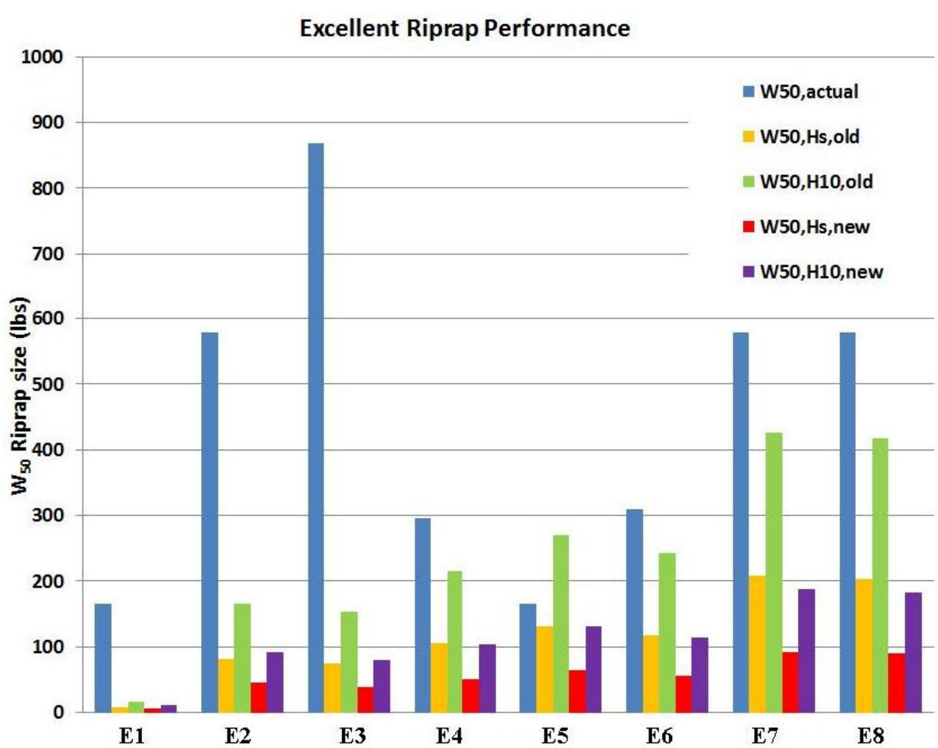

Figure D.2. Comparison of W_{50} **sizes for riprap on dams where F<1.2.**

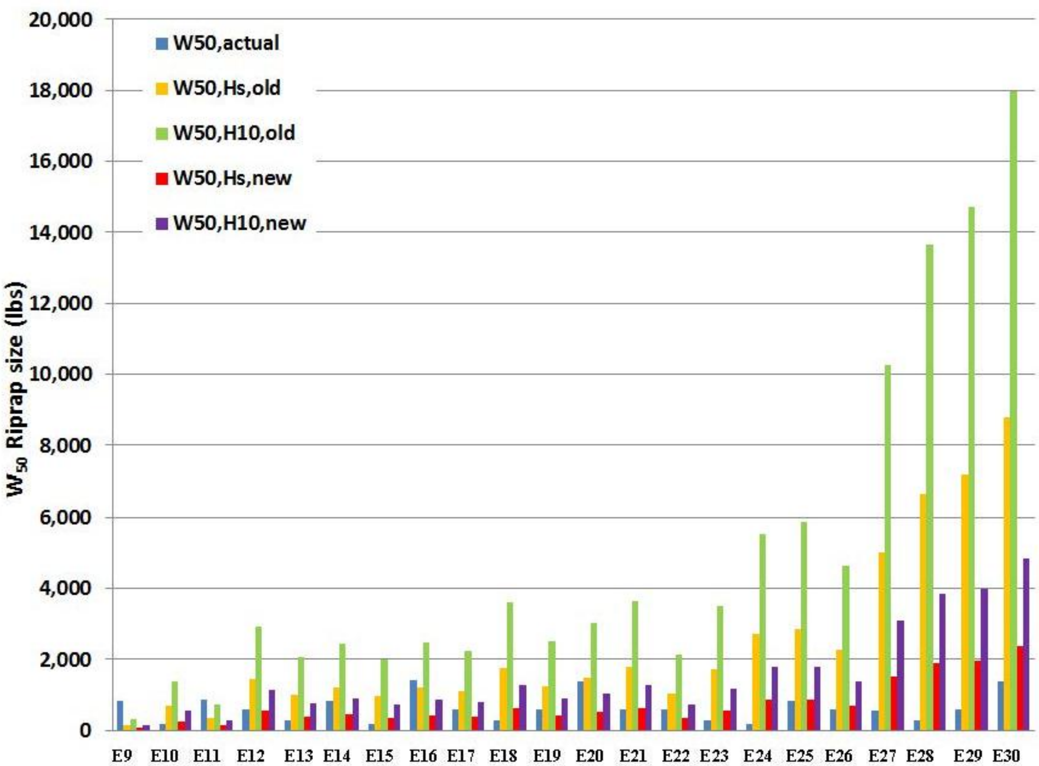

Figure D.3. Comparison of W_{50} sizes for riprap on dams where F>1.2

SUMMARY AND RECOMMENDATIONS

Reclamation has been using the same riprap size design criterion since 1975. The primary reason that the method has not been updated is because it has performed well. However, during that time-span, USACE has made multiple changes to their riprap size requirements, including modifying the way H_s is calculated (Equation 5), and using H_{10} instead of H_s to calculate W_{50} (Equation 7).

It is recommended that Reclamation adopt USACE's most recent riprap design methods (Equations 5 and 7) for the following reasons:

- $W_{50,H10,new}$ will reduce the required riprap size for dams with large fetch distances, reducing construction costs and overconservatism.

- $W_{50,H10,new}$ will increase the required riprap size for dams with small fetch distances.

- Previous method changes (the most significant being the change in Equation 5 for computing H_s) provided either too much overconservatism or too much underconservatism. However, adopting Equation 7 it is expected that this will not change the requirements by an unreasonable amount (among the dams analyzed, never by more than 45%, D.6).

It is possible that dams with small fetch distances may still need larger riprap to prevent failure. *It is therefore suggested that a minimum* W_{50} *requirement be used* to further reduce the risk of riprap failure. Based on data presented in D.6, as well as previously used requirements and specifications (Tables D.1 and D.2), it is recommended that a minimum W_{50} size of 160 lb be required for all dams. This assures that a minimum median-sized rock would not be less than 1 cubic foot in size. When an adequate rock source is available, consideration should be given to increasing this minimum requirement to 350 lb.

REFERENCES

[1] E. E. Esmiol, "Rock as Upstream Slope Protection for Earth Dams - 149 Case Histories", Dams Branch, Report No. DD-3, U.S. Department of the Interior, Bureau of Reclamation, 1968.

[2] Design of Small Dams, U.S. Department of the Interior, Bureau of Reclamation, 1960.

[3] "Design Standard No. 13, Chapter 7 - Riprap Slope Protection", U.S. Department of the Interior, Bureau of Reclamation, 1992.

[4] "Wave Tank Studies for the Development of Criteria for Riprap," R.R.W Beene, and J.P. Ahrens, 11th ICOLD, Madrid, 1973, vol. III, pp. 257-264.

[5] "Design Standard No. 13, Chapter 7 - Riprap Slope Protection", U.S. Department of the Interior, Bureau of Reclamation, 2013.

Addendum D-1

Additional Tables

Table D.5. Properties of dams used in analyses

CASE	Thickness (ft)	Original Spec	Dam	γ_r	Slope (S_E)	Fetch (miles)	*VMPH* (mph)
			EXCELLENT				
E1	2	C	Crane Prairie	2.65	3	0.25	59
E2	3	B	Gray Reef	2.65	2.5	0.53	75
E3	2	D	Palo Verde Diversion	2.62	4	0.68	70
E4	3	A	Jackson Gulch	2.65	3	0.85	66
E5	3	C	Island Park	2.65	4	0.85	74
E6	3	A	Willow Creek	2.78	3	0.89	70
E7	3	B	Scofield	2.65	2	1.14	64
E8	2	B	Wasco	2.65	2.5	1.15	66
E9	3	D	Casitas	2.55	3	1.40	55
E10	3	C	Pineview	2.65	3	1.80	76
E11	3	D	Bully Creek	2.65	3	1.80	64
E12	3	B	Glendo	2.64	2.5	1.96	86
E13	3	A	Tiber	2.65	3	2.12	78
E14	3	D	Wanship	2.50	3	2.17	76
E15	3	C	Green Mountain	2.69	3	2.26	76
E16	3	E	Trinity	2.75	2.5	2.43	77
E17		B	Little Wood River	2.65	3	2.47	74
E18	3	A	Shadehill	2.65	2.5	2.50	81
E19	3	B	Taylor Park	2.65	3	2.50	76
E20	3	E	Whiskeytown	2.67	2.5	2.63	76
E21	2	B	Sherburne	2.65	3	2.70	81
E22	3	B	Deer Creek	2.65	3	2.70	70
E23	3	A	North	2.65	3	3.00	76
E24	3	C	Bull Lake	2.65	3	3.40	81
E25	3	D	Foss	2.55	3	4.00	73
E26		B	Clark Canyon	2.69	3	4.17	71
E27	3	B	Granby Dikes	2.59	2	4.24	78
E28	3	A	Horsetooth	2.65	2.5	5.25	81
E29		B	Willard	2.65	2.5	5.91	78
E30	3	E	Fort Cobb	2.70	2.5	6.20	82
			FAILURES				
F1		50^{th} %= 0.25 CF	Nelson Dikes	2.65	3	0.77	60
F2		A	Olympus	2.65	3	1.10	72
F3		C	Unity	2.59	3	1.50	62
F4		B	Anderson Ranch	2.65	3	2.00	68
F5		A	Enders	2.65	2.5	2.40	80
F6		A	Cascade	2.65	3	2.80	66
F7		< 6”	Lower Deer Flat	2.65	3	3.00	67
F8		B	Caballo	2.65	3	5.40	80
F9		A	Trenton	2.76	2.5	5.60	83

Table D.6. Comparison of design equation requirements

CASE	FETCH (miles)	Dam	$W_{50,actual}$	Equation 1 $W_{50,Hs,old}$ (lb)	Equation 4 $W_{50,H10,old}$ (lb)	Equation 8 $W_{50,Hs,new}$ (lb)	Equation 7 $W_{50,H10,new}$ (lb)	% Change Equ. 1 to Equ. 7
				EXCELLENT				
E1	0.3	Crane Prairie	165	8	17	6	12	42%
E2	0.5	Gray Reef	579	78	160	43	89	14%
E3	0.7	Palo Verde Diversion	869	100	204	51	105	6%
E4	0.9	Jackson Gulch	296	114	233	55	112	-2%
E5	0.9	Island Park	165	174	355	84	172	-1%
E6	0.9	Willow Creek	310	124	255	59	121	-3%
E7	1.1	Scofield	579	172	353	76	155	-10%
E8	1.2	Wasco	579	196	401	86	176	-10%
E9	1.4	Casitas	845	170	348	70	144	-15%
E10	1.8	Pineview	165	739	1,514	286	586	-21%
E11	1.8	Bully Creek	878	392	803	150	308	-21%
E12	2.0	Glendo	577	1,382	2,832	529	1,083	-22%
E13	2.1	Tiber	296	1,092	2,236	403	826	-24%
E14	2.2	Wanship	829	1,350	2,766	494	1,012	-25%
E15	2.3	Green Mountain	168	1,041	2,132	376	771	-26%
E16	2.4	Trinity	1,409	1,129	2,313	400	819	-27%
E17	2.5	Little Wood River	579	1,184	2,424	416	851	-28%
E18	2.5	Shadehill	296	1,688	3,459	596	1,221	-28%
E19	2.5	Taylor Park	579	1,335	2,734	468	959	-28%
E20	2.6	Whiskeytown	1,368	1,414	2,896	488	1,000	-29%
E21	2.7	Sherburne	579	1,939	3,972	669	1,370	-29%
E22	2.7	Deer Creek	579	1,132	2,318	386	790	-30%
E23	3.0	North	296	1,853	3,796	615	1,260	-32%
E24	3.4	Bull Lake	165	2,937	6,015	945	1,936	-34%
E25	4.0	Foss	845	3,193	6,540	969	1,985	-38%
E26	4.2	Clark Canyon	587	2,439	4,996	730	1,495	-39%
E27	4.2	Granby Dikes	566	4,216	8,636	1,265	2,591	-39%
E28	5.3	Horsetooth	296	6,419	13,149	1,814	3,715	-42%
E29	5.9	Willard	579	6,914	14,162	1,877	3,846	-44%
E30	6.2	Fort Cobb	1,384	8,336	17,076	2,244	4,596	-45%
				FAILURES				
F1	0.8	Nelson Dikes	41	67	137	33	68	1%
F2	1.1	Olympus	296	249	511	111	228	-8%
F3	1.5	Unity	162	278	570	113	231	-17%
F4	2.0	Anderson Ranch	579	593	1,214	221	452	-24%
F5	2.4	Enders	296	1,499	3,070	535	1,095	-27%
F6	2.8	Cascade	296	972	1,992	327	669	-31%
F7	3.0	Lower Deer Flat	17	1,164	2,384	383	785	-33%
F8	5.4	Caballo	579	6,451	13,213	1,805	3,696	-43%
F9	5.6	Trenton	308	6,589	13,497	1,831	3,751	-43%

Table D.7. Comparison of design wave height equations

CASE	Dam	$H_{s,old}$ (ft)	$H_{s,new}$ (ft)	$H_{10,old}$ (ft)	$H_{10,new}$ (ft)	$H_{s,old}$/ $H_{s,new}$	% Change in H_s
			EXCELLENT				
E1	Crane Prairie	1.16	1.03	1.47	1.30	1.13	-12%
E2	Gray Reef	2.45	2.02	3.11	2.56	1.21	-18%
E3	Palo Verde Diversion	2.61	2.09	3.32	2.66	1.25	-20%
E4	Jackson Gulch	2.78	2.18	3.53	2.76	1.28	-22%
E5	Island Park	3.20	2.51	4.06	3.19	1.27	-22%
E6	Willow Creek	3.07	2.40	3.90	3.04	1.28	-22%
E7	Scofield	3.19	2.43	4.05	3.08	1.32	-24%
E8	Wasco	3.33	2.53	4.23	3.21	1.32	-24%
E9	Casitas	2.99	2.23	3.80	2.83	1.34	-25%
E10	Pineview	5.18	3.78	6.58	4.80	1.37	-27%
E11	Bully Creek	4.20	3.05	5.33	3.87	1.38	-27%
E12	Glendo	6.35	4.61	8.06	5.85	1.38	-27%
E13	Tiber	5.90	4.24	7.50	5.38	1.39	-28%
E14	Wanship	5.80	4.15	7.36	5.27	1.40	-28%
E15	Green Mountain	5.94	4.23	7.54	5.37	1.40	-29%
E16	Trinity	6.31	4.46	8.01	5.67	1.41	-29%
E17	Little Wood River	6.06	4.28	7.70	5.43	1.42	-29%
E18	Shadehill	6.83	4.82	8.67	6.13	1.42	-29%
E19	Taylor Park	6.31	4.45	8.02	5.65	1.42	-29%
E20	Whiskeytown	6.51	4.57	8.26	5.80	1.43	-30%
E21	Sherburne	7.15	5.01	9.08	6.37	1.43	-30%
E22	Deer Creek	5.97	4.17	7.59	5.30	1.43	-30%
E23	North	7.04	4.88	8.94	6.19	1.44	-31%
E24	Bull Lake	8.21	5.63	10.43	7.14	1.46	-31%
E25	Foss	7.96	5.35	10.11	6.80	1.49	-33%
E26	Clark Canyon	7.89	5.28	10.02	6.70	1.50	-33%
E27	Granby Dikes	8.95	5.99	11.36	7.61	1.49	-33%
E28	Horsetooth	10.65	6.99	13.53	8.88	1.52	-34%
E29	Willard	10.92	7.07	13.87	8.98	1.54	-35%
E30	Fort Cobb	11.95	7.72	15.18	9.80	1.55	-35%
			FAILURES				
F1	Nelson Dikes	2.33	1.84	2.96	2.34	1.26	-21%
F2	Olympus	3.61	2.76	4.58	3.50	1.31	-24%
F3	Unity	3.62	2.67	4.59	3.40	1.35	-26%
F4	Anderson Ranch	4.81	3.46	6.11	4.40	1.39	-28%
F5	Enders	6.56	4.65	8.33	5.91	1.41	-29%
F6	Cascade	5.68	3.95	7.21	5.01	1.44	-30%
F7	Lower Deer Flat	6.03	4.16	7.66	5.29	1.45	-31%
F8	Caballo	10.67	6.98	13.55	8.86	1.53	-35%
F9	Trenton	11.41	7.45	14.49	9.46	1.53	-35%

Table D.8. Effect of design method changes

Fetch (miles)	$VMPH$ (mph) 50	60	70	80	90	$VMPH$ (mph) 50	60	70	80	90	$VMPH$ (mph) 50	60	70	80	90	$VMPH$ (mph) 50	60	70	80	90
	$H_{S,old}$ from Equation 2 (ft)					$H_{S,new}$ from Equation 5 (ft)					$P = H_{s,new}/H_{s,old}$					$W_r = 100*P*f_{h10}$ (% of Equation 1)				
0.1	0.55	0.68	0.83	0.97	1.13	0.53	0.66	0.80	0.95	1.10	0.97	0.97	0.97	0.97	0.98	187	186	187	189	192
0.2	0.83	1.04	1.25	1.48	1.71	0.75	0.94	1.14	1.34	1.56	0.91	0.90	0.91	0.91	0.91	152	151	152	153	156
0.3	1.06	1.32	1.60	1.88	2.18	0.92	1.15	1.39	1.64	1.91	0.87	0.87	0.87	0.87	0.88	135	134	134	136	138
0.4	1.26	1.57	1.90	2.24	2.59	1.06	1.33	1.61	1.90	2.21	0.85	0.84	0.85	0.85	0.85	123	123	123	125	127
0.5	1.44	1.80	2.17	2.56	2.96	1.19	1.48	1.80	2.12	2.47	0.83	0.83	0.83	0.83	0.83	115	115	115	117	118
0.6	1.60	2.00	2.42	2.86	3.30	1.30	1.62	1.97	2.33	2.70	0.81	0.81	0.81	0.81	0.82	109	109	109	110	112
0.7	1.76	2.20	2.66	3.13	3.62	1.41	1.75	2.12	2.51	2.92	0.80	0.80	0.80	0.80	0.81	104	104	104	105	107
0.8	1.90	2.38	2.88	3.39	3.92	1.50	1.88	2.27	2.69	3.12	0.79	0.79	0.79	0.79	0.80	100	100	100	101	103
0.9	2.04	2.56	3.09	3.64	4.21	1.59	1.99	2.41	2.85	3.31	0.78	0.78	0.78	0.78	0.79	97	96	97	98	99
1	2.18	2.72	3.29	3.88	4.48	1.68	2.10	2.54	3.00	3.49	0.77	0.77	0.77	0.77	0.78	94	93	94	95	96
1.2	2.43	3.04	3.67	4.33	5.00	1.84	2.30	2.78	3.29	3.82	0.76	0.76	0.76	0.76	0.76	89	88	89	90	91
3	4.21	5.26	6.36	7.50	8.67	2.91	3.63	4.40	5.20	6.04	0.69	0.69	0.69	0.69	0.70	67	67	67	68	69
4	5.00	6.26	7.56	8.91	10.30	3.36	4.20	5.08	6.01	6.98	0.67	0.67	0.67	0.67	0.68	62	61	62	62	63
5	5.72	7.15	8.65	10.19	11.78	3.76	4.69	5.68	6.72	7.80	0.66	0.66	0.66	0.66	0.66	58	58	58	58	59
6	6.38	7.98	9.65	11.37	13.14	4.11	5.14	6.22	7.36	8.55	0.65	0.64	0.64	0.65	0.65	55	54	55	55	56
7	6.99	8.75	10.58	12.47	14.41	4.44	5.55	6.72	7.95	9.23	0.64	0.63	0.63	0.64	0.64	52	52	52	53	54
8	7.58	9.48	11.46	13.51	15.62	4.75	5.93	7.18	8.49	9.87	0.63	0.63	0.63	0.63	0.63	50	50	50	51	51
9	8.13	10.18	12.30	14.50	16.76	5.04	6.29	7.62	9.01	10.47	0.62	0.62	0.62	0.62	0.62	49	48	48	49	50
10	8.66	10.84	13.11	15.44	17.85	5.31	6.63	8.03	9.50	11.03	0.61	0.61	0.61	0.61	0.62	47	47	47	47	48

F_{h10} = 2.05 (Factor resulting from using H_{10} instead of H_s).

Addendum D-2

Method Used to Estimate $W_{50,\mathrm{actual}}$

							Totals
	% Passing (range)	from	100%	45%	35%	0%	
		to	100%	65%	55%	10%	
	(1) Assumed % passing		100%	55%	45%	5%	
	(2) Weight (lb)		4000	1000	600	150	
	(3) Expected % within each band			55%	35%	10%	100%
	weight range of each band	**(4)** from		4000	1000	600	
		(5) to		1000	600	0	
	(6) n*			2.5	2.25	4	
	(7) Assumed weight of each band = (max+min) / n = [(4)+(5)]/(6)			2000	640	150	
Weight, W_{50}	**(8)** Weight contribution of band = (3) x (7)			1100	224	15	1,339 lb
Volume, V_{50}	**(9)** Weight to volume = (8)/γ_r**		= 1339 / γ_r				8.10 ft^3
Diameter, D_{50}	**(10)** Volume to diameter = $[(9)*1.333]^{0.333}$		= $(8.10 * 1.333)^{0.333}$				2.21 ft

*n was assigned based on where the average weight was assumed to be within each band

**γ_r is assumed to be 165 lb/ft^3 (G_s = 2.65)

Addendum D-3

Dams Constructed After 1967

To further evaluate the success of dams constructed after "149 Case Histories" was published, several additional dams were reviewed, including Scoggins Dam (completed in 1975), Ririe Dam (1977), Ridgway Dam (1987), and Ridges Basin Dam (2007). The riprap at these dams has been found to perform successfully. The estimated W_{50} riprap sizes for these dams (based on gradations included in their specifications) were found to be larger than the W_{50} sizes required by the deterministic methods (except for Ririe Dam). This is probably because conservatism was built into the specifications.

Ririe dam's riprap specification varied from Reclamation's design standard; it specified the percent of material (by weight) that was required to be larger than a certain size. The W_{50} size is smaller than would typically be required today. The estimated $W_{50,\mathrm{actual}}$ size at Ririe was 288 lb., while the $W_{50,\mathrm{H10,new}}$ required by the new standard (Equation 7) would be 456 lb.

The riprap at Ridges Basin dam was designed in accordance with Chapter 7 of *Reclamation's Design Standard No 13*. $W_{50,\mathrm{H}}$ was calculated and minimum and maximum sizes were selected based on the $W_{50,\mathrm{H}}$ size. The gradation requirements included in the specification were altered to be more functional, but were selected based on these sizes. It is noted that the $W_{50,\mathrm{actual}}$ size estimated based on the specified gradation (1485 lb) was approximately 7% larger than the calculated $W_{50,\mathrm{Hs,old}}$ size (1,385 lb) documented in designs. This could be either due to the adjustment of the gradation itself, or it could be due to error in the method used to estimate W_{50} based on the gradation. The $W_{50,\mathrm{H10,new}}$ calculated using Equation 7 was 1030 lb. The riprap constructed at Ridges Basin Dam is larger than what would be required by the new Design Standard.

Ridgway dam's riprap specification followed the exact same guidelines as those presented in the *Design of Small Dams, 2nd Edition*. The $W_{50,\mathrm{actual}}$ calculated for Ridgway was 1,465 lb, significantly larger than the $W_{50,\mathrm{H10,new}}$ value of 233 lb required by Equation 7. Ridgway Dam was therefore constructed using riprap significantly larger than what would be required by the new Design Standard.

The riprap size specifications for Scoggins dam followed the exact same gradation requirements as those recommended in the main text within *Design of Small Dams, 2nd Edition*. The resulting $W_{50,\mathrm{actual}}$ value was estimated to be 1,641 lb. The $W_{50,\mathrm{H10,new}}$ value required by Equation 7 was 681 lb. Scoggins dam was therefore constructed using riprap significantly larger than what would be required by the new Design Standard.

RIRIE W_{max}=1000 W_{min}=75							Totals
	% Passing (range)	from	**100%**	**50%**	**0%**	**0%**	
		to	**100%**	**100%**	**50%**	**10%**	
	(1) Assumed % passing		**100%**	**75%**	**25%**	**0%**	
	(2) Weight (lb)		**1000**	**400**	**200**	**75**	
	(3) Expected % within each band			25%	50%	25%	**100%**
	weight range of each band	**(4) from**		**1000**	**400**	**200**	
		(5) to		**400**	**200**	**75**	
	(6) n*			2.5	2.5	2.5	
	(7) Assumed weight of each band = (max+min) / n = [(4)+(5)]/(6)			560	240	110	
Weight, W_{50}	**(8) Weight contribution of band = (3) x (7)**			140	120	27.5	**287.5 lb**
Volume, V_{50}	**(9) Weight to volume = (8)/γ_r****						**1.7 ft^3**
Diameter, D_{50}	**(10) Volume to diameter = [(9)*1.333]$^{0.333}$**						**1.3 ft**

Slope=2:1, F=1.3 miles, VMPH=77mph, G_s=2.65

RIDGES BASIN Wmax=5000 Wmin=50							Totals
	% Passing (range)	from	**100%**	**60%**	**20%**	**0%**	
		to	**100%**	**80%**	**45%**	**20%**	
	(1) Assumed % passing		**100%**	**70%**	**33%**	**10%**	
	(2) Weight (lb)		**5000**	**800**	**150**	**50**	
	(3) Expected % within each band		30%	38%	23%	10%	**100%**
	weight range of each band	**(4) from**	**5000**	**2500**	**800**	**150**	
		(5) to	**2500**	**800**	**150**	**50**	
	(6) n*		2.5	2.5	2.5	4	
	(7) Assumed weight of each band = (max+min) / n = [(4)+(5)]/(6)		3000	1320	380	50	
Weight, W_{50}	**(8) Weight contribution of band = (3) x (7)**		900	495	85.5	5	1485.5
Volume, V_{50}	**(9) Weight to volume = (8)/γ_r****						9.5
Diameter, D_{50}	**(10) Volume to diameter = [(9)*1.333]$^{0.333}$**						2.3

Slope=2:1, F=2.2 miles, VMPH=73mph, G_s=2. 5

RIDGWAY W_{max}=4500 W_{min}=100						Totals
	% Within Band	from	**30%**	**60%**	**0%**	
		to	**40%**	**70%**	**10%**	
	(1) Expected % within each band (avg)		35%	55%	10%	**100%**
	(2) Weight (lb)		**4500**	**2250**	**100**	
	(3) Assumed % passing		**100%**	**65%**	**10%**	
	weight within band	(4) from	**4500**	**2250**	**100**	
		(5) to	**2250**	**100**	**0**	
	(6) n*		2.5	2.5	4	
	(7) Assumed weight of each band = (max+min) / n = [(4)+(5)]/(6)		2700	940	25	
Weight, W_{50}	(8) Weight contribution of band = (3) x (7)		945	517	2.5	**1,464.5 lb**
Volume, V_{50}	(9) Weight to volume = (8)/γ_r**					**8.9 ft^3**
Diameter, D_{50}	(10) Volume to diameter = $[(9)*1.333]^{0.333}$					**2.3 ft**

Slope=3:1, F=1.4 miles, VMPH=67mph, G_s=2.65

SCOGGINS W_{max}=4500 W_{min}=100						Totals
	% Within Band	from	**40%**	**50%**	**0%**	
		to	**50%**	**60%**	**10%**	
	(1) Expected % within each band (avg)		45%	45%	10%	**100%**
	(2) Weight (lb)		**4500**	**2250**	**100**	
	(3) Assumed % passing		**100%**	**55%**	**10%**	
	weight range of each band	(4) from	**4500**	**2250**	**100**	
		(5) to	**2250**	**100**	**0**	
	(6) n*		2.5	2.5	4	
	(7) Assumed weight of each band = (max+min) / n = [(4)+(5)]/(6)		2700	940	25	
Weight, W_{50}	(8) Weight contribution of band = (3) x (7)		1215	423	2.5	**1,640.5 lb**
Volume, V_{50}	(9) Weight to volume = (8)/γ_r**					**9.9 ft^3**
Diameter, D_{50}	(10) Volume to diameter = $[(9)*1.333]^{0.333}$					**2.4 ft**

Slope=2.5:1, F=2.3 miles, VMPH=71mph, G_s=2.65