

Riprap Design Criteria, Specifications, and Quality Control

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I. INTRODUCTION

In the United States, many different techniques are currently used to determine the size and extent of a riprap installation, and existing techniques and procedures for design of riprap protection can be confusing and difficult to apply. Depending on the technique used to size riprap, the required size of stone can vary widely. Most state Departments of Transportation (DOTs) have their own specifications for classifying riprap size and gradation and there is not a consistent classification system or set of specifications that can be used when preparing plans or assembling a specification package for a project. In addition, various construction practices are employed for installing riprap; many of them are not effective and projects requiring the use of riprap historically have suffered from poor construction practices and poor quality control. National Cooperative Highway Research Program (NCHRP) Project 24-23 "Riprap Design Criteria, Specifications, and Quality Control" [1] was a synthesis study to develop a unified set of guidelines, specifications, and procedures that can be accepted by the state DOTs. The effort was similar in intent to the European Union's recently adopted unified standard for riprap, a standard that transcends geographic and institutional boundaries [2].

The basic objectives of NCHRP 24-23 were to develop design guidelines, material specifications and test methods, construction specifications, and construction, inspection and quality control guidelines for riprap for a range of applications, including: revetment on streams and riverbanks, bridge piers and abutments, and bridge scour countermeasures such as guide banks. A fundamental premise of this study is that riprap is an integrated system and that successful performance of a riprap installation depends on the response of each component of the system to hydraulic and environmental stresses throughout its service life.

This paper presents an overview of the philosophy that underpins the recommendations of NCHRP Project 24-23. Then, those recommendations are summarized as they relate to: (1) riprap design

equations, (2) filter requirements, (3) material and testing specifications, (4) construction and installation guidelines, and (5) inspection and quality control.

II. RIPRAP – AN INTEGRATED SYSTEM

A. Overview

Since riprap is a natural material composed of stone or boulders and is readily available in many areas, it has been used extensively in erosion protection works. In some areas, riprap is produced by quarrying hard, durable rock. In other areas, riprap is collected from talus or by excavating large river cobbles from alluvial deposits. Riprap, when properly designed and used for erosion protection, has an advantage over rigid structures because it is flexible when under attack by river currents, it can remain functional even if some individual stones may be lost, and it can be repaired relatively easily. Properly constructed riprap can provide long-term protection if it is inspected and maintained on a periodic basis as well as after flood events.

A properly designed, installed, and maintained riprap system has a functionality that is greater than the sum of its parts, i.e., successful performance depends on the system responding to hydraulic and environmental stresses as an integrated whole throughout its service life. Design of a riprap scour control system requires knowledge of: river bed, bank, and foundation material; flow conditions including velocity, depth and orientation; riprap characteristics of size, density, durability, and availability; location, orientation and dimensions of piers, abutments, guide banks, and spurs; and the type of interface material between riprap and underlying foundation which may be geotextile fabric or a filter of sand and/or gravel.

Designing riprap as an integrated system requires a life-cycle approach to the design, production, transport, installation, inspection, and maintenance of the system. The efficacy of rock riprap depends on quality of the rock; weight, shape, or size of individual rocks; slope of the embankment or

channel; thickness of the riprap layer; and stability of the bedding or filter on which the riprap is placed. Because of the size and weight of riprap, transport and placement is generally by mechanical means. Failure of riprap often is the result of poor construction techniques and poor quality control relating to weight or size. Quality control begins at the quarry. Inspection must ensure correct weight or size, density, and gradation. Transportation can be by truck, train, or barge where segregation can occur. Stockpiles at the job site should be checked for segregation and adjustments made to ensure that proper gradation is maintained.

Thus, uniform specifications and/or guidelines for riprap must be developed considering production capabilities and control at the quarry as well as at the job site and during transportation, handling, moving, and placement. Guidelines and procedures for on-site inspection and monitoring riprap also should be developed providing reasonable limits and tolerances for materials and workmanship that can be expected as construction industry standards. Constructability issues must be considered so as to accommodate site constraints, permit conditions, and the physical characteristics of the system. Additionally, the placement of ancillary system components, including filter and/or bedding requirements must be addressed for various riprap applications.

B. Life-Cycle Approach

Conceptually, a life-cycle approach, as applied to an erosion or scour countermeasure such as riprap, would incorporate a host of factors into a framework for decision making considering initial design, construction, and long-term maintenance. These factors could include engineering judgment applied to design alternatives, materials availability and cost, installation equipment and practices, and maintenance assumptions. Life cycle costs for a riprap project are influenced by three major components:

- Initial construction materials and delivery costs
- Initial construction installation costs associated with labor and equipment
- Periodic maintenance during the life of the installation

Obviously, quantity and unit cost of alternative materials will vary depending on the specific project conditions, as well as local and regional factors. Some issues to consider when developing a life-cycle cost estimate would include:

- Availability of materials of the required size and weight
- Haul distance
- Site access
- Equipment requirements
- Construction underwater vs. placement in the dry
- Environmental and water quality issues and permitting requirements
- Habitat mitigation for threatened and endangered species
- Traffic control during construction and/or maintenance activities
- Local labor rates
- Construction using DOT resources vs. outside contract
- Design life of the installation
- Anticipated frequency and extent of periodic maintenance and repair activities

While it was not the intent of NCHRP 24-23 to develop a life-cycle "formula" for riprap projects, the life-cycle concept emphasizes the need to consider riprap as an integrated system where the performance of all system components is considered throughout the design life of the project.

C. Risk and Failure

The risk of failure should be considered when evaluating the performance of riprap as an integrated system to prevent erosion or scour. There are a number of methods available for assessing the causes and effects of a wide variety of factors in uncertain, complex systems and for making decisions in the light of uncertainty. One approach, failure modes and effects analysis, is a qualitative procedure to systematically identify potential component failure modes and assess the effects of associated failures on the operational status of the system [3].

Applying a failure modes and effects analysis to a riprap installation emphasizes the integrated nature of the riprap system, and provides a method to identify system failure as a basis for evaluating riprap performance. In developing a risk-based method for selecting bridge scour countermeasures, reference [3] developed a failure modes and effects analysis for riprap similar to Table 1.

D. Service Life and Safety

When selecting a "service life" criterion for various types of bank protection measures for transportation facilities, safety must be a primary consideration. To assume that bank protection is installed to protect a facility (bridge, roadway embankment, etc.)

overlooks the mission and design goals of the highway agency. For DOTs in the U.S. safety of the traveling public is the first priority when setting service-life standards for riprap protection. Concurrent goals are protection of public and private

property, protection of fish and wildlife resources, and enhancement of environmental attributes. A riprap system does not protect a facility, but rather the lives of the public who use that facility [4].

TABLE I.
FAILURE MODES AND EFFECTS ANALYSIS FOR RIPRAP REVETMENT

Failure Modes	Effects on Other Components	Effects on Whole System	Detection Methods	Compensating Provisions
Translational slide or slump (slope failure)	Disruption of armor layer	Catastrophic failure	Mound of rock at bank toe; unprotected upper bank	Reduce bank slope; use more angular or smaller rock; use granular filter rather than geotextile fabric
Particle erosion (rock undersized)	Loss of armor layer, erosion of filter	Progressive failure	Rock moved downstream from original location, exposure of filter	Increase rock size; modify rock gradation
Piping or erosion beneath armor (improper filter)	Displacement of armor layer	Progressive failure	Scalloping of upper bank; bank cutting; voids beneath and between rocks	Use appropriate granular or geotextile filter
Loss of toe or key (under designed)	Displacement or disruption of armor layer	Catastrophic failure	Slumping of rock, unprotected upper bank	Increase size, thickness, depth, or extent of toe or key

Thus, service-life for a riprap installation should be based on the importance of the facility to the public, that is, the risk of losing the facility and how that loss may directly or indirectly affect the traveling public, as well as the difficulty and cost of future repair or replacement. The conditions that constitute an "end of service life" for a riprap installation are largely dependent on the confidence one has that a degraded condition will be detected and corrected in a timely manner (e.g., during a post-flood inspection). Generally, for facilities that are rarely checked or inspected a very conservative (i.e., shorter) service life would be appropriate, while a less conservative standard could be used for facilities that are inspected regularly.

Service life for a riprap installation can be considered a measure of the durability of the total, integrated bank, pier, abutment or countermeasure protection system. The response of a riprap system over time to typical stresses such as flow conditions (floods and droughts) or normal deterioration of system components must also be considered. Response to less typical (but plausible) stresses such as fire, vandalism, seismic activity or accidents may also affect service life. Maintenance during the life cycle of a riprap installation where such work does not constitute total reconstruction or replacement, should not be considered as the end of service life for the riprap system. In fact, a life-cycle approach to maintenance may extend the service life of a riprap installation and reduce the total cost over the life of the project.

III. RECOMMENDATIONS - NCHRP PROJECT 24-23

Conclusions and recommendations for each of the functional areas investigated for the riprap applications of interest to NCHRP 24-23 (revetment, bridge pier and abutment, and countermeasures) are summarized in the following paragraphs.

A. Riprap Design Equations

Design equations for sizing riprap were evaluated with sensitivity analyses using laboratory and/or field data, where available, for the applications of interest to this study. Based on the sensitivity analyses, the following design equations or design approaches are recommended for each application.

1. For revetment riprap, the U.S. Army Corps of Engineers EM1601 equation is recommended as the most comprehensive approach for sizing riprap considering the ability of the basic equation to discriminate between stable and failed riprap, bank and bend correction factors, and the reasonableness of safety/stability factors [5] [6].
2. For pier riprap, the HEC-23 [7] equation is recommended as the most reliable design equation for sizing riprap. The velocity multiplication factors for round and square nose piers were confirmed using available laboratory data [8].
3. For abutment riprap, the FHWA Set Back Ratio method as presented in HEC-23 [7] was confirmed, using 2-dimensional computer modeling, as an accurate approach for

estimating flow velocity and sizing riprap at an abutment. It is recommended, however, that the computed characteristic average velocity not exceed the maximum velocity in the channel [8].

4. For guide bank riprap, the abutment riprap design equations can be used [7]. The recommended velocity for computing riprap size at a guide bank is 0.85 times the velocity estimated using the Set Back Ratio method for an abutment [8].

B. Filter Requirements

In the U.S., filter design criteria is the most overlooked aspect of riprap design. More emphasis must be given to compatibility criteria between the filter (granular or geotextile) and the soil. Correct filter design reduces the effects of piping by limiting the loss of fines, while simultaneously maintaining a permeable, free-flowing interface. Filter processes and existing methods for design and placement were thoroughly investigated and discussed. Design and placement guidance for both granular and geotextile filters is provided.

1. Historically in the U.S., the Terzaghi criteria have been used for design of granular filters. It is recommended that an alternative approach, widely used in Europe, which follows the Cistin-Ziems methodology be considered as a practical alternative for filter design. As a rule of thumb, the gradation curve of the granular filter material should be approximately parallel to that of the base soil. Parallel gradation curves

minimize the migration of particles from the finer material into the coarser material. Reference [9] summarizes the procedure originally developed by Cistin and Ziems whereby the d_{50} size of the filter is selected based on the coefficients of uniformity (d_{60}/d_{10}) of both the base soil and the filter material. With this method, the grain size distribution curves do not necessarily need to be approximately parallel. Figure 1 provides a design chart based on the Cistin-Ziems approach.

2. For many applications, placing a geotextile filter under water is a challenge. For low-velocity applications a product similar to that used in Germany, the SandMat™, is recommended. The SandMat™ is essentially a blanket of two non-woven geotextiles (or a woven and a non-woven) with a layer of sand in between. The composite blanket has a high specific gravity so it sinks readily. For higher velocity or deep water applications, European practice calls for use of sand-filled geocontainers. For specific project conditions, geosynthetic containers can be chosen that combine the resistance against hydraulic loads with the filtration capacity demanded by the application. Geosynthetic containers have proven stable against erosive forces under a range of conditions, including wave-attack environments. There are many applications where adoption of these approaches to filter placement in U.S. practice would be highly beneficial.

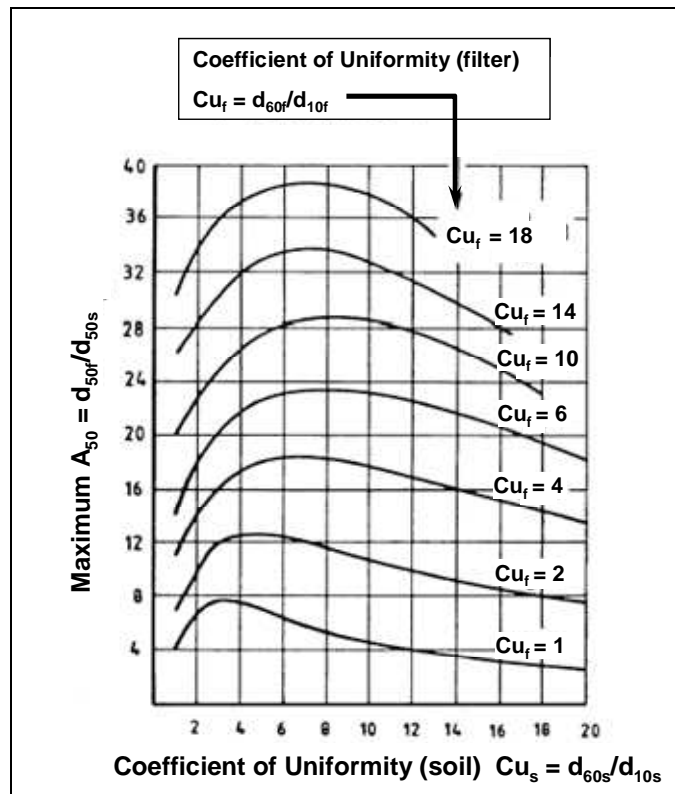


Figure 1. Filter design chart according to Cistin – Ziems [9].

3. The laboratory testing phases of NCHRP Projects 24-07(1) and 24-07(2) included evaluation of riprap as a pier scour countermeasure [10] [11]. For this application, it was found that granular filters performed poorly in the riverine case where bedforms are present. Specifically, during the passage of dune troughs past the pier that are deeper than the riprap armor, the underlying finer particles of a granular filter are rapidly swept away. The result is that the entire installation becomes progressively destabilized beginning at the periphery and working in toward the pier (see Figure 2). It is strongly recommended that only geotextile filters be used at bridge piers in riverine systems where dune type bedforms may be present during high flows. These laboratory studies also resulted in the finding that geotextile filters at piers should not be extended to the periphery of the riprap, but instead should terminate at two-thirds the riprap extent. With these two exceptions, the remainder of the guidance provided for filters for revetment riprap is appropriate for riprap installations at bridge piers.
4. The guidance provided for filters for revetment riprap is generally appropriate for riprap installations at bridge abutments located on floodplains and set back from the main channel.

In the case where the abutment is integral with the bank of the main channel, the same concern regarding the use of granular filters exists as for pier riprap. That is, if dune troughs passing the abutment are deeper than the riprap apron thickness, the underlying finer particles of a granular layer can be rapidly swept away. The result is that the entire riprap installation becomes progressively destabilized beginning at the periphery and working in toward the abutment. For this reason, it is strongly recommended that only geotextile filters be used at bridge abutments in riverine systems where dune type bedforms may be present during high flows, and where the abutment and/or abutment riprap apron extend into the main channel. In addition, where the abutment and/or abutment riprap apron extend into the main channel, the geotextile filter should not be extended to the periphery of the riprap, but instead should terminate at two-thirds the riprap extent.

5. The guidance provided for filters for revetment riprap is generally appropriate for countermeasures constructed of or armored by riprap, such as guide banks or spurs. Scour at the nose of the guide bank or spur is of particular concern. Additional riprap should be placed around the upstream end of the guide bank or spur to protect the embankment material

I	6 in	3.5	5.0	3.7	5.2	5.7	6.9	6.3	7.5	7.8	9.2	12.0
II	9 in	5.2	7.6	5.5	7.8	8.5	10.5	9.5	11.5	11.5	14.0	18.0
III	12 in	7.0	10.0	7.3	10.5	11.5	14.0	12.5	15.0	15.5	18.5	24.0
IV	15 in	8.7	12.5	9.2	13.0	14.5	17.5	16.0	19.0	19.5	23.0	30.0
V	18 in	10.5	15.0	11.0	15.5	17.0	20.5	19.0	22.5	23.5	27.5	36.0
VI	21 in	12.0	17.5	13.0	18.5	20.0	24.0	22.0	26.5	27.5	32.5	42.0
VII	24 in	14.0	20.0	14.5	21.0	23.0	27.5	25.0	30.0	31.0	37.0	48.0
VIII	30 in	17.5	25.0	18.5	26.0	28.5	34.5	31.5	37.5	39.0	46.0	60.0
IX	36 in	21.0	30.0	22.0	31.5	34.0	41.5	38.0	45.0	47.0	55.5	72.0
X	42 in	24.5	35.5	25.5	36.5	40.0	48.5	44.0	52.5	54.5	64.5	84.0

TABLE 3.
MINIMUM AND MAXIMUM ALLOWABLE PARTICLE WEIGHT IN POUNDS

Nominal Riprap Class by Median Particle Weight		W ₁₀		W ₁₅		W ₅₀		W ₆₀		W ₈₅		W ₁₀₀
Class	Weight	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Max
I	20 lb	3	10	4	12	15	27	20	34	39	64	140
II	60 lb	12	35	13	39	51	90	69	120	130	220	470
III	150 lb	27	83	32	93	120	210	160	270	310	510	1100
IV	300 lb	54	160	62	180	240	420	320	540	600	1000	2200
V	1/4 ton	93	280	110	310	410	720	550	950	1050	1750	3800
VI	3/8 ton	150	450	170	500	650	1150	850	1450	1650	2800	6000
VII	1/2 ton	220	670	260	740	950	1700	1300	2200	2500	4100	9000
VIII	1 ton	430	1300	500	1450	1900	3300	2500	4300	4800	8000	17600
IX	2 ton	740	2250	860	2500	3300	5800	4400	7400	8300	13900	30400
X	3 ton	1200	3600	1350	4000	5200	9200	7000	11800	13200	22000	48200

Note: Weight limits for each class are estimated from particle size by: $W = 0.85(d^3\gamma_s)$ where d corresponds to the intermediate ("B") axis of the particle, and particle specific gravity is taken as 2.65.

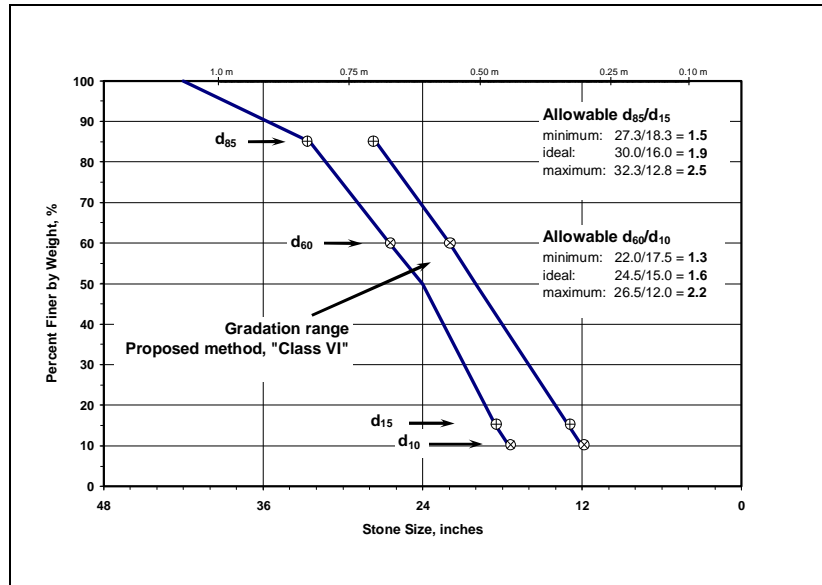


Figure 3. Recommended "well-graded" riprap with target $d_{50} = 51$ cm (20 inches).

4. It was apparent from the survey of current practice in the U.S. that very little field testing during construction or inspection is done on a programmatic basis. A simple methodology developed by the Office of Surface Mining is recommended to facilitate a decision to accept or reject a rock product at the quarry or on site [12]. In addition, a "pebble count" approach for verifying size distribution of riprap at the quarry or construction site is suggested for U.S. practice [13] [14].

D. Construction/Installation Guidelines

A generalized overview of riprap construction methods and placement techniques was developed for installations both in the dry and under water. Topics considered include:

- Quarry operations
- Equipment overview
- Loading and transportation of riprap
- Placing riprap and the filter
- Terminations and transitions
- Site considerations
- Measurement and payment

A set of Design Guidelines which include detailed application-specific construction and installation guidance were developed and are included as stand-alone appendices to reference [1].

E. Inspection and Quality Control

Based on a survey of current practice in the U.S., very little guidance is being promulgated by the

DOTs for riprap inspection and quality control either during construction or for long-term monitoring. A field test procedure described by [14] is presented as an example of a simple, practical approach to ensuring that an appropriate riprap size distribution is achieved during construction, and that the stone has not deteriorated over the long term. In addition, riprap failure mechanisms are identified as a basis for developing inspection guidance, and selected case studies of failures are used to emphasize the need for post flood/post construction inspection.

A suggested riprap inspection code was developed. This code parallels the format of Item 113 "Scour Critical Bridges" of the U.S. National Bridge Inspection Standards (NBIS) [15] and would be applicable to all riprap installations including revetments and riprap at bridge piers, abutments and countermeasures. The form provides a numeric ranking scheme based on both the observed condition of the entire riprap installation as well as the condition of the riprap particles themselves. The form is intended to serve for underwater inspections as well as for installations that can be observed in the dry. Action items associated with the coding guidance are also provided on the inspection form.

IV. SUMMARY

NCHRP Project 24-23 was a synthesis study to develop a unified set of guidelines, specifications, and procedures that can be accepted by the State DOTs in the U.S. for the design, installation, and inspection of riprap for a range of applications. These include riprap at streams and river banks, at bridge piers and abutments, and on countermeasures such as guide banks. This research effort was

comparable in intent to the recent work by the European Union that resulted in adoption of a unified standard for riprap that transcends geographic and institutional boundaries.

To guide the practitioner in developing appropriate riprap designs and ensuring successful installation of riprap armoring systems for bankline revetment, at bridge piers, and at abutments and guide banks, the findings and recommendations of the study are combined to provide an application-specific set of design guidelines as stand-alone appendices.

These application guidelines are presented in a standard three part format using the Federal Highway Administration's Hydraulic Engineering Circular (HEC) 23 [7] as a guide. Each guideline includes:

- Part 1 – Design and Specification
- Part 2 – Construction
- Part 3 – Inspection, Maintenance, and Performance Evaluation

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