Partially Grouted Revetment for Low-Volume Road Bridges

Final Report
March 2024



Iowa State University
Institute for Transportation

Sponsored by
Iowa Highway Research Board
(IHRB Project TR-710)
Iowa Department of Transportation
(InTrans Project 16-579)

The preparation of this report was financed in part through funds provided by the Iowa Department of Transportation through its "Second Revised Agreement for the Management of Research Conducted by Iowa State University for the Iowa Department of Transportation" and its amendments.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
IHRB Project TR-710		

4. Title and Subtitle	5. Report Date
Partially Grouted Revetment for Low-Volume Road Bridges	March 2024
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
Katelyn Freeseman (orcid.org/0000-0003-0546-3760), Brent Phares (orcid.org/0000-0001-5894-4774), and Alice Alipour (orcid.org/0000-0001-6893-9602)	InTrans Project 16-579

9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Bridge Engineering Center Iowa State University 2711 South Loop Drive, Suite 4700 Ames, IA 50010-8664	11. Contract or Grant No.

12. Sponsoring Organization Name and Address	13. Type of Report and Period Covered
Iowa Highway Research Board Iowa Department of Transportation 800 Lincoln Way Ames, IA 50010	Final Report
	14. Sponsoring Agency Code

15. Supplementary Notes

Visit https://bec.iastate.edu/ for color pdfs of this and other research reports.

16. Abstract

The Iowa secondary road system has a large number of scour-susceptible bridges or bridges with unknown foundation conditions. These structures are commonly required to have a plan of action (POA) to close them during flood events, or have countermeasures installed to keep them open. In the case of unknown foundations, countermeasures must be installed.

Among the many different countermeasures available is a potentially viable technique known as a partially grouted revetment. Partially grouted revetment construction involves the placement of rock, stone, and/or recycled concrete on a filter layer that is compatible with the subsoil. The voids of the matrix are then partially filled with a portland cement-based grout material.

Partially grouted revetment appear to achieve a desirable balance between full and no grouting of revetment. Specifically, partial grouting increases the stability of the system without eliminating the flexibility of a looser matrix. In addition, a partially grouted revetment system allows for the use of smaller (and less expensive) rock, stone, and/or recycled concrete, which also results in decreased layer thickness. The ideal system adheres adjoining pieces together while leaving relatively large voids between the stones.

This report presents background information on countermeasure types and their frequency of use, including a field review of existing countermeasures to determine quality of performance. These efforts were followed by several pilot installation sites on county infrastructure in Iowa using partially grouted riprap. These pilot installations are described and their performance documented after years of service.

17. Key Words	18. Distribution Statement
bridge pier protection—bridge scour countermeasures—grouted riprap—low-volume bridge abutments—partially grouted revetments—riverbed erosion countermeasures	No restrictions.

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified.	Unclassified.	67	NA

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

PARTIALLY GROUTED REVETMENT FOR LOW-VOLUME ROAD BRIDGES

Final Report
March 2024

Principal Investigator
Brent Phares, Research Associate Professor
Bridge Engineering Center, Iowa State University

Co-Principal Investigator
Alice Alipour, Associate Professor
Iowa State University

Authors
Katelyn Freeseman, Brent Phares, and Alice Alipour

Sponsored by
Iowa Highway Research Board and
Iowa Department of Transportation
(IHRB Project TR-710)

Preparation of this report was financed in part
through funds provided by the Iowa Department of Transportation
through its Research Management Agreement with the
Institute for Transportation
(InTrans Project 16-579)

A report from
Bridge Engineering Center
Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664
Phone: 515-294-8103 / Fax: 515-294-0467
https://bec.iastate.edu/

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

The authors would like to thank the Iowa Highway Research Board for sponsoring this research. Participation from Buchanan, Madison, Wayne, and Woodbury Counties in Iowa is also greatly appreciated for the pilot installation sites.

EXECUTIVE SUMMARY

The Iowa secondary road system has a large number of scour-susceptible bridges or bridges with unknown foundation conditions. These structures are commonly required to have a plan of action (POA) developed and implemented, which will close the structure during flood events, or have countermeasures installed that will allow the bridge to remain open during the event. In the case of unknown foundations, countermeasures must be installed.

Not surprisingly, installing the needed countermeasures can be a very costly endeavor. This is especially concerning given the fact that county budgets are already tight. Thus, there is a need to investigate various countermeasure options that are both affordable and effective.

Among the many different countermeasures available is a potentially viable technique known as a partially grouted revetment (also referred to as partially grouted riprap). Partially grouted revetments have been successfully used in Europe, and more recently in Minnesota. Partially grouted revetments are used in Europe to prevent scour and/or erosion of riverbeds and to prevent scour at bridge piers and abutments.

Partially grouted revetment construction involves the placement of rock, stone, and/or recycled concrete on a filter layer that is compatible with the subsoil. The voids of the matrix are then partially filled with a portland cement-based grout material.

Partially grouted revetments appear to achieve a desirable balance between full and no grouting of revetments. Specifically, partial grouting increases the stability of the system without eliminating the flexibility of a looser matrix. In addition, a partially grouted revetment system allows for the use of smaller (and less expensive) rock, stone, and/or recycled concrete, which also results in decreased layer thickness. Common sense leads to the conclusion that the ideal system adheres adjoining pieces together while leaving relatively large voids between the rock, stone, and/or recycled concrete.

The overall objectives of this project were as follows:

- Document the use of scour countermeasures—including grouted revetments—and assess the general performance of each through anecdotal evidence
- Document the performance and cost-effectiveness of existing, in-use countermeasures in the field
- Install partially grouted revetment pilot/demonstration projects
- Document and monitor the performance of partially grouted revetment pilot installations
- Develop guidance or best practices for scour countermeasures

This report presents background information on countermeasure types and their frequency of use, including a field review of existing countermeasures to determine quality of performance. These efforts were followed by several pilot installation sites on county infrastructure in Iowa

using partially grouted revetments. The performance of these sites after years of service is documented.

INTRODUCTION

Partially grouted revetment is used in Europe to prevent scour and/or erosion of riverbeds and to prevent scour at bridge piers and abutments. Partially grouted revetment construction involves the placement of rock, stone, and/or recycled concrete on a filter layer that is compatible with the subsoil. The voids in the surface matrix are then partially filled with a portland cement-based grout material.

In most commonly used installations, the partial grouting results in an armor layer that retains about 50 to 70 percent of the original surface void space. The partial grouting results in significantly increased hydraulic stability of the armor (versus an ungrouted surface or slope) due to the larger overall system mass and interlocking of the various components, and it does so without sacrificing flexibility or permeability.

Total grouting of the revetment, on the other hand, converts the flexible revetment material into a rigid mass that is also nearly impermeable. Total grouting, then, may cause the entire system to fail due to either undercutting or uplift of the matrix. Such a condition completely negates any value of adding the revetment because any developing scour holes cannot be mitigated by migration of loose pieces into a hole that is developing over time.

Partially grouted revetment appears to achieve a desirable balance between full grouting and no grouting. Specifically, partial grouting increases the stability of the system without eliminating the flexibility of a looser matrix. In addition, a partially grouted revetment system allows for the use of smaller (and less expensive) rock, stone, and/or recycled concrete, which also results in decreased layer thickness. Common sense leads to the conclusion that the ideal system adheres adjoining pieces together while leaving relatively large voids between the rock, stone, and/or recycled concrete.

The overall objectives of this project were as follows:

- Document the use of scour countermeasures—including grouted revetments—and assess the general performance of each through anecdotal evidence
- Document the performance and cost-effectiveness of existing, in-use countermeasures in the field
- Install partially grouted revetment pilot/demonstration projects
- Document and monitor the performance of partially grouted revetment pilot installations
- Develop guidance or best practices for scour countermeasures

This report presents background information on countermeasure types and their frequency of use, including a field review of existing countermeasures to determine quality of performance. These efforts were followed by several pilot installation sites on county infrastructure in Iowa using partially grouted revetments. The long-term performance of the partially grouted systems is documented.

LITERATURE REVIEW

Most bridges are built to span waterways, making scour susceptibility increasingly problematic for the structural integrity of existing infrastructure. Scour is caused by the removal of sediment surrounding the supporting structure of a bridge due to hydraulic pressure.

Scour causes 60 percent of bridge failures in the United States, providing further proof of the importance of proper scour countermeasures and revetment methods. The scour depth is affected by the velocity of the approach flow, depth of flow, width of pier, length of pier if skewed to flow, size and gradation of bed material, angle of attack of the approach flow to the pier, pier shape, and bed configuration (Lagasse et al. 2007).

To account for these damaging hydraulic forces, certain design measures can be taken. Newly constructed bridges can proactively include implementation of scour-minimizing options such as deep foundations, widened openings to minimize contraction scour, and/or selection of construction locations away from bends and dams where possible (Agrawal et al. 2007). For existing structures, it is critical to evaluate the structure first for vulnerability to scour, in conjunction with proper and timely inspection for scour (Arneson et al. 2012).

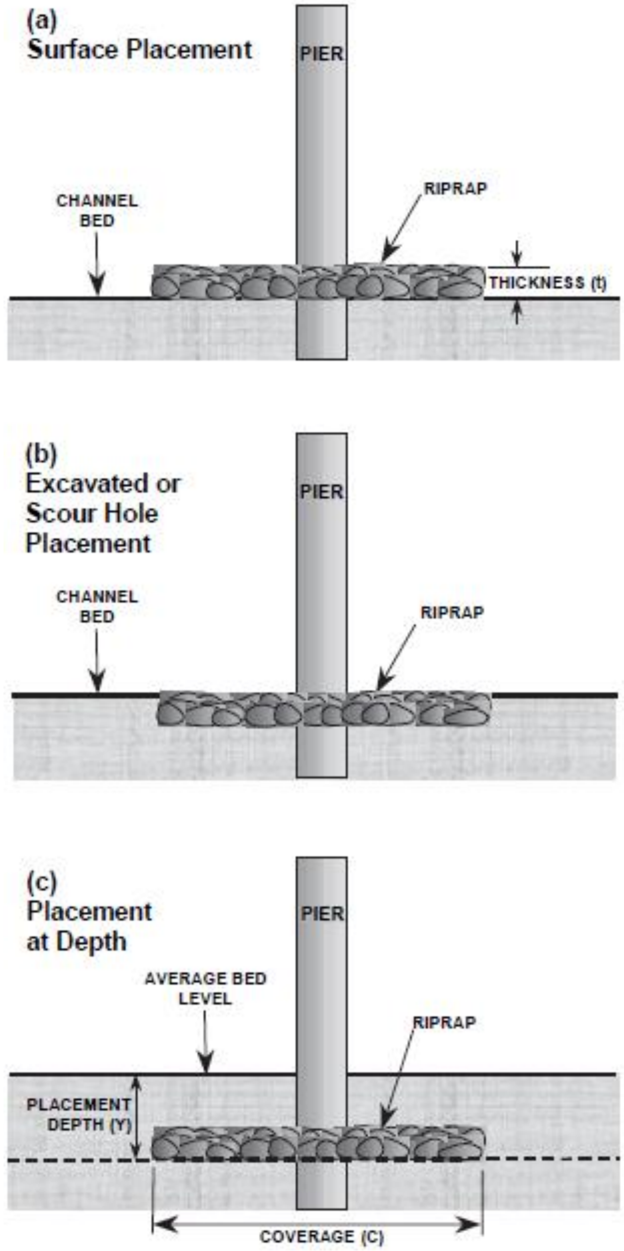
A scour-critical bridge is a bridge that is predicted to fail from a certain magnitude flood, either from analysis or observation. Once a bridge is deemed scour-critical, the Federal Highway Administration (FHWA) policy requires that a proper plan of action (POA) be developed that indicates the necessary implementation of monitoring and/or corrective measures.

Corrective measures include bridge replacement or the design and installation of bridge-scour countermeasures. In situ countermeasures have historically included conventional riprap, fully grouted riprap, partially grouted riprap, articulating concrete block systems, concrete armor units, gabion mattresses, and grout-filled mattresses. These countermeasures are described in further detail in the following sections.

Riprap

Riprap is an assortment of natural rock acting as a layer to protect the underlying sediment. Riprap can also include concrete rubble and varies based on the locally available material. It is the most common countermeasure due to its general availability, ease of installation, and relatively low overall cost. In addition, riprap remains flexible as a system and can continue to function even with intermediate stone loss (Lagasse et al. 2007).

Typical riprap installation methods are shown in Figure 1 and include surface placement, excavated placement for a flush surface, or placement at a depth below the surface.



Lagasse et al. 2007, NCHRP

Figure 1. Conventional riprap installation practices

Truck-placed riprap is considered less stable compared to hand-placed riprap, although increased labor costs are involved in the latter (Agrawal et al. 2007). Regardless of the installation type, periodic inspection and maintenance is necessary, especially after flood events. Riprap is most effective when used in conjunction with a filter layer of some type, as discussed further in a later section.

Riprap Design Guidelines

While the type and size of riprap is dependent on the resources logistically convenient to the project, a number of riprap sizing guidelines have been formulated. A summary of some of these suggested equations can be found in Table 1, with equations based on the median stone size.

Table 1. Riprap sizing guidelines

Reference	Equation	Standard Format (for comparison)	Comments
Bonasoundas (1973)	$d_{r50}\ (\text{cm}) = 6 - 3.3V + 4V^2$		Equation applies to stones with $S_s = 2.65$ V = mean approach velocity (m/s)
Quazi and Peterson (1973)	$N_{sc} = 1.14\left(\frac{d_{r50}}{y}\right)^{-0.2}$	$\frac{d_{r50}}{y} = \frac{0.85}{(S-1)^{1.25}} Fr^{2.5}$	N_{sc} = critical stability number $= V^2/[g(S_s-1)d_{r50}]$ Fr = Froude number of the approach flow $= V/(gy)^{0.5}$
Breusers et al. (1977)	$V = 0.42\sqrt{2g(S_s-1)d_{r50}}$	$\frac{d_{r50}}{y} = \frac{2.83}{(S_s-1)} Fr^2$	S_s = specific gravity of riprap stones y = mean approach flow depth
Farraday and Charlton (1983)	$\frac{d_{r50}}{y} = 0.547 Fr^3$	$\frac{d_{r50}}{y} = 0.547 Fr^3$	
Parola et al. (1989)	$\frac{d_{r50}}{y} = \frac{C^*}{(S_s-1)} Fr^2$	$\frac{d_{r50}}{y} = \frac{C^*}{(S_s-1)} Fr^2$	C* = coefficient for pier shape; C* = 1.0 (rectangular), 0.61 (round-nose)
Breusers and Raudkivi (1991)	$V = 4.8(S_s-1)^{0.5} d_{r50}^{1/3} y^{1/6}$	$\frac{d_{r50}}{y} = \frac{0.278}{(S_s-1)^{1.5}} Fr^3$	
Austroads (1994)	$\frac{d_{r50}}{y} = \frac{0.58K_pK_v}{(S_s-1)} Fr^2$	$\frac{d_{r50}}{y} = \frac{0.58K_pK_v}{(S_s-1)} Fr^2$	K_p = factor for pier shape; K_p = 2.25 (round-nose), 2.89 (rectangular) K_v = velocity factor, varying from 0.81 for a pier near the bank of a straight channel to 2.89 for a pier at the outside of a bend in the main channel
Richardson and Davis (1995)	$d_{r50} = \frac{0.692(f_1 f_2 V)^2}{(S_s-1)2g}$	$\frac{d_{r50}}{y} = \frac{0.346 f_1^2 f_2^2}{(S_s-1)} Fr^2$	f_1 = factor for pier shape; f_1 = 1.5 (round-nose), 1.7 (rectangular) f_2 = factor ranging from 0.9 for a pier near the bank in a straight reach to 1.7 for a pier in the main current of a bend
Chiew (1995)	$d_{r50} = \frac{0.168}{\sqrt{y}}\left(\frac{V}{U_*\sqrt{(S_s-1)g}}\right)^3$	$\frac{d_{r50}}{y} = \frac{0.168}{(S_s-1)^{1.5} U_*^3} Fr^3$ $U_* = \frac{0.3}{K_d K_y}$	$K_y = 0.783\left(\frac{y}{b}\right)^{0.333} - 0.106$ $0 \le (y/b) < 3$ $K_y = 1$ $(y/b) \ge 3$ $K_d = 0.398\ln\left(\frac{b}{d_{50}}\right) - 0.034\left[\ln\left(\frac{b}{d_{50}}\right)\right]^2$ $1 \le (b/d_{50}) < 50$ $K_d = 1$ $(b/d_{50}) \ge 50$ K_y = flow depth factor K_d = sediment size factor

Table 1. continued

Reference	Equation	Standard Format (for comparison)	Comments
Parola (1993, 1995)	Rectangular: $N_{sc} = 0.8 \quad 20<(b_p/d_{r50})<33$ $N_{sc} = 1.0 \quad 7<(b_p/d_{r50})<14$ $N_{sc} = 1.0 \quad 4<(b_p/d_{r50})<7$ Aligned Round-Nose: $N_{sc} = 1.4$	$\frac{d_{r50}}{y} = \frac{f_1 f_3}{(S_s - 1)} Fr^2$	b_p = projected width of pier f_1 = pier shape factor; $f_1 = 1.0$ (rectangular), 0.71 (round-nose if aligned) f_3 = pier size factor = $f(b_p/d_{r50})$: $f_3 = 0.83 \quad 4<(b_p/d_{r50})<7$ $f_3 = 1.0 \quad 7<(b_p/d_{r50})<14$ $f_3 = 1.25 \quad 20<(b_p/d_{r50})<33$
Croad (1997)	$\frac{V}{A\sqrt{(S_s-1)gd_{r50}}} =$ $1.16\left(\frac{y}{d_{r50}} - 2\right)^{1/6}$ $d_{r50} = 17d_{b50}$	$\frac{d_{r50}}{y}\left(1 - \frac{2d_{r50}}{y}\right)^{0.5} =$ $\frac{0.641}{A^3(S_s-1)^{1.5}} Fr^3$ $d_{r50} = 17d_{b50}$ Use larger of d_{r50} sizes given by the two equations	A = acceleration factor; A = 0.45 (circular and slab piers), A = 0.35 (square and sharp-edged piers) d_{b50} = median size of bed material. Equation given for factor of safety = 1.25, as recommended by Croad (1997)
Lauchlan (1999)	$\frac{d_{r50}}{y} = 0.3S_f\left(1 - \frac{Y_r}{y}\right)^{2.75} Fr^{1.2}$	$\frac{d_{r50}}{y} = 0.3S_f\left(1 - \frac{Y_r}{y}\right)^{2.75} Fr^{1.2}$	S_f = safety factor, with a minimum recommended value of 1.1 Y_r = placement depth below bed level

Source: Melville and Coleman 2000 from Lagasse et al. 2007

A summary of pertinent design equations based on historical information from Table 1 was provided in Melville and Coleman (2000) and is summarized in Table 2.

Table 2. Riprap design guide

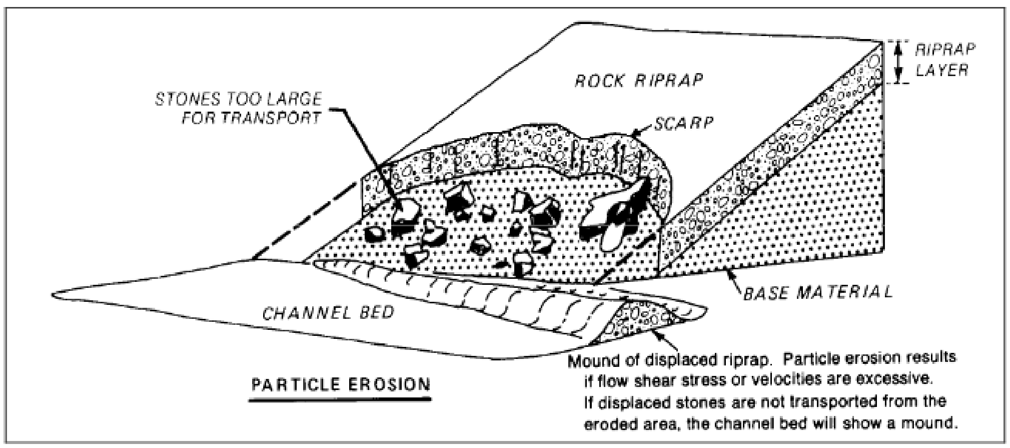
Element	Recommendation	Variable Definition
Riprap size	$\frac{d_{50}}{y_0} = 0.3\left(1 - \frac{Y}{y_0}\right)^{2.75} F^{1.2}$	d_{50}=median riprap size; y_0=undisturbed approach flow depth; F=Froude number
Riprap layer thickness	$t = 2d_{r50}$ *to* $3d_{r50}$	
Coverage of riprap layer	*width = 3 to 4 pier widths or* *1 to 1.5 pier widths from pier face*	
Placement level	*1 to 1.5 pier widths from pier face*	
Grading	*at lowest dune trough level*	
Synthetic filter layer	$0.5d_{r\,max} < dr_{50} < 2d_{r15}$	
Inverted stone filter layer	$t = d_{r50}$	

This table presents a single equation for the sizing of riprap and includes guidelines for the layer thickness, coverage, placement level, suggested grading, and filter layer design parameters.

Riprap Failure Mechanisms

Failure of riprap systems often occurs due to incorrect particle sizing. Riprap is often sized too small due to underestimation of the shear stress or velocity, inadequate allowance for channel curvature, incorrect characterization of channel capacity or design discharge, or inadequate assessment of abrasive forces. Riprap failure is also attributed to channel changes causing varying flow, improper riprap gradation, improper placement, side slopes that are too steep, excess pore pressure, differential settlement, or failure to install a proper filter layer.

The four general failure modes for riprap are particle erosion, translational slide, modified slump failure, and slump failure. Particle erosion, shown in Figure 2, is the most common erosion mechanism and occurs when individual particles are dislodged due to the hydraulic forces in the waterway.

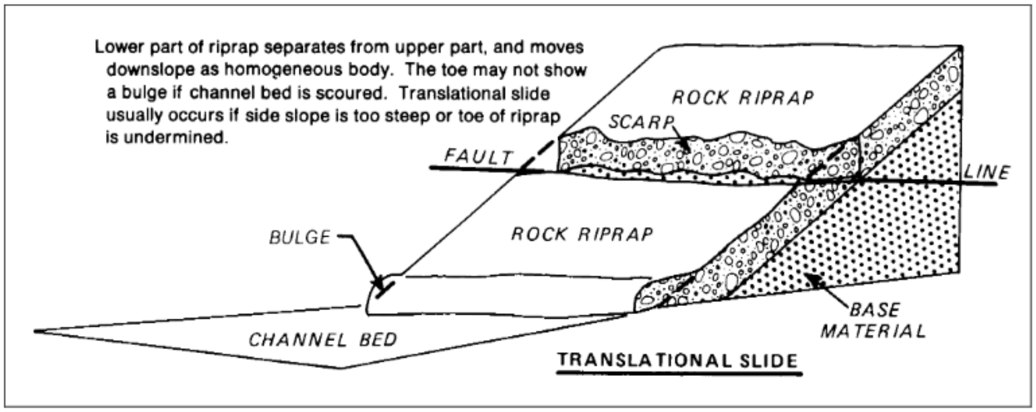


Blodgett and McConaughy 1986, U.S. Geological Survey, from Lagasse et al. 2009

Figure 2. Particle erosion riprap failure

Particle erosion is caused by the riprap stone size not being large enough, removal of individual stones by impact or abrasion, a bank slope that is too steep, or a riprap gradation that is too uniform.

Translational slide is a failure mechanism caused by mass movement of stones with a fault line on the horizontal plane, as shown in Figure 3.

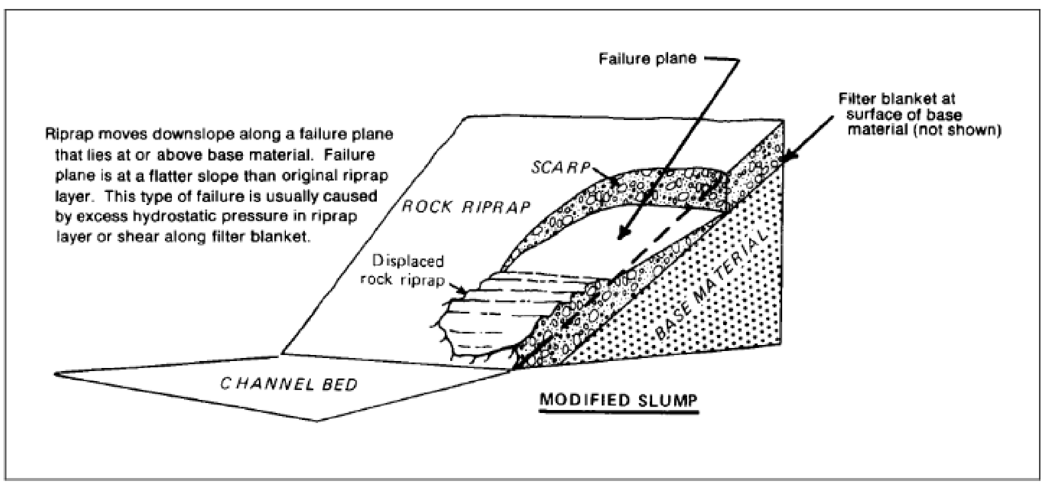


Blodgett and McConaughy 1986, U.S. Geological Survey, from Lagasse et al. 2009

Figure 3. Translational slide riprap failure

Indications of this type of failure typically arise via cracks in the upper part of the riprap bank extending parallel to the channel. Translational slide is caused by a bank side slope that is too steep, the presence of excessive hydrostatic pressure, or the loss of foundational support at the toe due to erosion.

Modified slump failure is a mass movement of the riprap material along an internal slip surface, as shown in Figure 4.

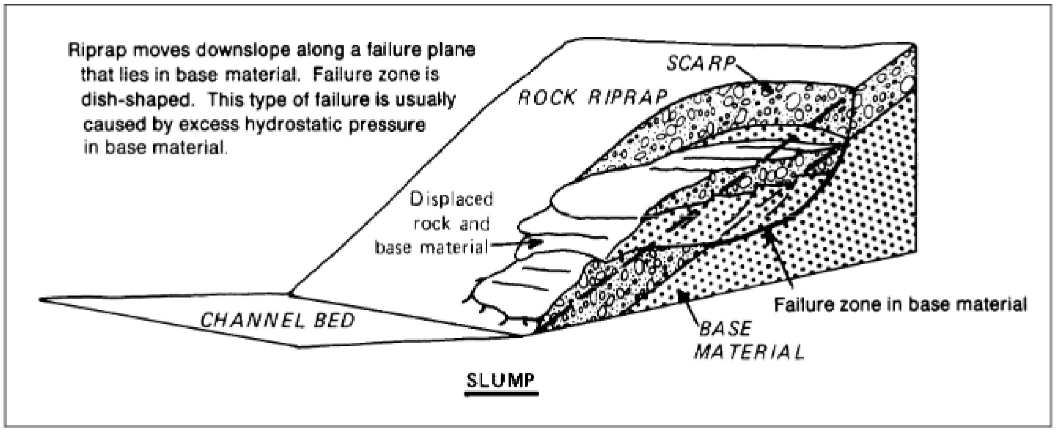


Blodgett and McConaughy 1986, U.S. Geological Survey, from Lagasse et al. 2009

Figure 4. Modified slump riprap failure

With this failure mechanism, the base soil supporting the riprap does not fail, similar to translational slide failure, but the geometry of the riprap is similar to that of particle erosion. Modified slump riprap failure is typically caused by a bank slope that is too steep or dislodged riprap material in an area critical to the support of the upslope.

The fourth general riprap failure mechanism, slump failure, is characterized by rotational-gravitational movement of system material along a surface that has a concave upward curve, as shown in Figure 5.



Blodgett and McConaughy 1986, U.S. Geological Survey, from Lagasse et al. 2009

Figure 5. Slump riprap failure

The causes of slump failure are related to shear failure of the base soil, excess pore pressure causing a reduction of friction along the fault line, nonhomogeneous base material with layers of impermeable material acting as a fault line, side slopes that are too steep, excessive overburden at the top of the slope, and gravitational forces exceeding the riprap inertial forces.

While there are many benefits to riprap, this type of system is not often considered a permanent solution for scour problems in the United States. In Europe, however, riprap is a permanent preventive measure, likely due to higher standards of care and quality control in the placing of the system. In addition, diligent efforts are made to inspect and monitor the condition of existing riprap after placement (Lagasse et al. 2007).

Should these same standards be followed in the United States, such as the inspection tips shown in Figure 6, riprap could be a more successful permanent countermeasure.

1. Riprap should be **angular and interlocking** (old bowling balls would not make good riprap). Flat sections of broken concrete paving do not make good riprap.
2. Riprap should have a **granular or geotextile filter** between the rock and the subgrade to prevent loss of the finer subgrade material, whether on the bed or thebank.
3. Rlprap should be **well graded** (a wide range of rock sizes). The maximum rock size should be no greater than about twice the median (d_{50}) size.
4. When Inspecting rlprap, the following would be strong Indicators of problems:
   - Have riprap stones been **displaced** downstream?
   - Has the riprap blanket **slumped** down the slope?
   - Has angular riprap material been **replaced** over lime by smoother river run material?
   - Has the riprap material physically **deteriorated, disintegrated,** or been **abraded** over lime?
   - Are there **holes** in the riprap blanket where the filter has been exposed or breached?
5. **Riprap revetment** must have an adequate burial depth at the toe (toe down) to prevent it from being undermined. Toe down should be deeper than the expected long-term degradation and contraction scour.
6. For **piers and abutments,** riprap should generally extend up to the bed elevation so that the top of the riprap is visible to the inspector during and after floods.

FHWA 2009 from Arneson et al. 2012

Figure 6. Riprap inspection tips

Moreover, the reputation of riprap as a temporary countermeasure is generally misleading and based on riprap that is either improperly sized or installed without proper filtration (Heibaum 2000).

Fully Grouted Riprap

Fully grouted riprap is a system that utilizes grout to fill all voids between the riprap. Fully grouting the riprap allows for smaller stones to be utilized, also enabling decreased layer thicknesses. The addition of grout increases the stability of the unit, but it also eliminates the beneficial flexibility of conventional riprap. As such, fully grouted riprap is susceptible to mass failure, especially when proper drainage is not present. In addition, although the system is rigid, it is not significantly stronger, such that a small loss in support can be detrimental to the whole structure (Lagasse et al. 2009). Because of these drawbacks, fully grouted riprap is not widely used.

Partially Grouted Riprap

Partially grouted riprap is a system consisting of specifically size rocks, grouted together with 50 percent or less of the voids filled by the grout, as shown in Figure 7.

Lagasse et al. 2007, NCHRP, from Lagasse et al. 2008

Figure 7. Partially grouted riprap

The partial grouting increases the overall stability of the system without sacrificing flexibility or permeability. Degrees of grouting differ, but surface or pattern grouting is typically utilized. Surface grouting results in roughly one-third of the voids being filled because the grout does not penetrate the entire thickness. Pattern grouting is similar to surface grouting, although only part of the surface area is filled.

Laboratory studies have been conducted in the past to test the performance of conventional and partially grouted riprap. One such study involved prototype-scale tests of both partially grouted and loose riprap simultaneously (Lagasse et al. 2008). The results showed that the partially grouted riprap was undamaged, whereas the loose riprap experienced failure via particle erosion or displacement, as shown in Figure 8.

Lagasse et al. 2007, NCHRP, from Lagasse et al. 2008

Figure 8. Laboratory test results on loose and partially grouted riprap

Flume studies have also shown that the shear strength of partially grouted riprap is more than three times greater than that of conventional riprap (Marr et al. 2015).

Just as with fully grouted riprap, partially grouted riprap allows for the use of smaller stones and thus decreased layer thickness. However, for practical placement of partially grouted riprap, stones with a median diameter of less than 9 in. typically exhibit voids that are too small for the grout to penetrate to the required depth.

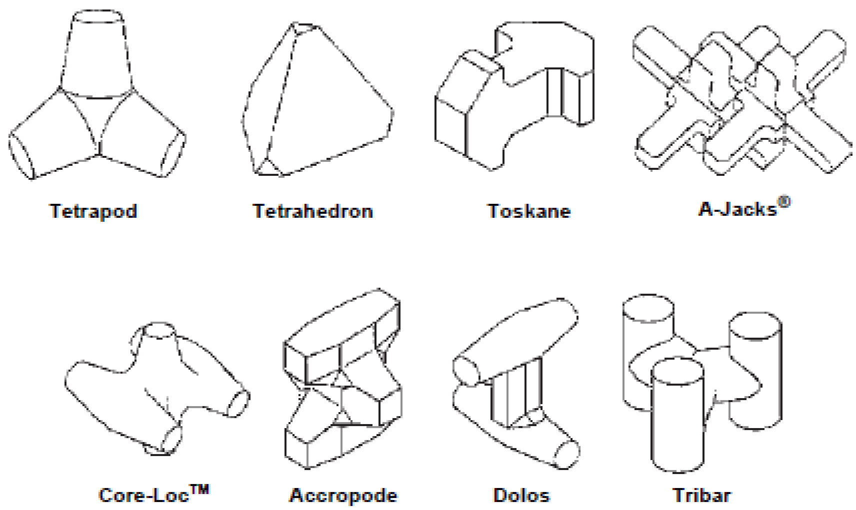
On the other hand, riprap with a diameter greater than 15 in. has voids that are too large for the contact areas of adjacent rocks to allow for proper adhesion to one another. It is also recommended that the riprap layer should have a thickness of at least two times the median diameter. However, when placement must occur underwater, the thickness should be increased by 50 percent (Lagasse et al. 2007).

Partially grouted riprap can be difficult to install in the field due to the presence of water and the necessary grout installation. The riprap should be placed in a pre-excavated hole so that the top of the layer is level with the bed elevation to allow for ideal inspection circumstances. This also reduces obstruction to the flow of the water channel.

Partially grouted riprap also functions optimally when used in conjunction with a filter layer based on compatibility with the subsoil. In addition to geotextile or granular filters, success has been seen when sand-filled geo-containers have been used for underwater placement (Lagasse et al. 2007). Sand-filled geo-containers are composed of nonwoven, needle-punched geotextile that is filled with sand.

Concrete Armor Units

Concrete armor units are individual precast concrete units, sometimes referred to as artificial riprap. They come in many complex shapes and sizes, as shown in Figure 9.



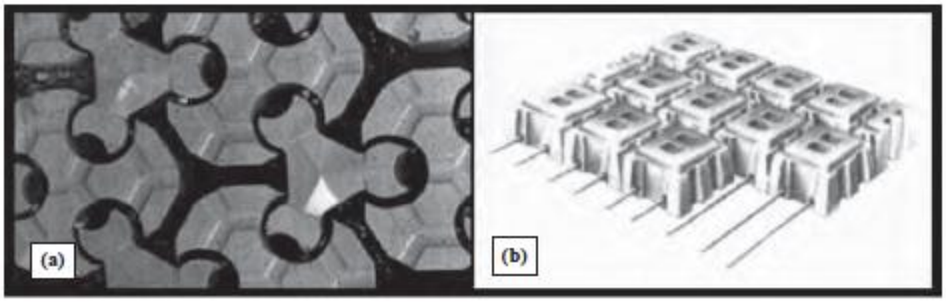
Lagasse et al. 2007, NCHRP

Figure 9. Concrete armor unit shapes

The individual units are designed to allow for maximum interlocking and can be placed individually or as interconnected groups. Concrete armor units typically have greater stability than conventional riprap due to these overlapping characteristics, although artificial riprap is more expensive due to the fabrication costs. Despite the higher costs, concrete armor units serve as a good substitute for conventional riprap when natural stones are not geographically or logistically available.

Articulating Concrete Block Systems

Articulating concrete block (ACB) systems consist of preformed concrete units that can interlock, be held together via cables, or a combination of both. Two examples of ACB components can be seen in Figure 10, with an interlocking system shown on the left and a cable-connected system on the right.



American Excelsior Company (left) and Armortec (right) from Lagasse et al. 2007

Figure 10. Articulating concrete block members: interlocking (left) and cable-connected (right)

ACB systems also come in both open- and closed-cell varieties. After installation, the ACB system acts as a continuous unit while still allowing individual units to conform to changes in the subgrade, providing valuable system flexibility.

There is very little experience using ACB systems for bridge scour prevention alone. More frequently, ACB systems are used for bank revetment and channel armoring. As such, few installation guidelines exist for installation on in situ bridges.

Two failure mechanisms are typically seen when ACB systems are used: (1) overturning and rollup of the edge when it is not adequately anchored and (2) uplift at the center of the system when the edge is properly anchored. Optimal performance has been seen when the blocks extend a distance of at least two times the pier width in all directions around the pier.

Gabion Mattresses

Gabion mattresses are containers constructed of wire mesh that are then filled with rocks. An example of this system is shown in Figure 11.

Figure 11. Gabion mattress after installation

Traditionally, diaphragms are inserted along the width to create individual compartments within the mattresses. During installation, these compartments are then connected by lacing wire. Past performance has shown that physically connecting the individual mattresses is very beneficial (Lagasse et al. 2007). The utilization of wire mesh allows the gabions to adapt to changes in the subsoil while still exhibiting stability.

Gabion mattresses are more frequently used for channel slope stabilization with limited use for scour alone. As with most other scour countermeasures, gabion mattresses perform best when installed with a filter or geotextile layer. The maintenance requirements of gabion mattresses can be high due to the susceptibility to abrasion and corrosion of the wire.

Grout-Filled Mattresses

Grout-filled mattresses are composed of a double layer of synthetic fabric, often nylon or polyester material, sewn into a series of compartments. Adjacent mattresses are sewn together, as shown in Figure 12, and individual compartments are then filled with grout, which flows between compartments via ducts.

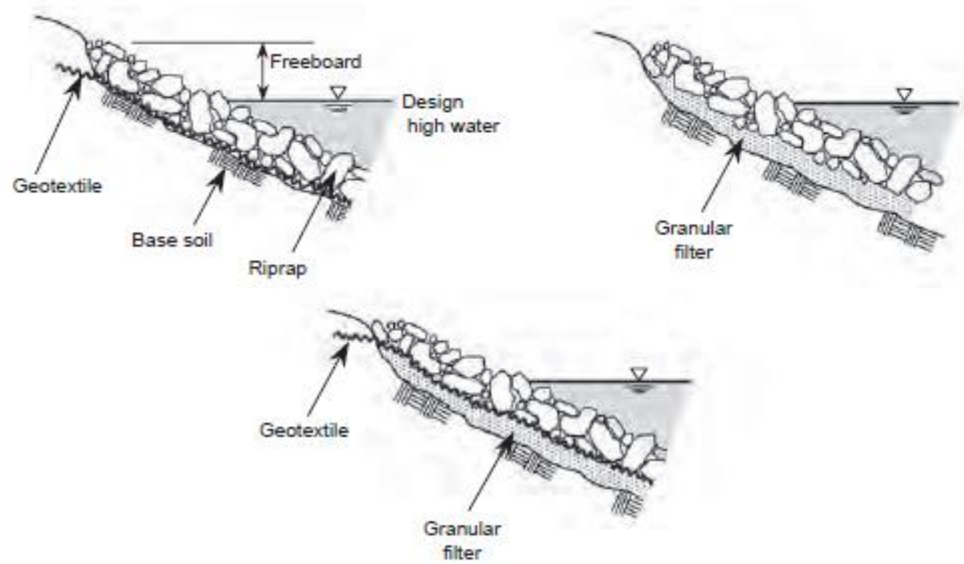
Figure 12. Grout-filled mattresses after installation

Grout-filled mattresses exhibit similar benefits to those seen in gabion mattress applications, while added benefits from the flexibility of the fabric allows for pumping of the grout into areas where space is limited during the construction process.

Quick installation times, and no need for dewatering, provide further benefits. However, there is limited experience in using grout-filled mattresses for pier applications, as they are most often used for shoreline protection or channel armoring.

Filter Layers

All of the countermeasures discussed in the previous sections are most effective when used in conjunction with a filter layer of some type. Possible filter layers include a geotextile filter, granular filter, or combination of the two to form a composite filter. These three types of filters are illustrated in Figure 13.



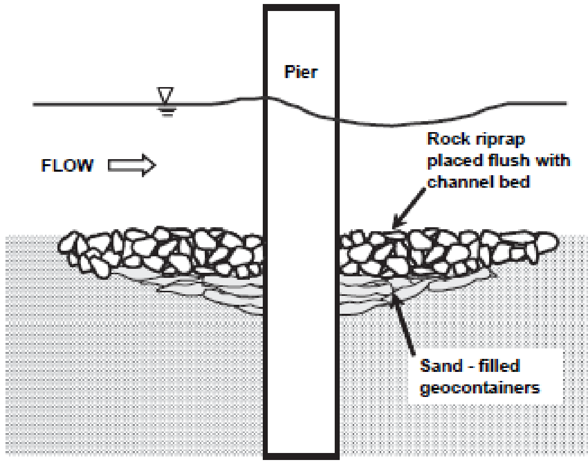
Lagasse et al. 2007, NCHRP

Figure 13. Riprap filter layers: geotextile filter (upper left), granular filter (upper right), and combination of the two to form a composite filter (bottom)

These filter layers allow for infiltration and exfiltration of the system while still aiding in particle retention. While filter layers retain the coarse subgrade particles, smaller particles can pass through, creating a more beneficial coarse substrate (Lagasse et al. 2009).

For dune-type bedforms, geotextile filter layers are strongly recommended over granular layers. For gabion mattresses, filter layers should extend only two-thirds of the distance from the pier to the edge of the armor unit, whereas the other countermeasures should have filter layers extending to their full perimeter.

The latest developments in filter layers have come from Europe and are called geotextile sand containers, which are strongly recommended for filter placement underwater (Lagasse et al. 2007). Geotextile sand containers as filter layers consist of large bags of mechanically bonded fabric that are partially filled with granular materials such as sand and gravel. The containers are sewn on three sides in the factory and filled on-site to roughly 80 percent capacity, with the final side sewn closed in the field. The partial filling of the bags allows for the filter layer to conform to irregularities such as existing scour holes, as shown in Figure 14.



Lagasse et al. 2007, NCHRP, after Heibaum 2000

Figure 14. Sand-filled geotextile container to fill an existing hole

When used in conjunction with one of the previously mentioned revetment methods, the system as a whole serves as a purposeful armor layer to protect against scour. However, it is essential that there are no gaps between the individual containers to ensure continuous contact with the subsoil.

Literature Summary

Selection of the proper countermeasure is based on a number of factors and, probably most importantly, the condition of the existing bridge and any fiscal constraints. Previous economic studies have shown that partially grouted riprap is more economically feasible than grout-filled mattresses and gabion mattresses (Yanmaz and Apaydin 2011).

While riprap is the most economical of all countermeasures described here, the costs associated with partial grouting are offset by the added benefits to the stability and resilience of the system over time. Based on the countermeasure information from this literature review, partially grouted riprap was emphasized in subsequent tasks for this project.

SURVEY OF COUNTY ENGINEERS

Based on the findings of the literature review, a survey was developed and sent to both local and national county engineers via email. A summary of the findings of the survey is included in this chapter, with full results presented in the appendix.

The survey responses showed that loose riprap is by far the most common revetment type used by county engineers, as shown in Figure 15.

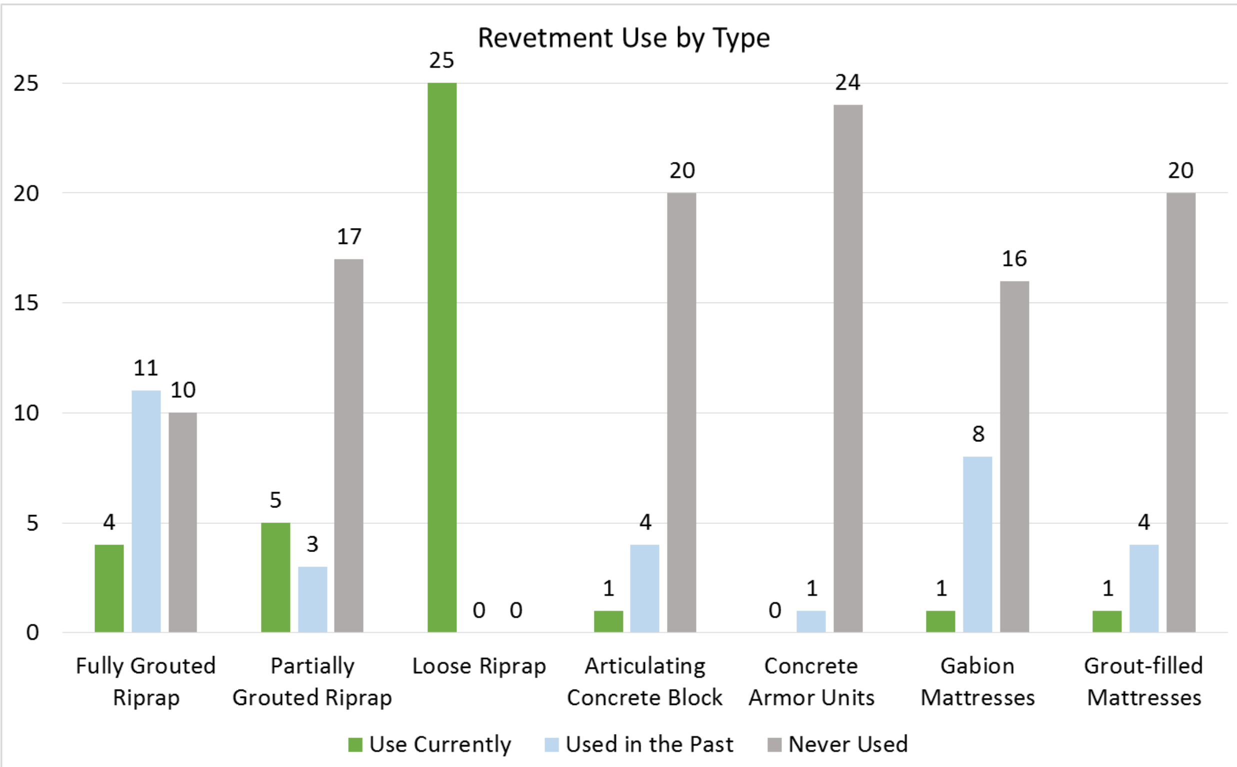


Figure 15. Survey responses regarding revetment use by type

Partially grouted and fully grouted riprap were the most common after loose riprap, although more counties expressed using fully grouted riprap in the past than currently do, alluding to negative aspects of the revetment type.

Follow-up questions were also asked regarding any negative experiences or application limitations that have been seen with each revetment type. Table 3 summarizes the most commonly received comments for each countermeasure.

Table 3. Summary of survey responses by revetment type

Revetment Type	General Comments
Fully grouted riprap	• Increased expense over traditional riprap, but the performance does not justify the added costs • Loss of flexibility due to grouting
Partially grouted riprap	• Better system flexibility than fully grouted systems • Not as much familiarity with this method • Those that have used it are pleased with performance if it is properly installed
Loose riprap	• Most used method, in large part due to low costs • Short-term cost is less, but long-term maintenance costs can be greater than grouted/partial • All responses indicated issues with riprap washing away
Articulating concrete block systems	• Very limited applications due to expense, more for access locations to rivers and lakes than for scour countermeasures
Concrete armor units	• No counties currently using this method • Have not had a need for them at the county level
Gabion mattresses	• Limited current use, but some have used in the past • Would recommend for continued use if the application is correct, but there are limited uses at the county level that justify the expense
Grout-filled mattresses	• Same responses as those received for gabion mattresses; similar use cases and expense

FIELD MONITORING OF EXISTING COUNTERMEASURES

Existing countermeasures were identified by members of the technical advisory committee (TAC) as well as via phone conversations with surrounding state agencies. Based on this site information collection, several sites in Buchanan, Madison, and Woodbury Counties in Iowa as well as sites in Minnesota were selected for field visits to assess current performance. Photos and overall performance are highlighted in this chapter.

Minnesota Partially Grouted Sites

Four sites in Minnesota were visited and inspected to determine countermeasure performance. Photos from these sites are shown in Figure 16 through Figure 19.

Figure 16. Minnesota Site 1: Partially grouted riprap

Figure 17. Minnesota Site 2: Partially grouted riprap

Figure 18. Minnesota Site 3: Partially grouted riprap—thin grout

Figure 19. Minnesota Site 4: Partially grouted riprap—splash of grout

Overall, partially grouted riprap was seen to perform well when it is grouted correctly. This same finding was conveyed via conversations with the Minnesota Department of Transportation (MnDOT). All of the systems were approximately five years old at the time of the field visits.

Of the four sites, one site (Site 3, Figure 18) had thin grout compared to specification requirements; all others appeared to follow the specified mix. One site (Site 4, Figure 19) also had excessive splash noted on the face of the stones. This is not detrimental to the performance of the system but is likely a sign of excessively high flow from the grout pump, a mix that is too fluid, or placement of the grout too far from the surface of the stone.

Iowa County Revetment Sites

A number of local county sites in Iowa were also visited, with a variety of revetment types. Brief observations are included with each site via the captions for Figure 20 through Figure 32.

Figure 20. Undersized loose riprap in Woodbury County, Iowa

Figure 21. Loose riprap with some grouting in Woodbury County, Iowa

Figure 22. Grouted and loose riprap in Woodbury County, Iowa

Figure 23. Recently installed loose riprap in good condition in Woodbury County, Iowa

Figure 24. Partially grouted riprap in Woodbury County, Iowa

Figure 25. Failing stream grade control in Woodbury County, Iowa

Figure 26. Loose riprap in Buchanan County, Iowa

Figure 27. Grout-filled blankets in Buchanan County, Iowa

Figure 28. Grouted riprap in Buchanan County, Iowa

Figure 29. Loose riprap during low water levels in Madison County, Iowa

Figure 30. Loose riprap and failing fabric in poor condition in Madison County, Iowa

Figure 31. Undersized loose riprap in Madison County, Iowa

Figure 32. Loose riprap, many washed-away stones in Madison County, Iowa

In general, there was a good assortment of performance levels and revetment types. There were very few partially grouted sites to visit, and those that were visited did not appear to be grouted via the methods outlined in the FHWA guidelines and used by MnDOT. However, the performance of each revetment was meeting the expectations of the engineer despite different mix designs and placement methods being used.

PILOT INSTALLATION SITES

As part of this research project, funding was allocated to cover the cost of grouting pilot installation sites. Potential installation sites were identified by the TAC and were narrowed down based on geographic location, site characteristics, and general infrastructure type to include a wide variety of variables in the study. An overview of the site locations is given in Table 4, and each installation is elaborated upon in the following sections.

Table 4. Overview of pilot installation sites

Site Location	Project Description	Grouting Details
Buchanan County	Two bridges located in close proximity along the same channel; retrofit	Bridge 1 used FHWA-specified grout on both banks with one bank using shotrock and one using Class E riprap; Bridge 2 used Buchanan County mix design with shotrock
Madison County	Low water crossing; new construction	FHWA-specified grout
Wayne County	Bridge; new construction	FHWA-specified grout
Woodbury County	Stream stabilization; new construction	Woodbury County mix design

Note that the FHWA-specified grout used the target mix design in Table 5.

Table 5. FHWA target mix design

Material	Quantity by Weight (lb)
Ordinary portland cement	740–760
Fine concrete aggregate (sand)	1,180–1,200
1/4 in. crusher chips (very fine gravel)	1,180–1,200
Water	420–450
Air entrained	5%–7%
Target slump	6.5–7.5 in.

Buchanan County Pilot Installation

The pilot installation efforts in Buchanan County, Iowa, were selected to incorporate a number of variables that may affect performance. Two bridges were selected of similar design, in close proximity, and along the same channel. Bridge 1 had a revetment plan that would allow for the size/quality of the revetment stone to be compared when using the FHWA mix specifications. One bank used Class E revetment, while the other used recycled shotrock. Shotrock is considerably cheaper but includes a greater variety of stone sizes, including small gravel. Figure 33 shows the difference in stone properties associated with Bridge 1.

Figure 33. Grouting of Class E revetment (left) and shotrock (right) used for Bridge 1 in Buchanan County

Bridge 2 in Buchanan County used shotrock for both banks and a mix design that the county has had success in using in the past. The mix design is given in Table 6.

Table 6. Buchanan County Bridge 2 mix design

Material	Quantity by Weight (lb)
Ordinary portland cement	1,200
Fly ash	1,200
Sand	1,200
Water	875
Air entrained	0.5%

Photos showing the difference between the two mix designs are included in Figure 34.

Figure 34. Grout consistency of FHWA mix (left) and Buchanan County grout (right)

As evident from the photos, the grout used on Bridge 2 was significantly more flowable than that used for Bridge 1 due to the crusher chips found in the mix for Bridge 1. Because of this difference in consistency, different placement methods were used based on the pump capabilities. The two hose sizes used for placement are shown in Figure 35.

Figure 35. Grout placement of FHWA mix (left) and Buchanan County grout (right)

As expected, placement was more labor intensive when the large hose size was used due to the weight of the hose, often requiring multiple workers to help move it along. The condition of the two countermeasures shortly after placement is shown in Figure 36.

Figure 36. Condition shortly after placement for Bridge 1 (left) and Bridge 2 (right) in Buchanan County

Madison County Pilot Installation

The pilot installation in Madison County, Iowa, was a new construction project involving a low water crossing that utilized the specified FHWA mix with Class E revetment. Due to the size of the project site (shown in Figure 37), a 4 in. hose size was used to get adequate reach with minimal pump setup locations given the costs associated with each move of the pump. Since placement did not involve maneuvering under a bridge deck, grouting was less labor intensive than under deck placement scenarios.

Figure 37. Low water crossing installation site in Madison County with pump shown

Figure 38 shows the grouting that was achieved as part of this pilot installation.

Figure 38. Madison County pilot installation grouting

There was initially some splash on the stones, and it took a few trucks before the mix consistency was right where desired. While the 4 in. hose size was needed due to other project constraints, it was observed that the hose size was too large for controlled placement and would not be advised for future projects whenever possible.

In addition, while the FHWA specifications allow for placement in water, this is not recommended due to wash out, as shown in Figure 39.

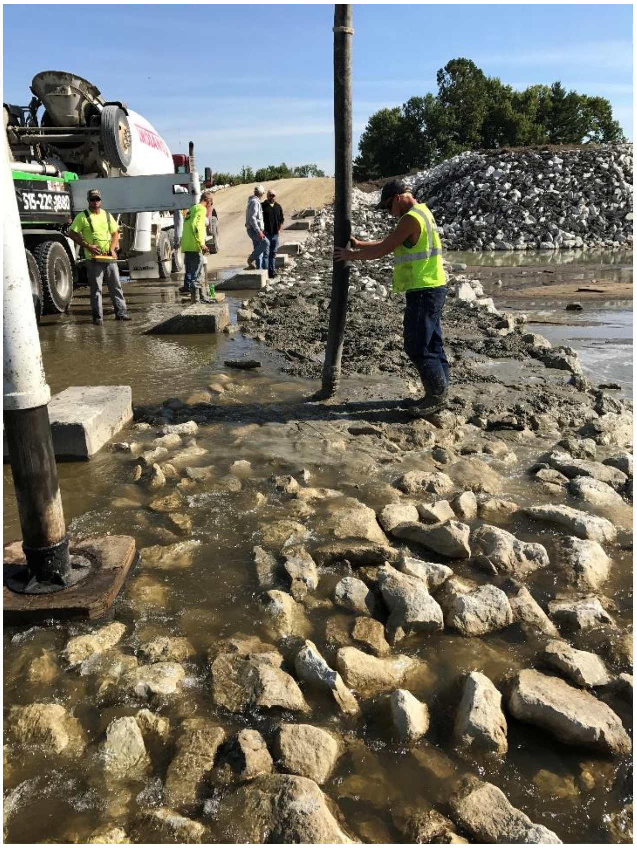


Figure 39. Grout placement in water in Madison County

Wayne County Pilot Installation

The pilot installation in Wayne County, Iowa, was part of a bridge reconstruction project and used the FHWA guidelines for the grout mix. Due to temporary supports and other constraints, the grouting for this project was done in several phases. The project site is shown in Figure 40.

Figure 40. Wayne County pilot installation site

Photos of the placement procedure are shown in Figures 41 and 42.

Figure 41. Wayne County pilot installation grouting

Figure 42. Initial grout consistency (left) and desired grout consistency (right) in Wayne County

As with the Madison County installation, it took a few trucks before the grout consistency was as desired (Figure 42). Placement was again significantly easier at this site than in Buchanan County since grouting took place prior to pouring of the deck. It would be preferred if the hose size were smaller, but, again, there were project constraints associated with pump availability.

Woodbury County Pilot Installation

The pilot installation grouting in Woodbury County, Iowa, was part of a stream stabilization project that used both Class B and Class E revetment. This site used a grout mix that Woodbury County has used in the past and has been happy with, performance-wise. The mix design is shown in Table 7.

Table 7. Woodbury County mix design

Material	Quantity
Ordinary portland cement	940 lb
Sand	2,100 lb
Water	46 gallons
Chloride	2% added on site

The site both before and after grout placement is shown in Figure 43.

Figure 43. Woodbury County site before (left) and after grouting (right)

Photos of the grout consistency and placement method are included in Figure 44.

Figure 44. Woodbury County grouting (left) and grout consistency (right)

While this grout mix was not according to the FHWA-suggested guidelines, it was closer in consistency and placement type than that used in Buchanan County.

FINDINGS

Lessons learned regarding the placement of the pilot installations include the following:

- Use a hose size smaller than 4 in. for the controlled placement that is desired if possible (2 to 3 in. is ideal).
- Control the flow out of the pump; the flow should be slow enough that placement can be controlled, but placement efficiency should be maintained as well.
- Communicate early (during plan development/bidding) what is expected of the contractor regarding placement: a common complaint from contractors was that there are no Iowa DOT guidelines or specifications for partial grouting of revetments, so they are not sure what is desired. Unclear plan language and specifications cause problems down the line when expectations are not met.
- When using the FHWA mix design, make sure the consistency is correct, as large variability was seen. If the mix is too flowable, it will all seep down to the bottom layer of the riprap; if the mix is too stiff, it will sit on top of the stones.
- When using partially grouted revetments for new construction/bridge replacement, encourage the contractor to grout prior to deck placement to considerably lessen the labor intensity.
- Placement in water is not recommended.

Photographs of each of the pilot installations after approximately five years of service are shown in Figures 45 through 48.

a. Union Avenue

b. Union Avenue

c. Thomas Avenue

d. Thomas Avenue

Figure 45. Buchanan County pilot installations as of February 2024

Figure 46. Madison County pilot installation as of February 2024

Figure 47. Wayne County Pilot installation as of February 2024

Figure 48. Woodbury County Pilot installation as of February 2024

REFERENCES

Agrawal, A. K., M. A. Khan, and Z. Yi. 2007. *Handbook of Scour Countermeasures Designs*. University Transportation Research Center, New York, NY.

Arneson, L. A., L. W. Zevenbergen, P. F. Lagasse, and P. E. Clopper. 2012. *Evaluating Scour at Bridges*. Fifth Edition. Hydraulic Engineering Circular No. 18. FHWA-HIF-12-003. Federal Highway Administration, Washington, DC.

Austroads. 1994. *Waterway Design – A Guide to the Hydraulic Design of Bridges, Culverts, and Floodways*. Sydney, Australia.

Blodgett, J. C. and C. E. McConaughy. 1986. *Rock Riprap Design for Protection of Stream Channels Near Highway Structures, Volume 2 – Evaluation of Riprap Design Procedures*. U.S. Geological Survey, Water Resources Investigations Report 86-4128. Sacramento, CA.

Bonasoundas, M. 1973. *Strömungsvorgang und kolkproblem*. Report No. 28. Oskar V. Miller Institute, Technical University of Munich, Germany.

Breusers, H. N. C., G. Nicollet, and H. W. Shen. 1977. Local Scour Around Cylindrical Piers. *IAHR Journal of Hydraulic Research*, Vol. 15, No. 3, pp. 211–252.

Breusers, H. N. C. and A. J. Raudkivi. 1991. *Scouring: Hydraulic Structures Design Manual Series, Volume 2*. International Association for Hydro-Environment Engineering and Research (IAHR), CRC Press.

Chiew, Y. M. 1995. Mechanics of Riprap Failure at Bridge Piers. *Journal of Hydraulic Engineering*, Vol. 121, No. 9, pp.635–643.

Croad, R. N. 1997. *Protection from Scour of Bridge Piers Using Riprap*. Transit New Zealand Research Report No. PR3-0071. Wellington, NZ.

Farraday, R. V. and F. H. Charlton. 1983. *Hydraulic Factors in Bridge Design*. Hydraulic Research Station, Wallingford, England.

FHWA. 2009. *Stream Stability, Bridge Scour, and Countermeasures: A Field Guide for Bridge Inspectors*. FHWA-NHI-08-106.

Heibaum, M. 2000. Scour Countermeasures Using Geosynthetics and Partially Grouted Riprap. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1696, pp. 244–250.

Heibaum, M. and J. Trentmann. 2010. Partial Grouted Riprap for Enhanced Scour Resistance. 5th International Conference on Scour and Erosion (ISCE-5), November 7–10, San Francisco, CA. https://ascelibrary.org/doi/pdf/10.1061/41147%28392%291.

Lagasse, P. F., P. E. Clopper, L. W. Zevenbergen, and L. W. Girard. 2007. *NCHRP Report 593: Countermeasures to Protect Bridge Piers from Scour*. National Cooperative Highway Research Program, Washington DC.

Lagasse, P. F., P. E. Clopper, and L. A. Arneson. 2008. Partially Grouted Riprap as a Pier Scour Countermeasure. World Environmental and Water Resources Congress, May 12–16, Honolulu, HI.

Lagasse, P. F., P. E. Clopper, J. E. Pagan-Ortiz, L. W. Zevenbergen, L. A. Arneson, J. D. Schall, and L. G. Girard. 2009. *Bridge Scour and Stream Instability Countermeasures: Experience, Selection, and Design Guidance. Volume 1*. Third Edition. Hydraulic Engineering Circular No. 23. FHWA-NHI-09-111. National Highway Institute and Federal Highway Administration, Washington, DC.

Lauchlan, C. S. 1999. Pier Scour Countermeasures. PhD thesis, University of Auckland, Auckland, NZ.

Marr, J. D. G., R. R. Weaver, O. Mohseni, C. Taylor, J. Hilsendager, and S. Mielke. 2015. *Matrix (Partially Grouted) Riprap Lab Flume Study*. Minnesota Department of Transportation St. Paul, MN.

Melville, B. W. and S. E. Coleman. 2000. *Bridge Scour*. Water Resources Publications, LLC, Highlands Ranch, CO.

Parola, A. C. 1993. Stability of Riprap at Bridge Piers. *Journal of Hydraulic Engineering*, Vol. 119, No.10, pp. 1080–1093.

——. 1995. Boundary Stress and Stability of Riprap at BridgePiers. In *River, Coastal, and Shoreline Protection: Erosion Control Using Riprap and Armourstone*. C. R. Thorne, S. R. Abt, F. B. J. Barends, S. T. Maynord, and K. W. Pilarczyk (eds.). John Wiley &Sons Ltd., Chichester, pp. 149–158.

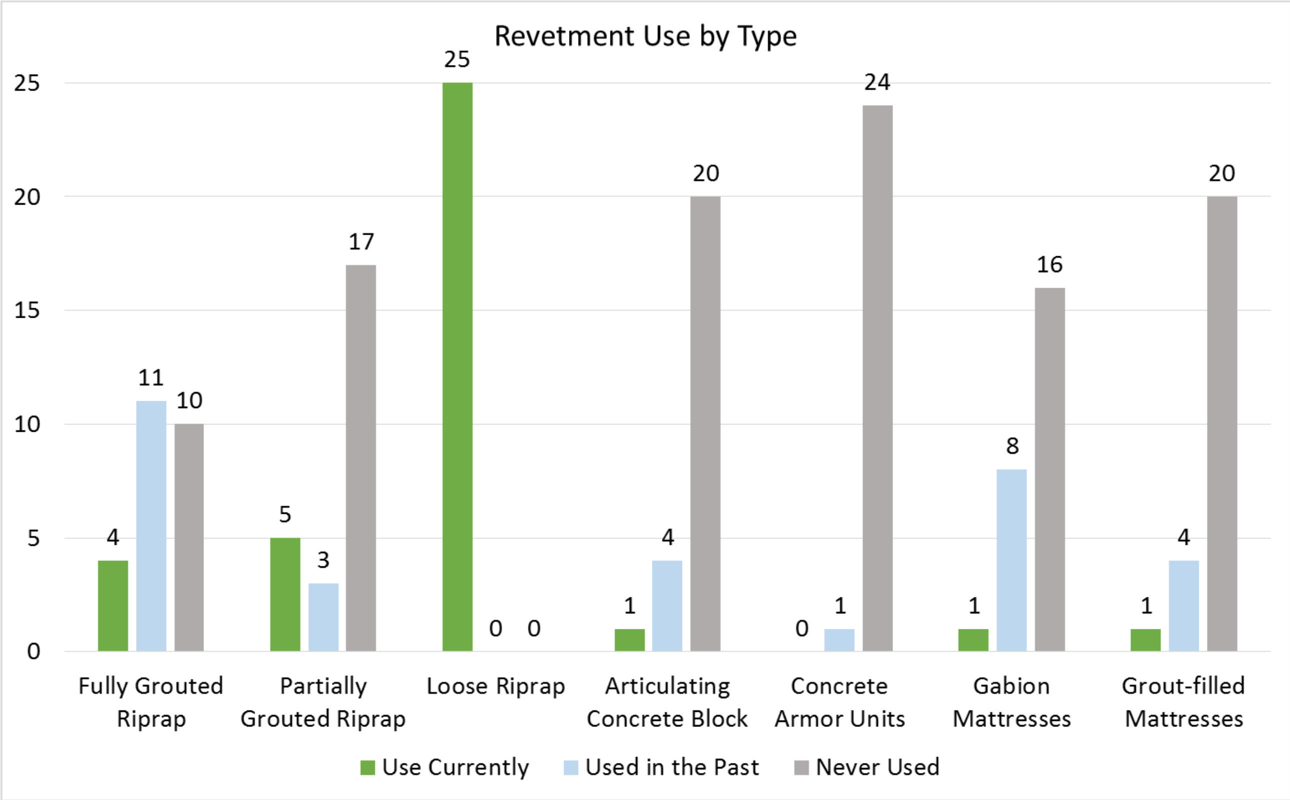
Parola, A. C., J. S. Jones, and A. C. Miller. 1989. Model Study on the Stability of Riprap Placed in Local Scour Holes at Bridge Piers. In *Proceedings of the Bridge Scour Symposium*. FHWA-90-035. Subcommittee on Sedimentation, Interagency Advisory Committee on Water Data. October 17–19.

Quazi, M. E. and A. W. Peterson. 1973. A Method for Bridge Pier Riprap Design. In *Proceedings, First Canadian Hydraulics Conference*. Edmonton, Canada, pp. 96–106.

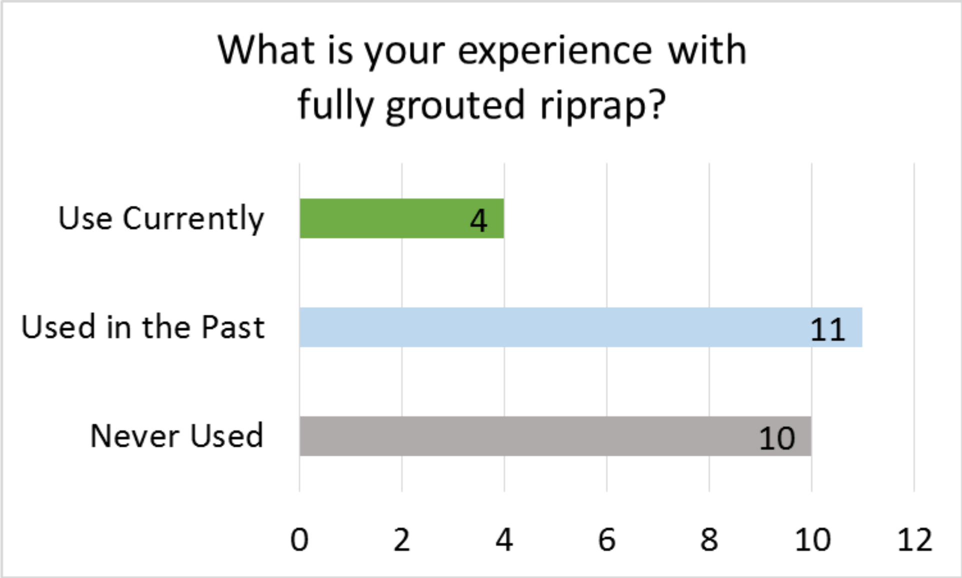
Richardson, E. V. and S. R. Davis. 1995. *Evaluating Scour at Bridges*. Third Edition. Hydraulic Engineering Circular No. 18 (HEC-18). FHWA HI 96-031. Federal Highway Administration, Washington, DC.

Yanmaz, A. M. and M. Apaydin. 2011. Bridge Scour Risk Assessment and Countermeasure Design. *Journal of Performance of Constructed Facilities*, Vol. 26, No. 4, pp. 499–506.

APPENDIX: FULL SURVEY RESPONSES



Fully Grouted Riprap



Why is fully grouted riprap no longer used?

- Over time with our substrate conditions we have seen the grout failing due to flexing
- Once failed the riprap doesn't hold much longer
- Typically use it on downspout or runoff locations, occasionally on some slopes, but not a lot of current locations that would fit the need
- Need confined area that won't be undercut- situations such as this are infrequent
- Costly and recent studies show that it could create other scour issues
- Moved to partial grouting for bridge slopes and abutments as the fully grouted riprap is rigid and fails if there is any channel degradation or undermining
- Grouted riprap prevents the riprap from launching when undermined
- I've only used fully grouted riprap once- it worked well but can be expensive, so I don't use it at every location
- The water gets under it and erodes the ground worse, or it floats the riprap like a sail
- Only used when cannot get a flatter slope
- Wasted money- frost and ice will break it up eventually
- Expense of materials

Do you have any negative experiences with fully grouted riprap?

- Local residents have complained about it- especially those who fish near our bridges
- FEMA won't pay for any project that is anything associated with it
- Causes a loss of flexibility in the revetment

Are there any application limitations for fully grouted riprap?

- There are some places where it is difficult to install
- Most effective on smaller creeks and ditches, less effective on larger streams and rivers with high velocities
- Sites have to be carefully selected

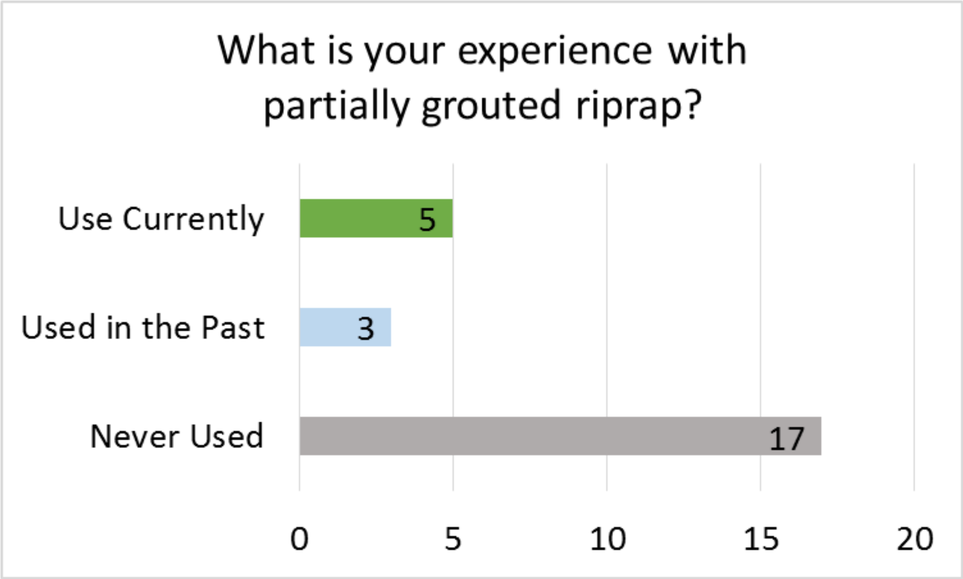
Do you have any cost information for fully grouted riprap?

- $10,000 per site
- $325/yd for 60 yd^3

Would you recommend fully grouted riprap for continued use?

- Yes (x4)
- In the right place, yes

Partially Grouted Riprap



Why is partially grouted riprap no longer used?

- Not very effective
- It is used in certain circumstances
- Same as fully grouted (Wasted money, frost and ice will break it up eventually leaving you with normal revetment)

Do you have any installation tips/suggestions for partially grouted riprap?

- We've had good experiences with using regular concrete mixes in lieu of grout to achieve some cost savings
- You want to make sure that the top riprap is at least 50% exposed so you do not streamline the surface
- Don't have a great deal of experience with it
- Make sure you have the area dewatered so that you can control the grout placement

Do you have any negative experiences with partially grouted riprap?

- Only when not properly installed
- Can get scour behind the riprap
- Not yet—but we haven't had a 2008 or 2010 event yet

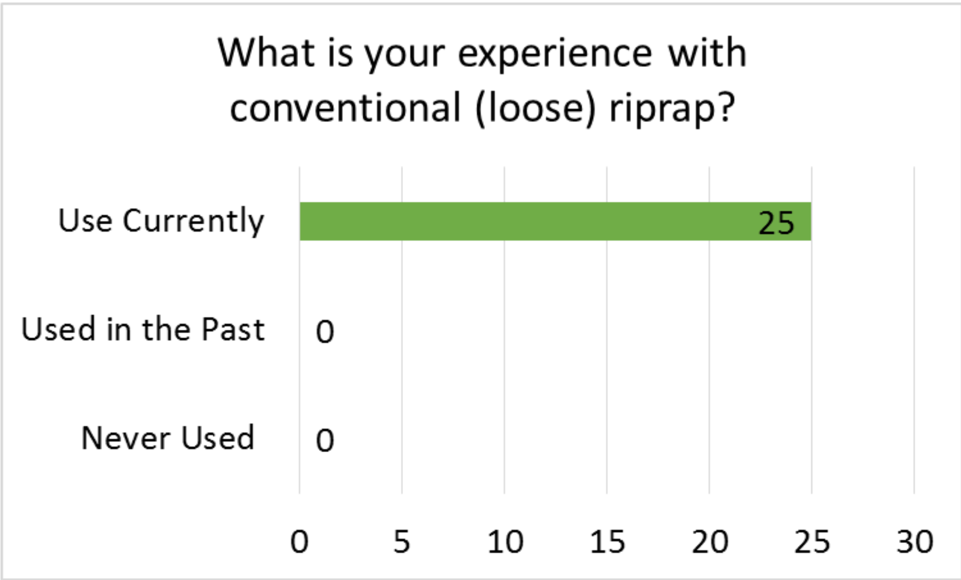
Are there any application limitations for partially grouted riprap?

- Perhaps on certain bridges on larger (for Guthrie County) rivers
- Certainly want to consider slope of channel, characteristics of channel, vegetation, velocity of water, etc.

Would you recommend fully grouted riprap for continued use?

- Yes (x4)
- In the right place, yes (x2)

Loose Riprap



Do you have any installation tips/suggestions for partially grouted riprap?

- It is time consuming, so we use prisoners from our county jail to install it. This saves our workers' labor for other things, and it also allows us to install more quickly
- Ensure that you know the substrate conditions. Provide the correct fabric layer to handle the site such as seepage, particle size, size of riprap, etc.
- I had a situation where the riprap was intermixed with gravel and dirt, and it stayed packed in place on the riverbank in a 75-year flood event, but the loose riprap placed on top of it was all washed downstream
- When installing, ensure that the riprap is set into place not just dumped
- We make sure it is keyed in not only at the toe of the slope but also at the beginning of the placement
- Key riprap into channel bottom and banks
- Use fabric under

- For the poor quality riprap areas, broken concrete is a must
- We prefer to install with fabric under riprap—don't always use it when doing repairs
- I have had no luck with fabric under the riprap—I have better luck when it is just seated into the bank
- Have used quite a bit, it is relatively inexpensive and easy to install
- 2:1 slope or flatter
- Keep the installation consistent and do not shortchange the amount and length of riprap placed
- No engineering fabric, the integration with the soil and vegetation is the best for stabilization
- Use fabric underneath
- Works well to protect banks—it is repairable
- Fabric should always be laid down prior to placing conventional (loose) riprap

Do you have any negative experiences with conventional (loose) riprap?

- We have a problem with local residents building dams with it underneath our bridges to create "fishing holes"
- Only when we make a miscalculation in sizing the riprap and it fails
- I had a situation where the riprap was intermixed with gravel and dirt, and it stayed packed in place on the riverbank in a 75-year flood event, but the loose riprap placed on top of it was all washed downstream
- Sometimes it does erode
- In high velocity situations the riprap can be dislodged and carried downstream
- We have used broken concrete from building foundations. This needs to be broken into small enough slabs to lock together
- Back to back years with flood events the loose riprap did not stay
- Several, although it's not really the fault of the loose riprap. It's more an application in poor conditions, such as steep slopes, narrow bridge high velocity conditions or too much energy exiting culverts
- Does tend to degrade and flow downstream overtime
- If it is not grouted and placed at a high velocity location it may be washed away during a high water event
- Yearly we lose it to high water
- Riprap washes out/away down into ditch, farm field, etc.
- During high flows, on highly erosive soils the riprap can get dislodged and float downstream
- Only with too large of slabs or broken concrete
- When building a new slab bridge, the contractor builds the abutment, and then attaches a support to the abutment for building the falsework. Then they place riprap. They can't place riprap where the support is. After riprap, they construct the deck. When complete with the deck, they remove the falsework, but it is difficult to get riprap up against the abutment where the support was. Erosion often develops here.
- Yes, if it is too small
- Use larger size riprap on streams under bridges, Class E. Have had smaller material rolled out by floods

- Yes—doesn't always stay in place

Are there any application limitations for conventional (loose) riprap?

- It is time consuming
- Some locations the accessibility is an issue as well as being unappealing to the passer by. Also, in some cases, due to the sheer power of the water in flood conditions or at the lake shore due to wave action requiring such large units
- When it gets too large (because of the velocity it must overcome), it gets hard to haul without punching holes in the truck box while being loaded
- Location within the ROW. Do not want it to become an obstruction. Sometime hard to install under an existing bridge
- Extreme velocity situations
- Yes—high velocities
- High velocity areas, degrading stream beds, and culvert outlets
- Do not use on high volume and high velocity flow areas
- Yes—too high a velocity, downstream land use considerations
- Riprap will not stay on steep banks
- More difficult to place when a bridge is in place
- Material availability
- Use fabric under riprap only in areas where soil filter is necessary, and repair is difficult such as under bridges.
- Yes—high velocity locations—if the current gets underneath the fabric, the riprap will not hold

Do you have any cost information for conventional (loose) riprap?

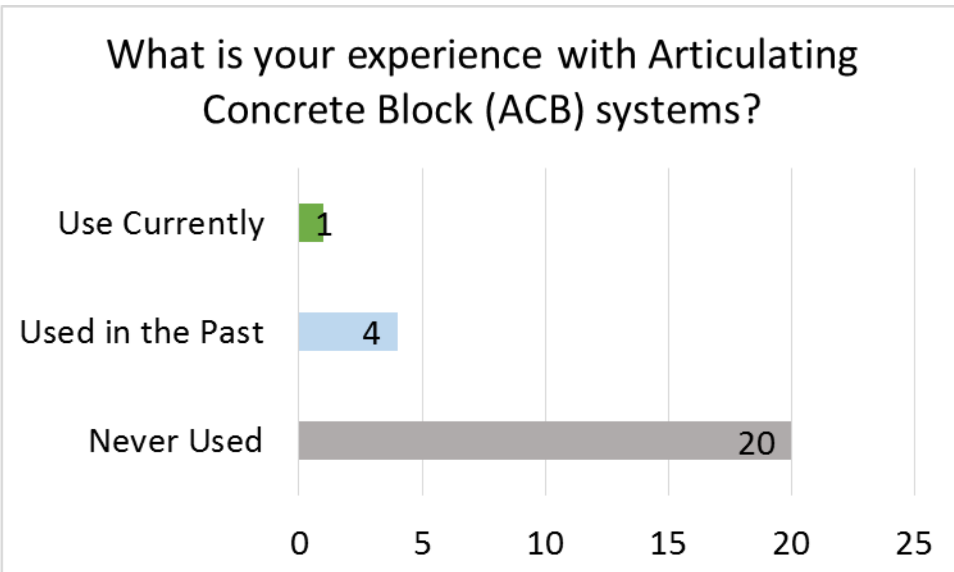
- The short-term cost is less but the long-term maintenance cost is more than grouted riprap
- Depending on size of the riprap we are seeing approximately \$50/yd^2 for large and closer to \$25 for plain riprap
- I have paid \$20.00 per ton, installed for large quantities of quarried riprap
- Material cost only \$20 per ton
- We are currently paying around \$22 per ton for Iowa DOT Class E riprap
- \$21/ton material cost, plus delivery and installation cost
- For 500 ton, we paid \$45/ton
- Generally, we use broken concrete so it's more of a loading and hauling cost than material cost
- \$22 to \$23 per ton at quarry
- We use a large amount of broken concrete from other projects or citizen donations. We don't buy very much from a quarry for local projects
- \$14 per ton delivered from a local trucking company when using broken concrete. \$30 per ton delivered if using mined riprap which is nearly unavailable in our area
- \$11.95 per ton

- \$72 per ton placed (\$7.17/yd^2 placed)

Would you recommend conventional (loose) riprap for continued use?

- Yes (x19)
- Smaller streams and seasonal creeks, it works. Also on new inlet and outlets and culvert projects
- In proper locations, absolutely, it's the only choice in many circumstances
- Usually is cheap and easy to install- would still use on many typical repairs
- It has its place where it is effective and cost saving

Articulating Concrete Block (ACB) Systems



Why is articulating concrete block no longer used?

- Haven't had the right situation where I thought it would be useful. It tends to work better in a location where conventional riprap is carried downstream during a flood event
- Cost
- Has been, but infrequently. Primarily costs are higher than riprap, harder to place under some structures
- Have not had the correct application for it and its cost

Do you have any installation tips/suggestions for articulating concrete block (ACB)?

- As with riprap, need to know the details of the substrate soils and site conditions or failure will happen

Do you have any negative experiences with articulating concrete block (ACB)?

- None to date

Are there any application limitations for articulating concrete block (ACB)?

- We have only been limited by river flow conditions in our efforts to provide a shaped bottom condition, install separation fabric and set the ACB without the first two disappearing

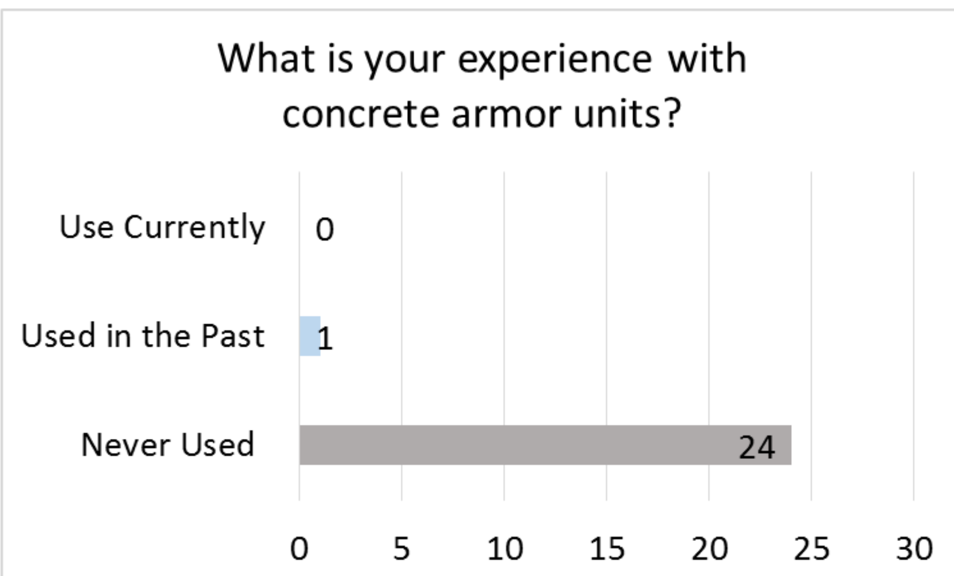
Do you have any cost information for articulating concrete block (ACB)?

- I don't recall the exact figures, but it seems to me that something on the order of \$7.50 to \$10/yd^2

Would you recommend articulating concrete block (ACB) for continued use?

- Yes, it does have its uses and we have used for access locations to rivers and lakes as well as for some limited scour countermeasure installations

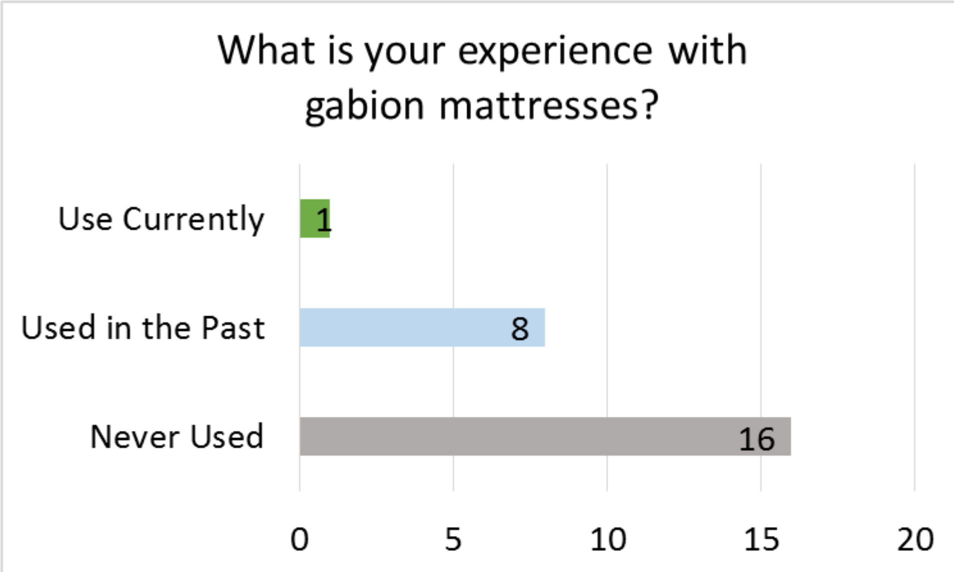
Concrete Armor Units



Why are concrete armor units no longer used?

- We haven't had the use for them recently. We installed A-Jax units in a river to reestablish a riverbank in the bend that was coming close to undercutting the roadway

Gabion Mattresses



Why are gabion mattresses no longer used?

- We have not had a recent situation where we feel they would be appropriate to use
- No reason—would use them if needed
- Very labor intensive
- Have recently always had other options
- Riprap in the gabion baskets eroded away and the baskets became dislodged and severely damaged. Cost to repair was high
- Have not had an application to use
- They are expensive and I have had failures of the baskets
- Gabion baskets work very well but are labor intensive and we are operating with limited manpower

Do you have any installation tips/suggestions for gabion mattresses?

- Fabric underneath

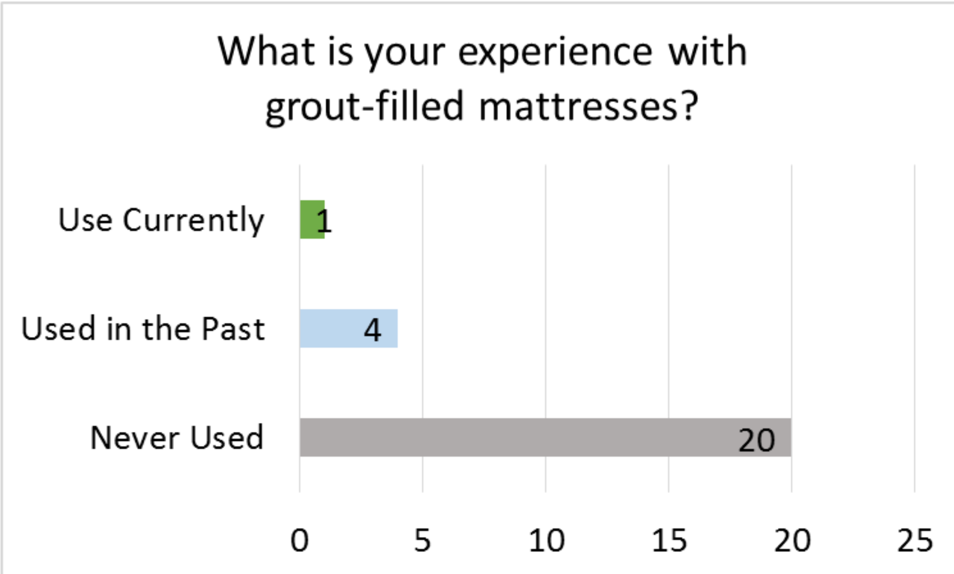
Are there any application limitations for gabion mattresses?

- Can't think of any other than a high cost due to labor expense

Would you recommend gabion mattresses for continued use?

- Yes

Grout-Filled Mattresses



Why are grout-filled mattresses no longer used?

- We have not had a use in some time. We used to do in-place scour countermeasure around several piers. Not easy to install in the river condition…
- I would absolutely use again, but have not had the right application
- Expensive

Do you have any installation tips/suggestions for grout-filled mattresses?

- Tie the bottom and sides in well

Would you recommend grout-filled mattresses for continued use?

- Yes, where applicable

THE INSTITUTE FOR TRANSPORTATION IS THE FOCAL POINT FOR TRANSPORTATION AT IOWA STATE UNIVERSITY.

InTrans centers and programs perform transportation research and provide technology transfer services for government agencies and private companies;

InTrans contributes to Iowa State University and the College of Engineering's educational programs for transportation students and provides K–12 outreach; and

InTrans conducts local, regional, and national transportation services and continuing education programs.

INSTITUTE FOR TRANSPORTATION

IOWA STATE UNIVERSITY

Visit **InTrans.iastate.edu** for color pdfs of this and other research reports.