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Vol 1

COUNTERMEASURES TO PROTECT BRIDGE PIERS FROM SCOUR

USER'S GUIDE

Prepared for
National Cooperative Highway Research Program
Transportation Research Board
National Research Council

NCHRP 24-7

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In Cooperation with

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Arthur C. Parola and D. Joseph Hagerty, University of Louisville, Kentucky

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ABSTRACT

This report is in fulfillment of NCHRP Project 24-7, Countermeasures to Protect Bridge Piers from Scour. The focus of the report concerns alternatives to standard riprap installations as pier scour countermeasures. Two kinds of countermeasures were examined: flow altering countermeasures such as sacrificial piles and armoring countermeasures such as mattresses of cable tied blocks. None of the flow altering countermeasures were found to be overly effective. Under flood conditions in sand bed streams, riprap placed in the absence of a geotextile or granular filter layer was found to gradually settle and lose effectiveness over time even under conditions for which the riprap is never directly mobilized by the flow. This settling is due to deformation and leaching of sand associated with the passage of bedforms. Riprap performance can be considerably improved with the use of a geotextile, especially if the geotextile is sealed to the pier. Another countermeasure that provides excellent protection is a mattress of cable tied blocks underlain by a geotextile tied to the pier. Design recommendations are provided for a number of armoring countermeasures.

ACKNOWLEDGMENTS

Pat Swanson, Senior Editor at St. Anthony Falls Laboratory, put in many hours above and beyond the call of duty to prepare this report. Benjamin Erickson, Assistant Scientist, spent extensive hours formatting photographs, figures and the supplementary videotape associated with this report. The authors sincerely thank the many personnel of various state departments of transportation for their time and help in regard to bridge scour and countermeasures.

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1. INTRODUCTION

The material presented here constitutes Volume 1 of a two-volume report prepared for the NCHRP Project 24-7, Countermeasures to Protect Bridge Piers from Scour. This volume constitutes a user's manual for the implementation of scour countermeasures at bridge piers. In accordance with the project statement for 24-7, the recommended countermeasures apply only to bridge piers in rivers, and not abutments, floodplains etc. The countermeasures are further limited to *existing bridge piers* in *stable streams*.

A detailed report of the entire research effort is presented in Volume 2. In that document a wide range of countermeasures was considered and studied in varying degrees of detail. Many countermeasures, such as grade control structures and foundation rehabilitation, were rejected as being outside the scope of the 24-7 study. Many more countermeasures were rejected after a determination was made that they were not likely to be effective. Several others look promising, but lack sufficient detail for implementation guidelines. Only those for which fairly complete implementation guidelines could be specified are included here. This notwithstanding, not all of the countermeasures listed herein can be highly recommended by the 24-7 research team. At least one, grout filled bags, is recommended only when better countermeasures cannot be implemented.

The justifications for the design recommendations offered here are contained in Volume 2. One of the conclusions in that document bears repeating here. In the absence of a geotextile filter or a granular filter layer, riprap and related armoring countermeasure units tend to sink into the bed of sand bed streams during floods. This is caused by the passage of bedforms. This sinking can greatly reduce or negate the effectiveness of the countermeasure. With this in mind, considerable importance is attached to the use of a geotextile filter or a granular filter layer below an armoring countermeasure on a sand bed stream.

In this report D denotes pier width, L denotes pier length, d_{50} denotes the median size of the bed sediment (or granular filter material) and D_{r50} denotes median riprap size. These and other symbols are defined in Appendix A.

2. DESIGN RECOMMENDATIONS FOR SELECTED COUNTERMEASURES

Only a select few of the countermeasures investigated in this study were selected for this user's manual. They are enumerated below:

- Riprap with prior excavation and with geotextile or granular filter;
- Riprap without prior excavation and with geotextile or granular filter;
- Riprap without prior excavation, without geotextile or granular filter;
- Cable tied blocks;
- Grout filled bags; and
- Gabions.

For design criteria for toskanes and related devices such as tetrapods, the reader is referred to Fotherby and Ruff (1995). (All references in this volume are given in Chapter 3.) The following countermeasures were either not deemed of sufficient value or not yet sufficiently documented for the specification of implementation recommendations.

- Pier attached vanes;
- Sacrificial piles;
- Pier suction;
- Permeable sheet piles;
- Slot in pier;
- Collars and horizontal plates;
- Pavement;
- Riprap augmented by submerged permeable sheet piles;
- High density riprap; and
- Iowa Vanes.

In fact, all but the last three of the above countermeasures were deemed to have limited potential by the 24-7 team.

The following caveats apply in general to all the implementation recommendations given below. They are directed toward the protection of *existing bridge piers* against local scour in streams that are otherwise *stable*. This is in accordance with the language of the initial Project Statement for NCHRP Project 24-7, "Countermeasures to Protect Bridge Piers from Scour." Local protection of piers against scour may be ineffective in cases involving severe channel degradation, channel migration, debris problems, ice jams etc. The type of river considered here is an alluvial sand bed or gravel bed river. These notes are not applicable to piers with footings on bedrock, nor are they applicable to piers on floodplains.

The material is presented as follows. Implementation notes are provided in regard to geotextile filters and granular filter layers. Guidelines are then provided for each of the countermeasures selected above. Design recommendations are presented for each countermeasure. These are followed by a list of notes in bullet form on implementation of the countermeasure, and in particular pertaining to feasibility, effectiveness, constructability, durability, maintainability, and cost. Each of these terms is defined below for the purpose of this report.

Feasibility. For a given situation is the method or technique applicable?

Effectiveness. When is the method technically effective? Under how wide a range is the method effective?

Constructability. - Does the method require specialized labor, supplies or placement equipment or can it be done using standard equipment and readily available materials? This obviously must allow for some regional variation and environmental constraints.

Durability. Is the method capable of working for a period of several flood seasons without requiring replacement or repair?

Maintainability. Is the method easily maintained or does it require specialized equipment and supplies?

Cost. Original construction cost on a unit cost basis and for a hypothetical installation.

For the purpose of this user's manual, a gravel bed stream is one with a surface median bed material size d_{50} in excess of 2 mm, and a sand bed stream is one for which 0.06 mm $< d_{50} <$ 2 mm. Streams with values of d_{50} between 2 and 8 mm are, however, relatively uncommon.

2.1 IMPLEMENTATION NOTES FOR GEOTEXTILE FILTERS AND GRANULAR FILTER LAYERS

The research conducted in the course of this project indicates that under flood conditions in sand bed streams with developed bedforms the leaching of sand from the interstices of any armoring countermeasure may ultimately result in failure of the countermeasure. With this in mind, and in light of the positive results of experimental testing, it is recommended here that such an armoring countermeasure in a sand bed stream be underlain by an appropriately selected geotextile filter. The functions of the geotextile are to a) keep fine particles underneath in place, b) allow for the release of pore pressure, and c) help reinforce the countermeasure above. The following further recommendations are made.

- It is recommended that the areal cover of the geotextile filter be less than that of the armoring countermeasure in order to allow for anchoring of the edges of the geotextile filter. More specific recommendations are made below for several selected armoring countermeasures.
- It is recommended that the permittivity of the geotextile filter be sufficient to allow release of pore pressures without causing uplift of the fabric under flood conditions. The selection of a relatively open fabric, i.e. one which retains all sizes finer than one modestly finer than the median size d_{50} of the bed material may be advantageous. Such a selection may encourage the formation of a natural granular filter layer below the geotextile filter. Failure to properly release the buildup of pore pressure may lead to uplift and catastrophic failure of the geotextile filter and armoring countermeasure above.
- It is recommended that the geotextile filter be resistant to tearing or puncturing during countermeasure placement or settling. Testing indicates that even gaps as small as 0.25 in can allow the leaching of a significant quantity of bed material.
- It is recommended that the geotextile filter have a lifetime of at least 100 years without decay when placed on the bed of a natural river in the vicinity of a bridge pier.
- It is recommended that the geotextile filter be fabricated from ultraviolet light resistant materials.
- In a reach subject to periodic scour and fill, it is recommended that both the geotextile filter and countermeasure above be placed at a level characteristic of ambient bed level near the pier at time of maximum scour. If this is not done the scour may leave the geotextile filter and armoring countermeasure perched during floods, possibly leading to the loss of both. At the very least the bottom of the countermeasure should be at or below the maximum anticipated scour depth.

Geotextile filters are not recommended for gravel bed streams both due to the abrasive nature of gravel and its low potential for leaching.

The technology for the use of geotextile filters in tandem with armoring countermeasures at bridges remains insufficiently developed. The following ideas pertaining to field installation of geotextile filters are offered with the recommendation that they be pursued by bridge engineers working together with geotextile filter manufacturers.

The geotextile filter is provided with two sleeves, one around the outer circumference and one around the inner circumference to be placed in contact with the bridge pier. The outer sleeve contains a cable attached to several hooks projecting from the outer edge. In addition, it is filled with a quantity of ballast (in the form of fine riprap, for example). The ballast helps weigh the outer edge of the geotextile filter down as it is spread underwater at low flow. The hooks are attached to external cables manipulated from a crane on the bridge deck. The external cables and crane are used to spread the geotextile filter underwater. It is weighed down from behind by properly sized riprap, taking care not to rip the geotextile. The hooks are released upon successful installation. The procedure is illustrated in Figures 2.1 and 2.2.

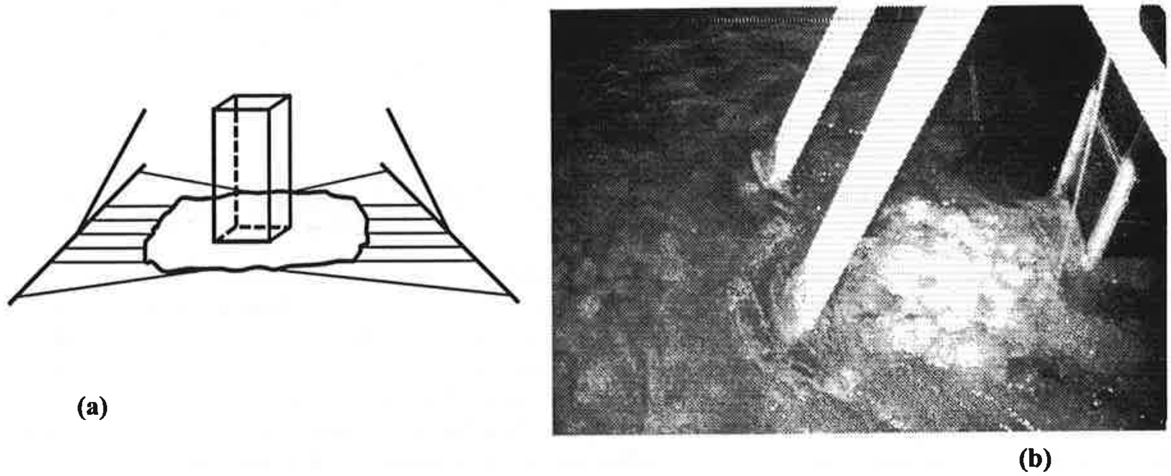

Figure 2.1. a) Schematization of the geotextile installation under water. b) View of actual installation of the geotextile underwater.

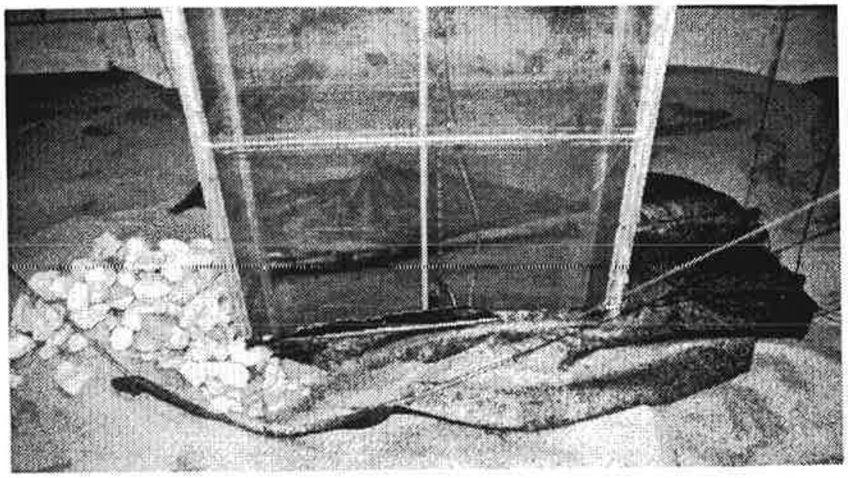

Figure 2.2. Illustration of the low-water installation technique for geotextile and riprap. The flow has been temporarily halted to improve visibility.

The inner sleeve is fitted with a durable but flexible tubing, inside of which is placed a cable of durable material. The cable is then tightened around and clamped to the circumference of the pier, so sealing the geotextile filter to it. Experiments indicate that such sealing can considerably enhance the performance of an armoring countermeasure.

Granular filter layers were not tested experimentally in this study. Information collected in the course of the field site visits and in consultation with other engineers indicates that the underwater installation of granular filter layers can be difficult, and is often omitted even though recommended by e.g. Neill (1973). In addition, granular filter layers may be subject to reworking by river bedforms such as dunes, and thus may fail where a geotextile filter would not. This notwithstanding, the overall accumulation of experience with granular filter layers indicates that they are recommended for use in place of a geotextile filter in the event that a geotextile filter cannot be installed.

The guidelines due to Richardson et al. (1990) in the document "Highways in the River Environment" are recommended for the design of filter layers. These call for satisfying three criteria involving the sizes d_{15} (such that 15 % by weight is finer), d_{50} (such that 50 % is finer) and d_{85} (such that 85 % is finer) of the granular filter material and the base material, or ambient bed sediment below the filter layer.

$$\frac{d_{50}(\text{filter})}{d_{50}(\text{base})} < 40 \qquad 5 < \frac{d_{15}(\text{filter})}{d_{15}(\text{base})} < 40 \qquad \frac{d_{15}(\text{filter})}{d_{85}(\text{base})} < 5 \tag{2.1a,b,c}$$

In the case for which the riprap itself satisfies these criteria no granular filter layer is required. This may often be the case for gravel bed streams. In other cases multiple filter layers may be required to meet the criteria.

Neither a geotextile nor a filter layer is normally necessary or desirable in the case of a gravel bed stream.

2.2 COUNTERMEASURE DESIGN GUIDELINES

2.2.1 Design Recommendations for Riprap with Prior Excavation and with Geotextile or Granular Filter

Required information

- Pier width D
- Pier shape: round nosed or square nosed
- Depth averaged approach flow velocity U upstream of the pier at design flow conditions
- Angle of attack β of flow at bridge pier at design flow conditions
- Density ρ_r of the riprap to be used

The design flow conditions might correspond to anything from a 10 year flood to a standard project flood, depending upon the economic and social importance of the bridge. Standard software such as WSPRO, HEC-RAS, RMA-2 and FESWMS is available to help the user predict U and β at design conditions.

Riprap sizing

It is recommended that the median size of the riprap be determined using the following relation due to Parola and Jones (1991), which also appears in the HEC-18 manual (Richardson et al., 1993).

$$D_{r50} = \frac{U^2}{\frac{2.89}{K^2}\left(\frac{\rho_r}{\rho} - 1\right)g} \tag{2.2}$$

where

g is the acceleration of gravity,
ρ_r/ρ is the specific gravity of the riprap,
K = 1.5 for round nosed piers and 1.7 for square-nosed piers.

If U is input in m/s, g = 9.81 m/s^2 and D_{r50} is specified in meters. If U is input in ft/s, g = 32.2 ft/s^2 and D_{r50} is specified in ft.

Riprap size distribution

It is recommended that riprap be durable, angular rock with a wide range of size distributions. The following size distribution, modeled after Neill (1973) is recommended.

100% finer than	1.5 D_{r50}
80% finer than	1.25 D_{r50}
50% finer than	1 D_{r50}
20% finer than	0.6 D_{r50}

Riprap installation

Recommended riprap installation for the case of prior excavation is outlined in Figures 2.3 and 2.4. The placement technique shown in the figures is predicated on the recommended use of a geotextile, as outlined below. The riprap cover, c (i.e. the transverse extent from edge to edge of the riprap layer) is equal to 4 D. That is, the riprap extends outward at least a distance 1.5 D from every face, so that the total lateral distance from one edge of the riprap to the other is at least 4 D, as illustrated in Figure 2.4. In the event that the angle of attack β exceeds 15°, the cover is taken to be at least 4 D/cos(β), and distributed spatially as shown in the Figure 2.4. The bed is excavated to a depth t of at least 2 D_{r50} before placing the riprap. The riprap is placed in the excavation in a layer with a thickness of at least 2 D_{r50}, such that the top of the riprap layer is flush with the bed at low flow. The depth of excavation might best be increased to the level of deepest expected scour if significant scour and fill associated with e.g. a contraction or a bend is expected at the site. Such a deep placement may inhibit future inspection, but may provide more reliable protection in the long run.

Inspection and quality control during construction are crucial to successful riprap installation.

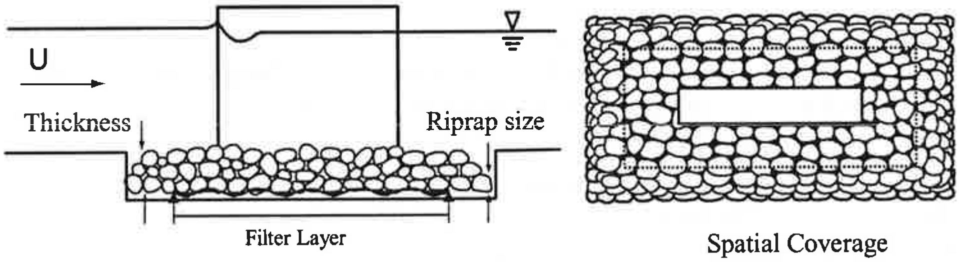

Figure 2.3. Riprap installation with prior excavation.

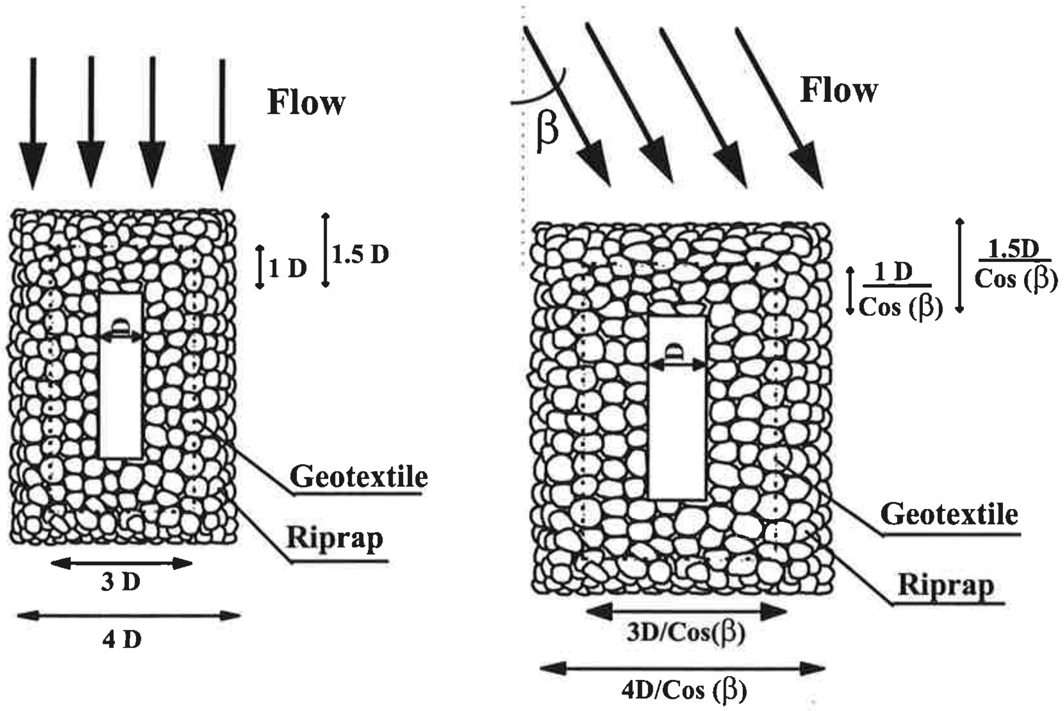

Figure 2.4. Riprap and geotextile cover with prior excavation.

Geotextile filter or granular filter layer

In the case of a gravel bed river it is recommended that a geotextile filter not be used. In the case of a sand bed river, it is recommended that a geotextile filter be placed underneath the riprap. It is recommended that the cover of the geotextile filter be 3 D as shown in Figure 2.4. Thus if the riprap extends 1.5 D outward from every face, the geotextile filter should extend 1 D out from every face. It is recommended that the geotextile filter never extend out as far as the riprap. Best performance can be obtained by sealing the geotextile filter to the pier. Sealing can be implemented by means of a flexible tube containing a cable that can be tightened around the pier. The flexible tube must be attached to the geotextile. Alternately, sealing can be implemented by installing a granular filter layer around any gap between the geotextile filter and the pier itself.

In the event that the use of a geotextile filter is not possible, a standard granular filter layer may be used in place of a geotextile filter. In such case it is recommended that special care be given to installation of both the filter layer and the riprap around the edges of the pier. The granular filter layer should have the same cover as the riprap itself.

It is recommended that riprap not be installed in a sand bed stream without a geotextile filter, or at least a granular filter layer. In the event that the means for such installation are unavailable, however, experiments suggest that at least some degree of protection is provided by a riprap layer with a thickness of at least 4 D_{r50} and a cover of 5 D, i.e. extending out 2 D from every pier face. Prior excavation may be essential for such a case to realize any long term protection at all. Monitoring of such installations should be made frequently as riprap settling into the bed may necessitate replenishment.

Implementation notes

Feasibility

- Sand bed or gravel bed streams.
- Not necessary to apply the geotextile or granular filter on gravel streams.
- With no blockage of flow area, it is advantageous at sites with limited bridge conveyance area.
- Some resource agencies object to excavation in streams.
- Granular filters are a potential substitution for the geotextile, but will increase the degree of blockage due to filter layer thickness.
- Geotextile not easily sealed to pile bents.

Effectiveness

- Good filter seal around pier is critical.
- Offers reduced tendency for rock dispersal.
- Areal footprint of countermeasure is smaller than that for riprap placed on grade. Thickness of the countermeasure is also less, and decrease in rock volume is 50 percent or more.
- Consider granular filter as an alternate to geotextile filter; granular filter may be subject to degradation due to passage of dunes during floods.
- Increased effectiveness if tied into abutment countermeasure when pier is located within 3 pier diameters of abutment footings.

Constructability

- Decrease riprap volume from [5D x (4D + L)] x 3D_{50} to [4D x (3D + L)] x 2D_{50} as compared to installation without excavation.
- Pier footing and/or pile geometry may limit ability to pre-excavate.
- If the piles are already exposed, a slurry of river bed material should be placed underneath the pile cap to provide needed support.
- Specialized construction techniques are needed for geotextile placement. Recommendations in regard to their development are contained in this report.
- The height of riprap rockfall on top of the geotextile should be limited to avoid rupturing.
- Construction sequence is important for good performance; however, specifications generally dictate final placement, not construction sequence.

Durability

- Generally provides a broad band of failure threshold.
- Catastrophic failure potential if the geotextile is exposed; this possibility can be minimized by designing the geotextile with a cover area that is less than that of the riprap.
- Prior excavation reduces exposure of rock to flow and increases durability.

Maintainability

- University of Minnesota tests indicate decreased rock dispersal with this method (as compared to the case of no prior excavation), thus lowering maintenance requirements.
- The tensile strength and elongation properties of the geotextile should allow for some settlement of the countermeasure.
- High permittivity, high strength nonwoven geotextiles with large mass per unit area should be easier to maintain.
- Difficult to repair if the geotextile rips; riprap must be removed before repair.
- Difficult to identify exact location of geotextile failure.
- Rebuilding/repairing gravel filters is easier than geotextile repair.
- Geotextile fails abruptly.
- Clean up is difficult after a failure.

Cost

- Cost for hypothetical 4 ft x 20 ft rectangular pier is $5,000/pier (as of 1998) when placed over a granular filter and about $15,000 (as of 1998) when placed over a geotextile. Of this $15,000, the cost for the installation of the submerged geotextile filter is about $10,000. This cost includes a 4-person setup crew for 2 days per pier, a 6 person 1-day installation crew, plus one diver per day. The cost may come down with the development of specialized installation technology. A granular filter is less expensive to install using existing technology.
- Pre-excavation costs are about $25/yd^3 with on-site disposal as of 1998.
- Disposal costs for excavated material may add to the cost.
- Lower rock requirements than without prior excavation due to smaller thickness and footprint. Approximately 50% less rock than without excavation.
- Traffic disruption should be considered.

2.2.2 Design Recommendations for Riprap Without Prior Excavation but with Geotextile or Granular Filter

Required information

- Pier width D
- Pier shape: round nosed or square nosed
- Depth averaged approach flow velocity U upstream of the pier at design flow conditions
- Angle of attack β of flow at bridge pier at design flow conditions
- Density ρ_r of the riprap to be used

The design flow conditions might correspond to anything from a 10 year flood to a standard project flood, depending upon the economic and social importance of the bridge. Standard software such as WSPRO, HEC-RAS, RMA-2 or FESWMS is available to help the user predict U, y_o and β at design conditions.

Riprap sizing

It is recommended that the median size of the riprap be determined using Eq. (2.2) due to Parola and Jones (1991), which also appears in the HEC-18 manual (Richardson et al., 1992).

Riprap size distribution

It is recommended that riprap be durable, angular rock with a wide range of size distributions. The following size distribution, modeled after Neill (1973) is recommended.

100% finer than	1.5 D_{r50}
80% finer than	1.25 D_{r50}
50% finer than	1 D_{r50}
20% finer than	0.6 D_{r50}

Riprap installation

The recommended placement is outlined in Figures 2.5 and 2.6. In the case for which the bed is not excavated in advance it is recommended that riprap cover, c should be increased to 5 D. That is, the riprap extends outward at least a distance 2 D from every face, so that the total lateral distance from one edge of the riprap to the other is at least 5 D, as illustrated in Figure 2.6. In the event that the angle of attack β exceeds 15°, the cover is taken to be at least 5 D/cos(β), and distributed spatially as shown in Figure 2.6. It is recommended that the river bed be smoothed, and any existing scour hole filled with finer riprap before the installation of the riprap sized by the method recommended above. The riprap is placed over the smoothed bed with a thickness of at least 3 D_{r50}. If this thickness is in excess of 0.25 y_o at design flood, a condition that may prevail particularly in shallow gravel bed streams, it is recommended that this method of installation be abandoned and the bed be excavated before installation. If significant scour and fill associated with e.g. a contraction or a bend is expected at the site then riprap should not be installed without prior excavation.

Inspection and quality control during construction are crucial to successful riprap installation.

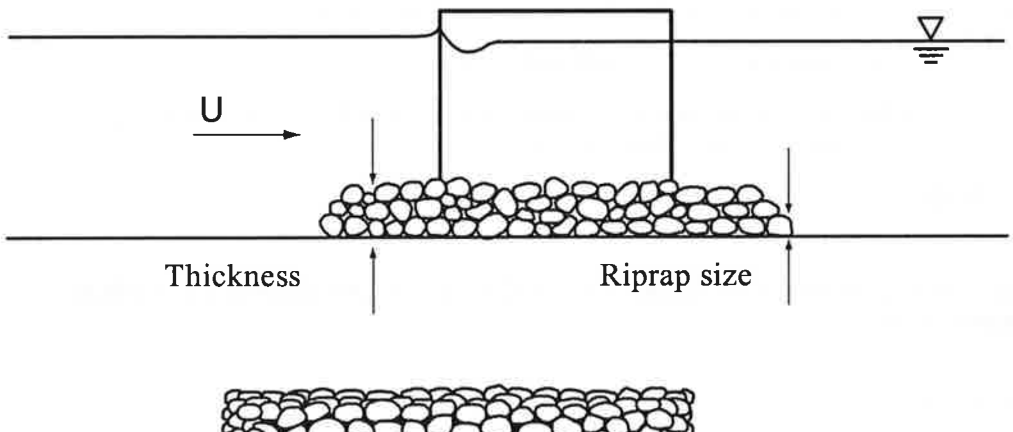

Figure 2.5. Riprap installation without prior excavation.

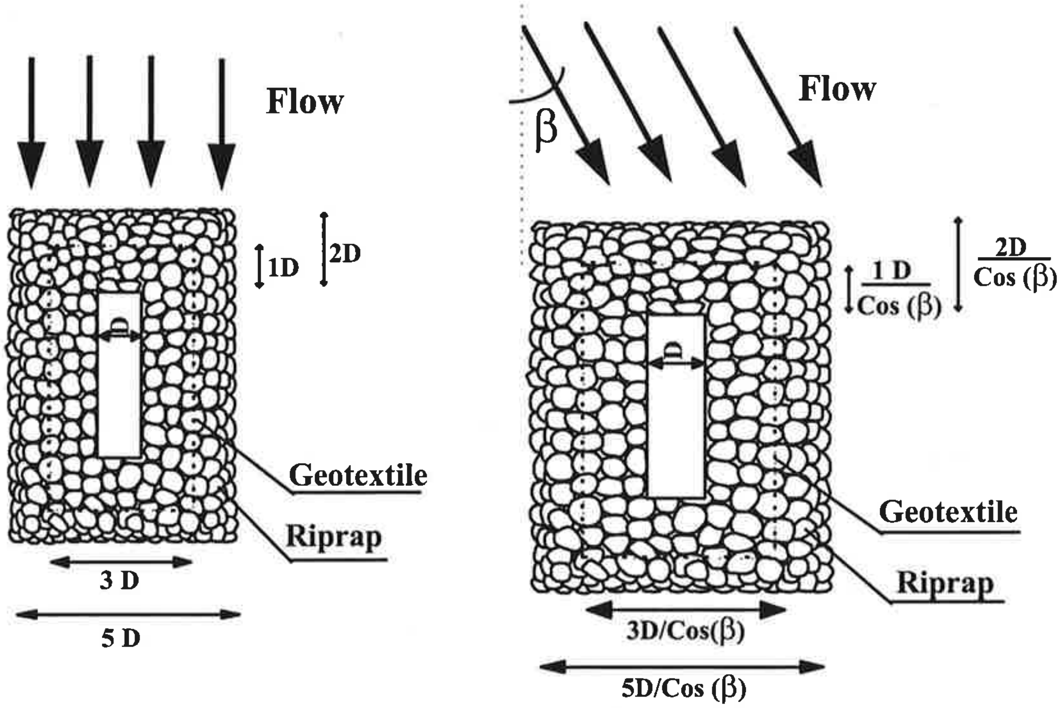

Figure 2.6. Riprap and geotextile cover without prior excavation.

Geotextile filter or granular filter layer

It is recommended that in the case of a gravel bed river a geotextile filter not be used. In the case of a sand bed river, it is recommended that a geotextile filter be placed underneath the riprap. The cover of the geotextile filter is 3 D, so that the geotextile filter extends out 1 D from every face. It is recommended that the geotextile filter never extend out as far as the riprap. Best performance is obtained by sealing the geotextile filter to the pier. Sealing can be implemented by means of a flexible tube containing a cable that can be tightened around the pier. The flexible tube must be attached to the geotextile. Alternately, sealing can be implemented by installing a granular filter layer around any gap between the geotextile filter and the pier itself.

In the event that the use of a geotextile filter is not possible, a standard granular filter layer may be used in place of a geotextile filter. In such case it is recommended that special care be given to installation of both the filter layer and the riprap around the edges of the pier. The granular filter layer should have the same cover as the riprap itself.

Implementation notes

Feasibility

- Use geotextile filter or granular filter on sand bed streams (bed material $d_{50} < 2$ mm).
- Not necessary to apply the geotextile or granular filter on gravel streams.
- Method may reduce conveyance of bridge opening to an unacceptable level; it is recommended that blockages be less than 10% flow area, or 25% flow depth at pier.

- Granular filters are a potential substitution for the geotextile, but will increase the degree of blockage due to filter layer thickness.
- Geotextile not easily sealed to pile bents.

Effectiveness

- Good filter seal around pier is critical.
- Adequate rock coverage is needed so that fabric is not exposed upon settling of riprap around perimeter.
- Consider granular filter as an alternate to geotextile filter; granular filter may be subject to degradation due to passage of dunes during floods.
- Increased effectiveness if tied into abutment countermeasure when pier is located within 3 pier diameters of abutment footings.

Constructability

- The height of riprap rockfall on top of the geotextile should be limited to avoid rupturing.
- If the piles are already exposed, a slurry of river bed material should be placed underneath the pile cap to provide needed support.
- Specialized construction techniques are needed for geotextile placement. Recommendations in regard to their development are contained in this report.
- Gravel cushion placed on geotextile is recommended to avoid rupturing.
- Construction sequence is important for good performance; however, specifications generally dictate final placement, not construction sequence.

Durability

- Generally provides a broad band of failure threshold.
- Catastrophic failure potential if the geotextile is exposed; this possibility can be minimized by designing the geotextile with a cover area that is less than that of the riprap.

Maintainability

- The tensile strength and elongation properties of the geotextile should allow for some settlement of the countermeasure.
- High permittivity, high strength nonwoven geotextiles with large mass per unit area should be easier to maintain.
- Difficult to repair if the geotextile rips; riprap must be removed before repair.
- Difficult to identify exact location of geotextile failure.
- Rebuilding/repairing gravel filters is easier than geotextile repair.
- Geotextile fails abruptly.
- Clean-up is difficult after a failure.

Cost

- Cost for a hypothetical 4 ft x 20 ft pier is $14,500, as of 1998.

- Submerged geotextile installation cost is about \$10,000 for a single pier, as of 1998. This cost includes a 4 person setup crew for 2 days per pier, a 6 person 1-day installation crew, plus 1 diver for a day. The cost may come down with the development of specialized installation technology.
- Traffic disruption should be considered.

2.2.3 Design Recommendations for Riprap Without Prior Excavation, Without Geotextile or Granular Filter

Required information

- Pier width D
- Pier shape: round nosed or square nosed
- Approach flow velocity U and approach flow depth y_o at design flow conditions
- Angle of attack β of flow at bridge pier at design flow conditions
- Density ρ_r of the riprap to be used

The design flow conditions might correspond to anything from a 10 year flood to a standard project flood, depending upon the economic and social importance of the bridge. Standard software such as WSPRO, HEC-RAS, RMA-2 or FESWMS is available to help the user predict U, y_o and β at design conditions.

Riprap sizing

It is recommended that the median size of the riprap be determined using Eq. (2.2) due to Parola and Jones (1991), which also appears in the HEC-18 manual (Richardson et al., 1992).

Riprap size distribution

It is recommended that riprap be durable, angular rock with a wide range of size distributions. The following size distribution, modeled after Neill (1973) is recommended.

100% finer than	1.5 D_{r50}
80% finer than	1.25 D_{r50}
50% finer than	1 D_{r50}
20% finer than	0.6 D_{r50}

Riprap installation

An installation without prior excavation and without either a geotextile filter or a granular filter layer is recommended only in the case of gravel bed streams of sufficient depth to allow good submergence of the riprap layer at flood flow. It is not recommended for either a sand bed stream or a shallow gravel bed stream.

In the event that such an installation can be justified, the recommended placement is as outlined in Figures 2.5 and 2.6 (but without the geotextile or granular filter layer). Since the bed is not excavated in advance it is recommended that riprap cover, c be 5 D. That is, the riprap extends outward at least a distance 2 D from every face, so that the total lateral distance from one edge of the riprap to the other is at least 5 D, as illustrated in Figure 2.5. In the event that the angle of attack β exceeds 15°, the cover is taken to be at least 5 D/cos(β), and distributed spatially as shown in Figure 2.6. It is recommended that the river bed be smoothed, and any existing scour hole filled with finer riprap before the installation of the riprap sized by the method recommended above. The riprap is placed over the smoothed bed with a thickness of at least 3 D_{r50}. If this thickness is in excess of 0.25 y_o at design flood, a condition that may prevail particularly in shallow gravel bed streams, it is recommended that this method of installation be abandoned and the bed be excavated before installation. If significant scour and fill associated with e.g. a contraction or a bend is expected at the site then riprap should not be installed without prior excavation.

Implementation notes

Feasibility

- For use in gravel bed streams only (bed material $d_{50} > 2mm$).
- Not suitable for sand bed streams.
- Gradation is important for effective performance.
- Must have good interlocking between stones.
- Quarry run stone with wide gradation may work (supplies its own filter).
- Blocking of bridge opening may inhibit use; it is recommended that blockages be less than 10% flow area, or 25 % flow depth at pier.
- End dumping is not recommended as it can cause segregation of rock sizes.
- If placed on a sand bed stream, frequent retrofitting and adding of stones are required.

Effectiveness

- Effective if bed material is sufficiently coarse so as not to winnow through the riprap.
- Gradation must be checked.
- Construction observation and communication of design requirements to the contractors are very important.
- Good quality control on riprap and installation is essential.
- Good for multiple events if rock size is adequate and rocks are not dispersed.
- Broad band of failure threshold exists (no catastrophic threshold).
- Increased effectiveness if tied into abutment countermeasure when pier is located within 3 pier diameters of abutment footing.

Constructability

- Standard construction techniques: dumped rock (limit drop to less than 4 feet to avoid segregation); front end loader will result in poor placement if simply dumped from bucket; a back-hoe or clam shell is recommended.
- Equipment access considerations: right of way, incised stream access, and low bridge clearance.
- Good quality control is essential.
- Areal extent of coverage must be verified.
- Seasonal constraints exist on installation.

Durability

- If properly designed, very durable; broad existing experience among practitioners.
- Rock can be expected to stay in place for events less than or equal to the design event.
- Broad band of failure threshold is provided; catastrophic failure of countermeasure is not typical.
- Self healing.

- Monitoring critical.

Maintainability

- Scour monitoring is critical for areal extent and depth of rock. Measurements taken during or immediately after events are best. Identify necessary maintenance before the protection becomes ineffective.
- Use common mapping techniques for which practitioners have wide experience (lead line, fathometer).
- Replacement rocks can usually be easily obtained.
- When displacement occurs, reuse of rocks is sometimes practical.

Cost

- For bridges of 3 or more spans, the typical unit prices as of 1998 for average wet placement conditions are about $35 - 45/ton when rock is available within a 25 mile radius of the site.
- Additional transportation costs will be $0.15 - 0.20/ton mile as of 1998.
- 50 to 100 yds^3 or riprap per pier is typical.
- Cost for a hypothetical 4 ft x 20 ft rectangular pier is estimated at $4500/pier as of 1998.
- Lack of local availability of suitable rock will raise cost.
- Access and equipment considerations are important cost factors.
- Mobilization costs (economies of scale).
- Seasonal constraints (environmental windows, flow conditions) contribute additional expenses.
- A silt curtain may be required by regulatory agencies.
- Unit price (i.e. engineers' thinking) vs. construction sequence costs (i.e. contractors' estimate): conversion from tons to yds^3 is 1.4 ± 0.1 T/yd^3.
- Verify how quantity of rock measured. Volume vs. tonnage.
- Traffic disruption should be considered.

2.2.4 Design Recommendations for Cable Tied Blocks

Required information

- Pier width D
- Pier shape: round nosed or square nosed
- Depth averaged approach flow velocity U upstream of the pier at design flow conditions
- Angle of attack β of flow at bridge pier at design flow conditions
- Density ρ_{cb} of the material of the blocks in the mattress
- Median size d_{50} of the bed material

The design flow conditions might correspond to anything from a 10 year flood to a standard project flood, depending upon the economic and social importance of the bridge. Standard software such as WSPRO, HEC-RAS, RMA-2 and FESWMS is available to help the user predict U, y_o and β at design conditions.

Weight per unit area of the cable tied block mattress

The weight per unit area of the mattress ζ may be sized as

$$\varsigma = a_{cb}\frac{\rho_{cb}}{\rho_{cb}-\rho}\rho U^2 \qquad a_{cb} = 0.20 \tag{2.3a,b}$$

where

ρ denotes the density of water.

If U is input in m/s and ρ_{cb} in kg/m^3 then ρ is 1000 kg/m^3 and ζ is specified in N/m^2. If U is input in ft/s then ρ is 1.94 slugs/ft^3, ρ_{cb} = (s.g.) x 1.94 slugs/ft^3 where s.g. = specific gravity of the block material, and ζ is specified in lbs/ft^2. The height of the blocks H_{cb} and the volume fraction pore space p in the mattress are related to ζ by the relation

$$\varsigma = \rho_{cb} g H_{cb}(1-p) \tag{2.3c}$$

It is recommended that the spacing between cable tied block units be enough to allow the mattress a sufficient degree of flexibility.

Cable quality

The vicinities of bridge piers at the bottom of rivers are abrasive environments. It is recommended that the cable connecting the blocks be sufficiently flexible so as to allow the mattress to deform, but sufficiently durable to last at least 20 years in a fast-water river environment. Review of field installations has shown that even well specified galvanized cabling experiences internal interstrand corrosion. Stainless steel cables are advised for harsh environments. UV stable poly rope may be a good alternative. It is recommended that cable tied blocks not be used for even moderately saline environments such as estuaries.

Mattress installation

Installation recommendations are summarized in Figure 2.7. Prior excavation is not needed in the case of cable tied block mattresses. An exception to this might be a case for which block height H_{cb} exceeds 0.25 y_o, where y_o denotes the flow depth under design conditions. The mattress cover, c is equal to 4 D. That is, the mattress extends outward at least a distance 1.5 D from every face, so that the total lateral distance from one edge of the mattress to the other is at least 4 D, as illustrated in Figure 2.7. In the event that the angle of attack β exceeds 15°, the cover is taken to be at least 4 D/cos(β), and distributed spatially as shown in Figure 2.7.

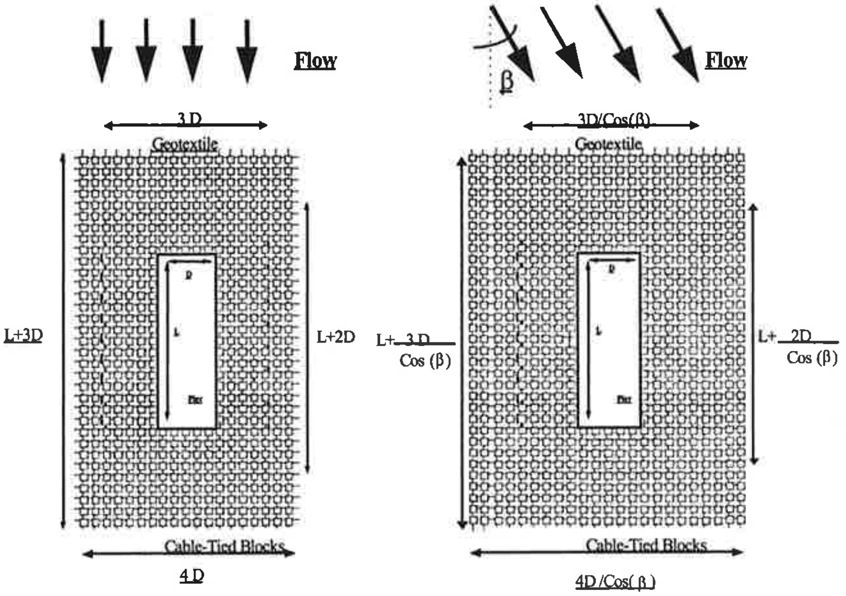

Figure 2.7. Installation of cable tied block mattress and geotextile.

Geotextile filter

It is recommended that in the case of a gravel bed river a geotextile filter not be used. In the case of a sand bed river, it is recommended that a geotextile filter be placed underneath the mattress. It is recommended that the manufacturer fasten the geotextile filter firmly to the base of the block mattress. The cover of the geotextile filter extends 2/3 of the distance from the pier face to the edge of the mat. Thus if the mattress extends 1.5 D outward from every face, the geotextile filter extends 1 D out from every face. It is recommended that the geotextile filter never extend out as far as the mattress. It is recommended that a granular filter layer not be substituted for a geotextile filter in the case of cable tied blocks, due to the relative ease of fastening the geotextile filter to the mattress prior to installation. A granular filter may be used to help seal the mattress and geotextile filter to the pier, as outlined below.

The cable-tied block mattress can be constructed so that they can be fastened and sealed to the pier in the same way as outlined for the case of a geotextile under riprap. That is, the geotextile fastened below the block mattress extends beyond the inside edge a distance of 2 to 3 times the mat thickness and is attached to a flexible tube spanning the circumference of the pier. Inside the flexible tube is a cable. Upon installation, the additional geotextile is folded up, and the cable is tightened around the pier, thus fastening the mattress. Alternatively, a granular filter can be used to fill in the gap between the mattress-geotextile and the pier.

Implementation notes

Feasibility

- Sand bed and gravel bed rivers.
- Not suitable for pile bents or complex pier shapes.
- Not suitable for rivers with large cobbles or rock.
- Water quality must be noncorrosive, and thus is not appropriate for e.g. saline or acidic environments.
- Filter or geotextile required for sand bed river (bed material $d_{50} < 2$ mm).

Effectiveness

- Requires good seal at seams and around piers.
- Adequate mat flexibility is needed to allow settlement around margin. This allows for self-anchoring in sand bed streams.
- Cable location should be very near the center of each unit to allow maximum flexibility.
- Block shape should not inhibit flexibility.
- Communication of details to the contractor is essential to good performance.
- Method is not self-healing and catastrophic failure can occur.
- Effective over a wide range of conditions. Method can sustain several flow events with minimal maintenance.

Constructability

- Site access for construction, cranes and equipment is needed.
- To allow the mat to settle properly, fabric must be cut away from blocks along the outer edge of the mat.
- A granular filter around the pier can be used to provide a seal at the pier.
- Allow no vertical discontinuity at junctions.
- Divers will potentially be required to tie mats together.
- On gravel streams, edges must be anchored (pre-excavation).
- Pre-excavation of upstream edge of the mat is required.

Durability

- Cable durability is critical, corrosive activity (salinity and/or acidity) of water is a factor.
- The issue of concrete durability should be considered; it is less severe than that of cable durability.

Maintainability

- Difficult to patch.
- Not self healing.

Cost

- Typically laid-in-place wet placement cost of approximately \$15 - 16/ft^2 as of 1998.
- Seal construction approximately \$2000 for a typical pier as of 1998.
- Cost to place cable tied blocks around a 4 ft x 20 ft rectangular pier is about \$9,000 as of 1998.
- Traffic disruption should be considered.

2.2.5 Design Recommendations for Grout Filled Bags

The authors of this report recommend avoiding grout filled bags. This is because their lack of angularity, relatively smooth surface and lack of flexibility make them more easily prone to failure than either properly designed riprap or cable tied block mattresses. It is suggested that grout filled bags not be installed in gravel bed streams. Circumstances that may warrant installation, however, include the following: a) riprap is not easily available; b) regulations do not permit the use of riprap or other alternatives; and c) the bridge is too small to allow the equipment needed to install riprap or other countermeasures.

In the event that a decision is made to install them, the guidelines are the same as those for riprap installation with prior excavation, but with cover width increased from 4D to 5D (Figure 2.8b). The calculation of bag size is done with the same relations as for riprap, but it is recommended that the user take account of the fact that grout is usually lighter than natural riprap by using the density ρ_r pertaining to the grout. In addition, it may be advisable to oversize the bag size (D_{r50}) by a factor of 1.2 to add some stability. If possible the surface of the bags should be rendered angular and rough. In the event that the angle of attack β exceeds 15 degrees, the cover area should be increased in accordance with Figure 2.6.

One possible installation of grout filled bags is presented in Figures 2.8a and 2.8b. The potential problems with grout filled bags are illustrated in Figure 2.8c.

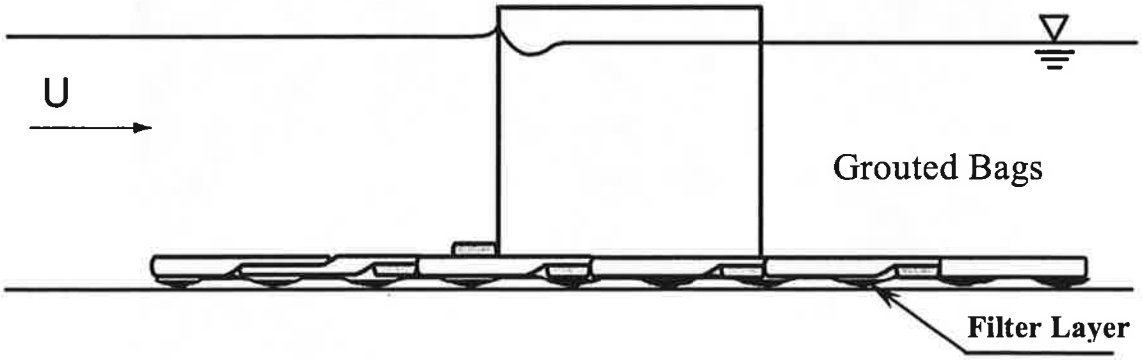

Figure 2.8a. Installation of grout filled bags.

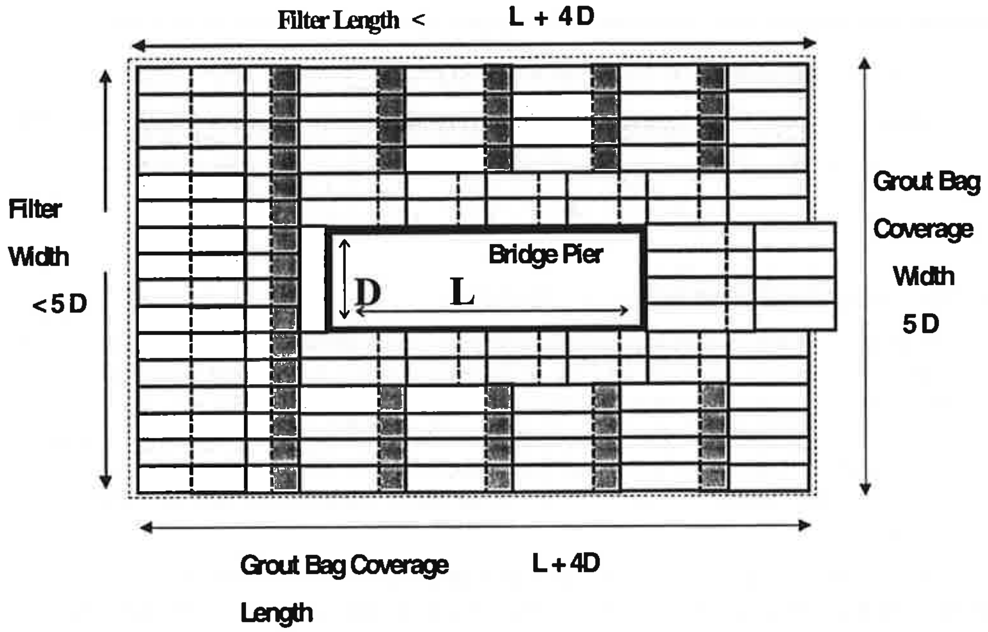

Figure 2.8b. Grout filled bag and geotextile cover. Flow is from left to right. In the event that the attack angle β exceeds 15° the installation follows the guidelines of Figure 2.6.

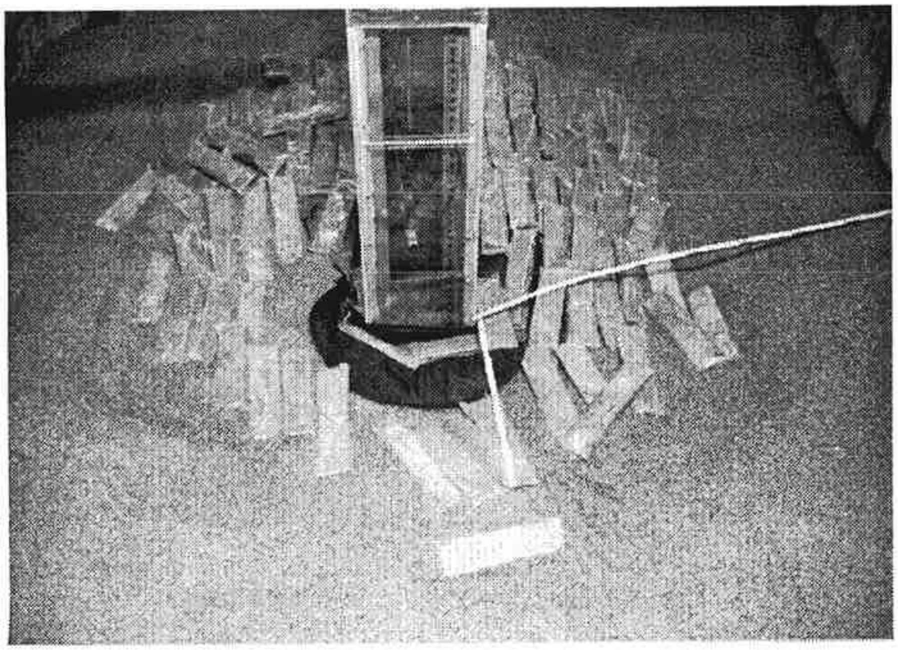

Figure 2.8c. Illustration of the dispersive sliding of grout filled bags under conditions for which the equivalent riprap did not fail.

Poor quality grout may degrade and break or crumble. Long grout filled sausages are not recommended unless they consist of multiple connected units, so as to possess some degree of flexibility.

Geotextile filter or granular filter layer

It is recommended that in the case of a gravel bed river a geotextile filter not be used. In the case of a sand bed river, it is recommended that a geotextile filter be placed underneath the grout filled bags. The cover of the geotextile filter should be less than that of the grout filled bags. Best performance is obtained by sealing the geotextile filter to the pier. Sealing can be implemented by means of a flexible tube containing a cable that can be tightened around the pier. The flexible tube must be attached to the geotextile. Alternately, sealing can be implemented by installing a granular filter layer around any gap between the geotextile filter and the pier itself.

In the event that the use of a geotextile filter is not possible, a standard granular filter layer may be used in place of a geotextile filter. In such case it is recommended that special care be given to installation of both the filter layer and the grout filled bags around the edges of the pier. The granular filter layer may have the same cover as the bag installation. Care must be given to the grain size distribution of the granular filter in light of the uniformity of bag size.

Implementation notes

Testing conducted at the University of Minnesota indicated that grout bags did not perform well during floods in sand bed streams with developed dunes. However, field observations of installations in Maryland have shown effective performance when located in streams with the following characteristics:

1. Minimal bedforms.
2. Small streams.
3. Bags large relative to scour hole size.

Feasibility

- Potentially applicable only to small streams or cases where pier width does not exceed the bag width (typically 3 to 4 ft).
- Useful in areas with no rock.
- Reduces amount of blockage compared to riprap without pre-excavation.
- Shallow water placement can be performed quickly.

Effectiveness

- Bags do not interlock well and are not flexible.
- Bag diameter adjustment is needed because of lower material density.

Constructability

- Bag size 10 ft x 3 ft x 1 ft.
- Easily constructable with use of concrete pump, bags, and diver.
- Requires less access for equipment and construction than other countermeasures.
- Use geotextile to seal the connection between the pier and the bags.

Durability

- Not as self healing as riprap.

Maintainability

- Catastrophic failure potential (cantilever failure of bag).

Cost

- Typical cost $600/bag for a 10 ft x 3 ft x 1 ft bag as of 1998.
- Typical installation of this countermeasure requiring six 10 ft x 3 ft x 1 ft bags is about $3500 as of 1998.
- Traffic disruption should be considered.

Special

- Investigate sand filled bags as an alternative as these offer greater flexibility.
- Compartmentalized bags may limit catastrophic failure of sand filled bags if bag rips.

2.2.6 Design Recommendations for Gabions

Caveat

It is recommended that gabions not be used for gravel bed streams due to the effect of abrasion on the wiring of the cages. The long-term durability of the wiring under the intense flow conditions associated with bridge piers in floods has not been demonstrated even in sand bed streams. The use of gabions for bridge pier protection thus has an element of uncertainty. The guidelines presented at the beginning of Chapter 8 of Volume II of this report should be considered in the selection of gabion casings.

Required information

- Pier width D
- Pier shape: round nosed or square nosed
- River type: sand bed or gravel
- Depth averaged approach flow velocity U upstream of the pier at design flow conditions
- Angle of attack β of flow at bridge pier at design flow conditions
- Density ρ_r of the rock to be used in the gabions

The design flow conditions might correspond to anything from a 10 year flood to a standard project flood, depending upon the economic and social importance of the bridge. Standard software such as WSPRO, HEC-RAS, RMA-2 and FESWMS is available to help the user predict U and β at design conditions.

Gabion and Reno mattress sizing

It is recommended that the minimum allowable basket volume V for individual unconnected baskets be estimated from the following relation;

$$V = 0.069 \frac{U^6 K^6}{(\frac{\rho_r}{\rho} - 1)^3 g^3} \tag{2.4}$$

In the above relation

g denotes the acceleration of gravity,
ρ_r denotes the density of the rocks in the basket,
ρ denotes the density of water so that ρ_r/ρ denotes the specific gravity of the rocks,
K = 1.5 for round nosed piers and 1.7 for square nosed piers.

If U is input in m/s, $g = 9.81$ m/s^2 and V is specified in m^3. If U is given in ft/s, $g = 32.2$ ft/s^2 and V is specified in ft^3. The above relation was adapted from the relation of Parola and Jones (1991) for riprap, Eq. (2.2), but with a bulk rock density of 100 lbs/ft^3.

It may be appropriate to choose gabions with a volume that is larger than the size indicated from the above relation. To reduce cross-sectional blockage and resist uplift the baskets should be kept relatively low in height. It is recommended, however, that the minimum height be 0.15 m (6 in). It is recommended that minimum rock size be at least 25% larger than the minimum spacing between the basket wiring. A maximum size not to exceed 2/3 of the minimum basket size (normally the height) is recommended.

In California practice, for example, the unit weight requirement for a gabion is 110 pounds per cubic foot. This is achievable for 1–foot or 1.5-foot high gabions when the following rock specifications are enforced: 0 – 5 percent passing a square grating 4 inches by 4 inches, and 100 percent passing a square grating 8 inches by 8 inches.

Basket materials

Basket flexibility combined with durability are paramount to the effective performance of gabions. Baskets should be made of single strand galvanized or PVC coated wiring in order to protect against corrosion. It is recommended that wire be formed with a double twist to help prevent unraveling.

Gabion installation

A recommended gabion installation is shown in Figures 2.9a and 2.9b. It is recommended that the gabion coverage, c be equal to 5 D. That is, the gabions extend outward at least a distance 2 D from every face, so that the total lateral distance from one edge of the gabions to the other is at least 5 D, as illustrated in Figure 2.10b. In the event that the angle of attack β exceeds 15° , the cover is taken to be at least 5 D/cos(β), and distributed spatially as indicated in the case for riprap without prior excavation (Figure 2.6). It is recommended that the river bed should be smoothed, and any existing scour hole filled with stones before the installation of the gabions. Adjacent baskets are joined together using the same wire as used for lacing the baskets. It is recommended that empty baskets be attached to gabions already in position, and the correct alignment be obtained prior to filling the basket. Hand work is typically necessary to minimize the percentage of voids.

Geotextile filter

In the case of interconnected gabions on a sand bed river, a geotextile filter placed underneath the baskets should be used to prevent sand leaching. It is recommended that the cover of the geotextile filter be somewhat less than the cover of the baskets. Best performance may be obtained by sealing the geotextile filter to the pier. Sealing can be implemented by means of a flexible tube containing a cable that can be tightened around the pier. The flexible tube must be attached to the geotextile. Alternately, sealing can be implemented by installing a granular filter layer around any gap between the geotextile filter and the pier itself.

An alternative to placing the geotextile below the gabions is to place it within the gabions. That is, the bottom of the inside of each gabion comprising the lowest layer would contain a lining of geotextile.

A filter layer may be used in place of a geotextile filter, but in such case special care should be given to installation of both the filter layer and the gabion placement around the edges of the pier. The granular filter layer may have the same cover as the baskets.

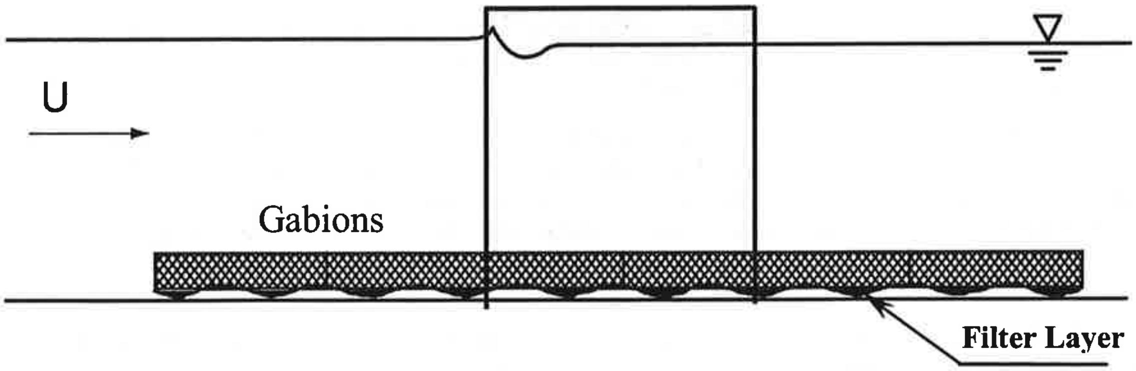

Figure 2.9a. Gabion installation.

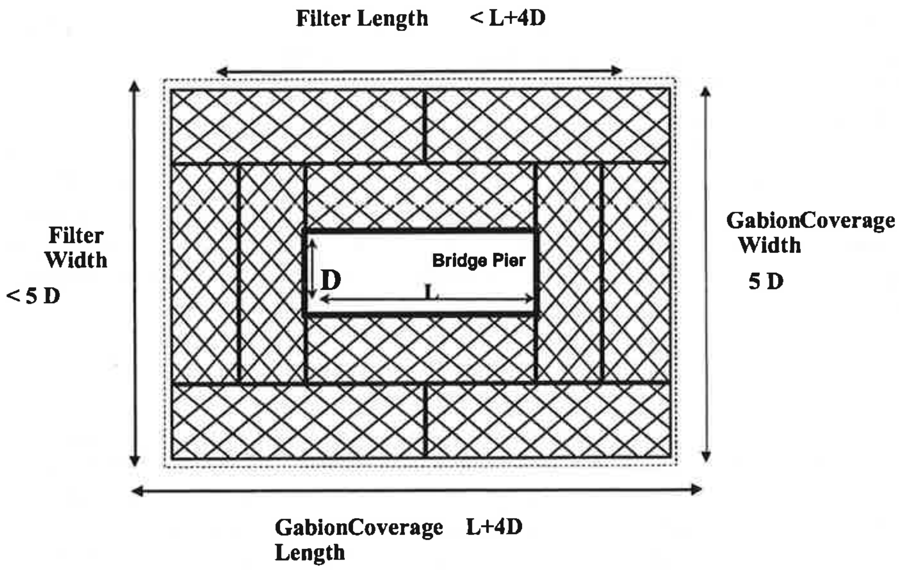

Figure 2.9b. Gabion and geotextile cover.

Implementation notes

Feasibility

- Appropriate for use in sand bed streams only (bed material $d_{50} < 2$ mm) due to wire abrasion by coarse bed load.
- Not suitable for gravel bed streams. Bedload abrasion can wear out the wire mesh causing gabion rupture.
- Makes use of smaller rocks. Applicable where big rocks are not easily found or are very expensive.
- Difficult method to use for non-uniform geometry.
- Water quality must be non-corrosive.

Effectiveness

- After installation, geotextile must be able to deform without failure to be effective.
- Junction discontinuities create weak points.

Constructability

- Constructed on site and lifted into place or filled and assembled in place. The latter method requires minimal equipment and can be completed by hand if necessary.
- Pre-excavation to make top of gabion installation flush with bed is advantageous.

Durability

- Limited wire durability. Not recommended in highly abrasive (e.g. gravel bed streams) or corrosive (e.g. saline or acidic water) settings.

Maintainability

- Some opportunity may exist to repair in place.
- Relatively easy to maintain by using custom fit baskets, wire mesh, and rock.

Cost

- Cost for hypothetical 4 ft x 20 ft rectangular pier is $5,000 as of 1998.

3. REFERENCES

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4. Richardson, E. V., Simons, D. B. et al., "Highways in the River Environment." U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., Report No. *FHWA-HI-90-016* (1990)
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APPENDIX A. NOTATIONS

a_{cb}	coefficient defined by Eq. (2.3b);
c	transverse cover of a riprap or other protection layer;
d_{15}	size such that 15% of the bed or the granular filter layer material is finer;
d_{50}	size such that 50% of the bed or the granular filter layer material is finer;
d_{85}	size such that 85% of the bed or the granular filter layer material is finer;
D	pier diameter for cylindrical (circular) pier; pier width for rectangular pier;
D_{r50}	median size of the riprap;
g	gravitational acceleration;
H_{cb}	height of blocks in cable tied block mattress;
K	coefficient in Eq. (2.2);
L	length of a rectangular pier;
U	depth averaged approach flow velocity upstream of pier;
V	basket volume of gabions;
y_o	depth of ambient approach flow in vicinity of pier;
β	angle of skew or attack;
ρ	density of water;
ρ_{cb}	density of blocks in cable tied block mattress;
ρ_r	density of riprap;
ζ	bulk weight per unit area of cable tied block mattress.