Alternatives to Riprap for Protection Against Local Scour at Bridge Piers

LISA M. FOTHERBY

Riprap is the most commonly applied material for protection of bridge piers against local scour. In some locations, however, riprap may be unavailable, costly, or physically untenable for installation. In this laboratory flume study, four alternatives to riprap—mats, grout bags, footings, and tetrapods—were investigated as scour prevention methods around bridge piers. Mats, grout bags, and footings were successful at preventing scour, and recommendations are included for elevating the protection surface in relation to the channel bed and the required size of installation. The method of failure and specific requirements for each material are also presented. The stability of tetrapods was compared with the stability of riprap based on the equivalent spherical diameters of the two materials. Tetrapods exhibited higher stability over riprap on the flat bed of a flume.

Local scour is the erosion of bed material resulting from secondary flows around an obstruction in the flow field. Large financial losses have resulted from local scour at bridge pier foundations. The most prevalent method of preventing local scour is to cover the natural bed around an obstruction with an erosion-resistant material. Riprap is the most commonly applied protection material, and the design process for riprap has been successfully quantified with recommendations for sizing the material, defining the required area of installation, setting the level of installation, and assigning filters.

In many instances, however, riprap cannot be installed or is too costly, depending on size requirements and availability. In contrast to riprap, the design process for alternative protective materials has received little attention and installers are often forced to rely on engineering judgment.

The objective of this study is to evaluate alternative protection materials for their effectiveness in protecting bridge piers from local scour and to provide design information. Many alternative protection materials are available; footings were selected for this study because they are the most prevalent alternative. Mats, grout bags, and tetrapods were chosen because of interest expressed by several state highway departments.

ROLE OF UPFLOW IN MECHANICS OF LOCAL SCOUR

To understand the success or failure of a protective material, it is useful to understand the mechanics of local scour. The primary component of local scour is the horseshoe vortex, but a secondary contributor to erosion is upflow. Upflow was described by Posey in the early 1950s as flow patterns generated by high- and low-pressure points at bridge piers (*1*). The stagnation point upstream of a pier is a high-pressure point, and low-pressure points are found at the upstream corners of the pier where flow accelerates around the pier and maximum velocities occur.

Stream flow enters the channel bed at the high-pressure point, flows underground parallel to the bed surface, and reemerges into the channel at the low-pressure points. The shear created by the upward, reemerging flow carries small particles to the bed surface and is referred to as "piping." In addition to soil piping, the reemerging flow creates a "quick" condition. The upward shear from the upflow counteracts the gravitational force of the particles at the channel bed surface (Figure 1), which allows stream flow passing over the quick particles to induce motion with lower shear forces.

The combination of horseshoe vortex and upflow produces the earliest stages of scour at the corners of a pier. The main scour hole develops from the corner points, which grow to join across the front of the pier. After the main scour hole forms, the erosive action from the horseshoe vortex plays a more significant role than upflow in expanding the scour hole.

If riprap is installed around a bridge pier, it reduces the permeable area of the channel bed. In a low-pressure region, upward flow is restricted to the area between the interstices of the riprap; this concentration of flow produces high shear forces. The preexisting quick condition at the low-pressure region is magnified by the presence of the riprap (*2*). Soil erosion occurs more readily as piping and the quick condition encourage the loss of particles from between the voids in the riprap. The rock settles into the bed of the river as material is eroded out around it. Riprap reduces the maximum depth of scour but does not arrest all scour-hole development. Alternative protection materials will settle in the same manner if they reduce the permeable area of the channel bed. Settling of riprap or other materials in the quick area can be prevented by placing a filter under the riprap layer.

EXPERIMENTAL TESTING

Laboratory testing was conducted at FHWA's Turner-Fairbank Research Center, in McLean, Virginia. A tilting-bed flume, 1.8 m wide × 21.3 m long, was used for all experiments. The pier model was a 1:20 scale rectangular pier, 15.2 cm × 30.5 cm, with the 30.5-cm length aligned with the flow. A sediment recess in the midsection of the flume was 1.3 m long × 0.46 m deep. The sediment recess was filled with a graded sand, D_{50} = 0.3 mm. Flow was supplied by a 0.31-m^3/sec pump and

Colorado State University Engineering Research Center, Fort Collins, Colo. 80521.

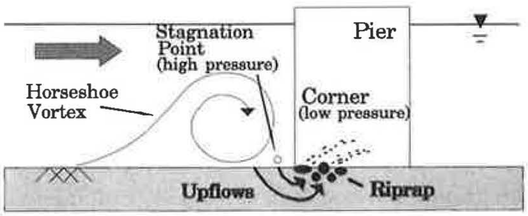

FIGURE 1 Upflows at riprap.

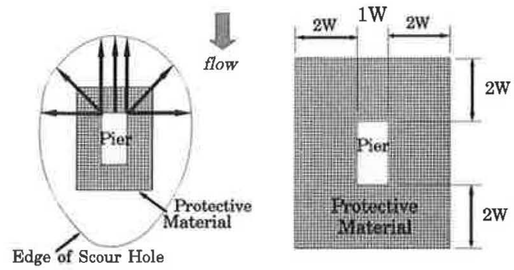

FIGURE 2 Seven locations for measuring lateral extent of scour hole (*left*) and lateral extent of a 2.0*W* protection pad (*right*).

measured by a venturi meter in the supply line. Average approach velocities were calculated from the venturi meter flow value and the flow depth. Point velocities were measured with a spherical, two-dimensional electromagnetic probe 1.3 cm in diameter.

All test runs of piers in a sand bed were conducted for 3.5 hr. Previous testing had established that 95 percent of maximum scour-hole formation, for the given flows and depths, occurred within 3.5 hr. Flow velocity for all tests in a sand bed was held at 0.3 m/sec. A velocity of 0.3 m/sec was just below incipient motion of sand particles in the flume, which afforded a maximum clear-water scour environment. Tests were conducted at flow depths of 0.15 and 0.30 m.

The protective materials were evaluated by comparing the dimensions of a scour hole in a protected bed with the dimensions of one in an unprotected sand bed; the dimensions measured were maximum scour depth and the lateral extent of the scour hole. The lateral extent of the scour hole was characterized by the horizontal distance from the side of the pier to the edge of the scour hole. The value was an average of measurements from seven locations in the front, semicircular area of the scour hole [Figure 2 (*left*)].

The lateral extent (size) of the protection pad for each material was designated by pier widths (*W*). The largest size tested was 2.0*W*, or two pier widths. A 2.0*W* pad of material covered an area around the pier that extended horizontally from the pier, a distance of twice the pier width [Figure 2 (*right*)].

Besides the sand-bed tests, incipient-motion tests were conducted on the mats, grout bags, and tetrapods. Incipient motion is the state at which movement first occurs in the test material. Incipient-motion tests were conducted on a fixed surface and, in most instances, with no pier. The sediment recess in the flume was covered with a sheet of treated plywood to match the elevation of the flume bed surface. The test materials were laid out on the fixed bed. Discharge was held constant throughout the run, but velocity was gradually increased. When a critical velocity was reached, the material "failed" by exhibiting motion. Velocity measurements were recorded for the point of failure.

Testing was conducted in four phases, the sequence of which is presented in Table 1. The first phase established the dimensions of a scour hole in an unprotected sand bed, created by the 15.2- 30.5-cm rectangular pier. This phase also determined the dimensions of a scour hole in a sand bed protected by riprap. Note that all tests of tetrapods (Phase 4) were incipient-motion runs carried out on a fixed, flat bed.

DESCRIPTION OF PROTECTION MATERIALS

Mats

Mats are formed with a double layer of nylon fabric sewn into a checkered series of compartments. The compartments are pumped full of cement grout, and they take on the appearance of pillows. The pillows are interconnected by the fabric and a reinforcing of laced steel cables that pass through them (Figure 3). The flexibility of the pillows within the structure provides tolerance for erosional adjustments in channel bed elevation.

Model mats had rectangular pillows approximately 1.5 × 3 cm. Each pillow was filled with a fine grout of sand and cement, giving the mat a depth of 0.6 cm. Each pillow weighed approximately 2.3 g, and a 1935 cm^2 section of mat weighed 834 g. Mat sizes tested were 1.0*W*, 1.5*W*, and 2.0*W* [see Figure 2 (*right*)].

TABLE 1 Testing Sequence

Phase	Protection Method	Testing Condition
I	Unprotected Sand	Sand Bed w/ Pier
	Riprap (Gravel)	Sand Bed w/ Pier
II	Mats	Sand Bed w/ Pier
	Grout Bags	Sand Bed w/ Pier
	Mats - Incipient Motion	Flat Bed
	Grout Bags - Incipient Motion	Flat Bed
III	Footings	Sand Bed w/ Pier
IV	A. Tetrapods - Incipient Motion	Flat Bed
	B. Tetrapods & Riprap, Side by Side - Incipient Motion	Flat Bed
	C. Tetrapods - Incipient Motion	Flat Bed w/ Pier

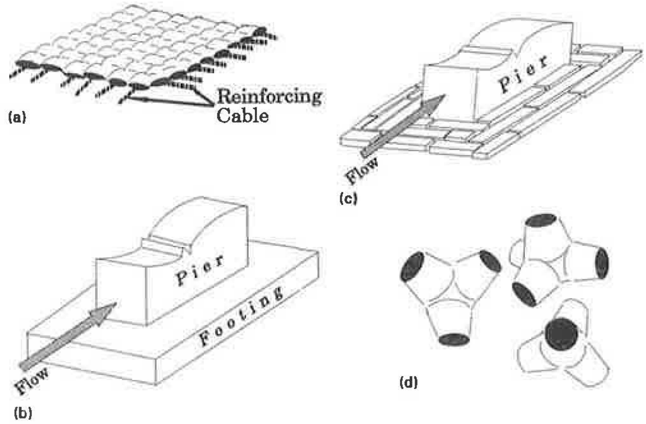

FIGURE 3 Alternative protective materials: (*a*) grout-filled mat, (*b*) footing, (*c*) grout bags, (*d*) tetrapods.

Grout Bags

Grout bags are individual nylon or acrylic bags fabricated from panels of material to create a rectangular block form. Every bag is large enough to resist movement from flows. The bags are positioned like tiles around the pier to form an erosion resistant floor (Figure 3). The bags are pumped full of grout after they have been located on the channel bed. Because the bags are formed in position, they fit snugly against each other. The bags can be installed at a dewatered site, or at a wet site if flow velocities do not inhibit access. There is no suggested or standard manufactured bag size.

The model bags were constructed from the same material used in the prototype bags and filled with a fine sand–cement grout mix. Four sizes of bags were tested. All the bags were roughly 4.3 cm wide and 2.8 cm tall, but lengths included 11.4, 14, 16.5, and 21.6 cm. The average specific gravity of the grout bags was 1.22. Sizes of grout-bag protection pads tested were 0.5*W*, 1.0*W*, and 1.5*W*.

Footings

Four footing sizes were tested: 0.5*W*, 1.0*W*, 1.5*W*, and 2.0*W*. The thickness of the footings was 7.6 cm, or half the pier width (0.5*W*) (Figure 3). The footings, like the pier, were constructed from marine plywood.

Tetrapods

Tetrapods are precast concrete forms with extending legs that are randomly placed like riprap for channel protection (Figure 3). The tetrapods considered in this study were modeled after designs presented in the U.S. Army Corps of Engineers *Shore Protection Manual* (*3*).

The size of the model tetrapod was selected to approximate the volumetric size of model riprap: D_{50} = 1.3 cm. Model tetrapods were 1.9 cm tall and were formed from fine cement grout intruded into plastic molds.

RESULTS

Mats

Method of Failure

Mats tested in the flume were susceptible to failure in three ways: rolling, undercutting, and scouring at gaps. Rolling of the mat was the most severe form of failure. Flows passing over the surface of the mat created lift in the same manner as air flows over an airplane wing. Flows over the top of the mat created a lower pressure than found at zero velocities underneath the mat. Once the mat was lifted slightly, the force of the current pushed it loose. At lower velocities, the front end lifted enough to obstruct flows and the mat rolled from front to back. If the lift occurred in the midsection of the mat, the mat lifted slowly until it was abruptly swept out and carried downstream.

Undercutting, the second method of mat failure, proceeded as a gradual erosion process. Undercutting was produced by (a) local scour generated by the edges of the mat, (b) local scour from the movement of bedforms, or (c) scour from the main horseshoe vortex spilling over the edge of the mat. When the mat was loosened by undercutting, it was more susceptible to lift. An eroding vortex generated by the obstruction of the mat edge scoured out channel bed material from under the mat. The trough of a passing dune would also expose the edge of the mat. Local scour was occasionally generated at the exposed edge and would continue to undercut the mat at the same location even after the trough of the dune had migrated. Undercutting also occurred when the horseshoe vortex produced by the pier exceeded the size of the mat. The horseshoe vortex would undercut the edge of the mat where it spilled over.

The final method of failure resulted from a gap between the mat and the pier wall. When a 0.3-cm gap was left between the mat and the front face of the pier, a significant scour hole was found underneath the mat at the front of the pier. A scour hole would also form at the side walls of the pier if a gap was left between the pier walls and the mat. The downflow in the horseshoe vortex worked like a jet against the channel bed below the mat. A 0.3-cm gap in the 1:20 scale model represented a 6.4-cm gap in the prototype. This minor opening allowed one-third of the unprotected scour depth to occur. Therefore, it is important to have a good seal between the pier and the mat at the time of installation.

Lateral Extent of Mat

When a mat was installed, the mean lateral extent of a scour hole was slightly less than 1.5*W*. A 2.0*W* mat is, therefore, necessary to protect against the high-end values of scour. A 1.5*W* mat would eventual fail through undercutting.

Elevation of Mat Surface

A mat installed on the surface of the channel (no excavation required because the mat rests on top of the channel bed) was subject to higher velocities from approach flows than a mat installed at bed level. (The mat is inset so that its top is level with the channel bed.) During testing, the mats installed on the surface required an anchor to hold them in position, whereas mats installed at bed level required no restraint. When the surface mats were anchored adequately, they created a slight increase in the lateral extent of scour but reduced the scour depth by 5 percent of unprotected scour depth, in comparison with the bed level mats. The reduction in scour depth by the surface installation may result from shifting the horseshoe vortex upward, away from the channel bed.

Despite the slight reduction in scour depth, a mat installed at bed level is preferred over a mat installed on the surface, because of the higher susceptibility of a surface installation to lift.

Anchoring Systems

A mat installed on the surface would roll at flow velocities less than 0.3 m/sec. To complete tests with a surface installation, the mat required an anchor system. Two anchor systems were tested. In the first system, the mat was tied down to several deadmen buried in the channel bed. Anchoring the mat to the deadmen was sufficient to retain the mat in position throughout the run; however, the mat was affected by increased undercutting because its edges were exposed to the flow field. In the second system, 2.5 cm of the front and side borders of a 2.0*W* mat was folded down and covered with sand at a 45- to 60-degree angle from the horizontal. After both normal and extended runs, the bottom edge of the toed-in mat was occasionally exposed, but undercutting was minimal.

Toed-in 2.0*W* mats were also tested in incipient-motion runs conducted on fixed beds. Mats that were not toed in failed at lower velocities than those that were. The border of the mat was either laid unrestrained in a recessed slot in the fixed bed or held in place in the recessed slot, with sand packed around the edges. A summary of results from the incipient-motion tests on mats is presented in Table 2.

Results show that toe-ins at the edge of mats are extremely advantageous. Toe-ins significantly increase resistance to rolling failure and prevent undercutting of the mat. For maximum effect, the edges of mats should be buried below the depth of sand dune troughs and predicted depth of channel degradation.

Grout Bags

Method of Failure

If grout bags are undersized, they fail by washing downstream, but the more common form of failure was found to be a gradual erosion process. Erosion failure resulted from three interrelated actions: local scour around the bags, a shift in the grout bags, and undercutting of the filter fabric. If the bags protruded into the flow, they created their own local scour pattern. Local scour uncovered the filter fabric and allowed undercutting of the channel bed material on which the bags rested. As the bags were undercut, they slid sideways into the scour hole, exposing more filter fabric and opening additional areas to attack by scour. High flows would accelerate the process.

Lateral Extent of Protection

Scour-hole depths from grout-bag testing are presented in Table 3. Grout bags were tested as protection pad sizes of 0.5*W*, 1.0*W*, and 1.5*W*. Lateral extent of the scour hole extended to 1.9*W* for grout bags.

If extra precautions are taken with the installation of grout bags, a 1.5*W* area of protection might suffice. Precautions include installing the grout bags at elevations lower than level, using a deep toe-in for the filter fabric, and using massive grout bags to prevent shift. A recommended and more conservative design, however, is to install a grout bag pad of 2.0*W*.

Elevation of Surface of Grout Bags

Model grout bags were tested both with installations on the surface and installations at bed level. Surface installations allowed the bags to rest on top of the channel bed and protrude into the flow field for the full height of the bag. Bed-level installations required excavation, since the tops of the grout bags were installed level with the channel bed. During testing, two disadvantages were noted to placing the grout bags on the surface. The first was that the bags, protruding into the flow, generated a local-scour system that made the filter fabric beneath the bags more susceptible to attack. The second disadvantage was that bags installed on the surface exhibited a higher propensity to movement. In contrast, bed-level installations exhibited little or no movement. An advantage of the surface installation was a slight reduction in maximum scour depth. The reduction in scour depth was not significant enough to override the disadvantage of a decreased life expectancy for the project that would result from the shifting bags.

Filter Fabric

Filter fabric was one of the most significant parameters for grout bags. Without filter fabric, grout bags settled in the

TABLE 2 Incipient Motion Tests for Mats

Size	Number of Runs	Toed-In	Mode of Failure	Average Velocity (mps)
1.0W	3	No	Rolled	0.28
2.0W	3	No	Rolled	0.24
2.0W	2	Yes - Not Packed	Rolled & Lifted Out	0.54
2.0W	2	Yes - Packed	Lifted Out	1.22

TABLE 3 Scour-Hole Dimensions for Grout Bags

Run No.	Lateral Extent of Bags	Elev. of the Top of the Bag	Rigid vs. Loose	Filter Fabric	Max. Depth in Front of the Pier [under blocks] (cm)	Max. Depth at the Edge of the Material (cm)
2.13	0.5W	Level	Loose	No	12.1	8.9
2.14		Surface			8.3	7.5
2.9		Level	Rigid		12.7	10.1
2.10					13.3	11.3
2.11		Surface			12.7	4.5
2.16	1.0W	Level	Loose	No	7.6	4.8
2.21					5.6	5.5
2.29				Yes	0	4.1
2.27					0	2.1
2.15		Surface		No	6.0	2.8
2.20					4.6	2.6
2.30				Yes	0	4.5
2.28					0	4.5
2.23	1.5W	Level	Loose	No	5.1	0.9
2.26				Yes	0	2.1
2.24		Surface		No	6.0	1.4
2.25				Yes	0	1.4

Average velocity for all test runs was 0.3 mps

sand and exhibited scour-hole formation underneath the bags at the front of the pier. Grout bags with no filter fabric could reduce scour depth to approximately one-third of the scour depth observed for an unprotected sand bed. Grout bags with filter fabric could eliminate the scour hole.

A disadvantage of filter fabric was demonstrated when the length of a flume run was extended beyond the 3.5-hr period to promote channel degradation. Although the bed of the channel eroded, the material under the grout bags (and filter fabric) did not degrade. The grout bags and covered material formed a platform in the channel. As a result, the grout bags extended higher into the flow field. If the filter fabric had not been present, the grout bags would have settled with the channel bed. With continued channel degradation, the toe of the filter fabric was undercut and erosion occurred under the platform. Bags on the perimeter of the pad shifted outward by sliding off the platform.

For effective performance of the grout bags, filter fabric should be toed down in the same manner required by mats. The outside edges of the filter fabric should be buried to a depth below the elevation of sand dune troughs and predicted bed degradation. The sides of filter fabric should be overlapped and the fabric sealed around the pier walls to prevent gaps.

Rigidly Connected Grout Bags

Model grout bags in rigid tests were locked together with grout so that the entire system functioned as one footing. The rigid connection of the bags eliminated the adjusting property of the grout bags. Scour from a 0.5*W* size of interconnected bags was the deepest encountered during testing, aside from an unprotected sand bed.

Size of Bags

Optimum grout-bag size was not addressed directly in this study; however, several considerations emerged from testing. The dimensions of a grout bag must be large enough to develop an adequate weight, but the dimensions are limited by the following criteria:

1. A shorter height in a rectangular bag is better able to resist overturning.
2. When a bag is exposed to the flow field, a shorter height produces less scour.
3. Length contributed to failure in the incipient-motion tests when the bags were aligned perpendicular to the flow. The longer bags failed first (Figure 4).
4. Longer bags are less able to adjust to elevation changes and tend to span scour holes rather than conform to the channel bed.
5. A wide bag reduces labor and installation costs when covering a large area.
6. Increased width helps to reduce overturning.
7. A wide bag does not adjust as well to elevation changes and loses its ability to conform to changes in the channel bed.

Footings

Method of Failure

Footings fail when scouring activity undercuts the structure. Undercutting can be a result of the pier-generated horseshoe vortex that spills over the coverage provided by the footing. A second cause of undercutting can be the result of a footing-generated vortex. A vortex off the footing wall develops when

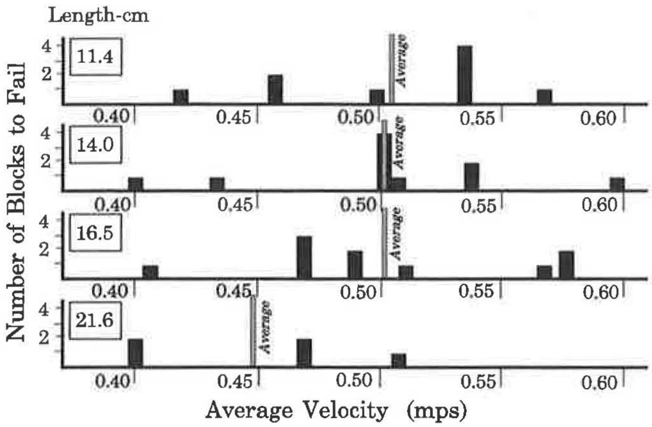

FIGURE 4 Incipient motion, grout blocks.

the footing is exposed to the flow field (*4*). Footing exposure can result from the movement of sand dunes, channel degradation, local scour holes from debris on the channel bed, and a footing installation above the surface of the channel bed. The strength of the footing vortex depends on the vertical distance that the footing extends into the flow field.

Lateral Extent of Coverage

Although a 2.0*W* size is effective coverage for most materials, a footing must extend 2.5*W* to completely contain scour from the pier horseshoe vortex. It may not be necessary, however, to completely arrest scour. If the footing can be buried deeper than bed level, or if it is thick enough, it can prevent local scour from undercutting the footing. For either instance, a 2.0*W* footing may be adequate. In addition, the footing may be able to tolerate a degree of undercutting. The sizing of a footing is primarily dictated by the applied load and by the bearing capacity of the soil. If the lateral extent of the footing is increased from the original geotechnical design to provide scour protection, it may contain some tolerance for loss of bearing area due to undercutting. Consultation with a geotechnical engineer would be required for this consideration.

Elevation of Footing in Relation to Channel Bed

Local scour depth increases as the footing is raised above the channel bed (*5*). The footing may prevent pier scour from undercutting the footing, but the footing can generate enough scour on its own to provoke failure, if it extends far enough into the flow field. Therefore, the optimum placement of a footing is level with the channel bed, or lower. An installation lower than the channel bed allows for channel degradation as well as bed movements due to sand dunes and debris. It also places the footing below the range of undercutting from pier scour.

Footing Thickness (Height)

Structural considerations are a primary factor in determining footing thickness, but scour prevention can provide a secondary consideration. When a footing is installed level with the channel bed or lower, increasing the height dimension of the footing may provide the extra scour protection needed. When the footing is thick, the vortex may expose only a fraction of the footing sidewalls, without undercutting. Burying a footing deeper than level is a more effective solution than increasing footing thickness. If the footing is in danger of becoming exposed to flows, the increased footing thickness will magnify the scour danger.

Tetrapods

Tetrapods were originally designed for shore protection. Tetrapod legs reduced erosional energy by breaking up waves as they approached shore, and they provided high porosity for the release of the wave. The question addressed in this study was whether the interlocking legs of a tetrapod would provide greater resistance to movement than riprap, in a fluvial system. The answer was approached by comparing the incipient-motion velocities for tetrapods with the incipient-motion velocities for an equivalent size of riprap in the flume. For surface runs, tetrapods were placed on top of the flat, plywood flume bed; and for bed level runs, tetrapods were placed in a recessed area (2.4 cm) of the plywood flume bed. The top of the tetrapods was even with the bed of the flume in bed-level runs. In Phase 4, Set B (see Table 1), a pad of tetrapods was tested next to an equal-sized pad of riprap in order to provide a direct comparison. In Phase 4, Set C, a pier was added to the flat bed, and the population of tetrapods per unit area (density) and the size of the protection pad were varied.

Incipient-motion velocities from Sets A and B of Phase 4 were used to compute the stability number, N_s. A comparison was made between tetrapods and riprap by plotting the stability number against the dimensionless parameter l/y, which is the significant length over the flow depth.

Equivalent Sphere

Knowing the specific gravity and mass of the material, the volume of the riprap and the volume of a tetrapod were converted to equivalent average sphere sizes. The diameter of the equivalent sphere was used as the significant length, l, for each particle.

	Tetrapod	*Riprap (average of one particle)*
Mass	3.52 g	5.81 g
Specific gravity	1.83	2.72
Diameter of equivalent sphere (l)	0.0155 m	0.0160 m

The stability number indicates the point at which the drag and inertia forces on a particle are balanced by the body force (weight) of the particle. This balance occurs at incipient motion.

Drag + inertia = weight

$$C_1 l^2(\gamma_w/g)V^2 = C_2 l^3(\gamma_s - \gamma_w) \qquad (1)$$

$$N_s = \frac{V^2}{g\, l(SG - 1)} \qquad (2)$$

TABLE 4 Stability Numbers for Tetrapods and Riprap

Set Description	Run Number	Ave Vel (mps)	Flow Depth (m)	l/y	Ns
Set A	4.1	0.704	0.131	0.118	3.93
Bed Level	4.2	0.802	0.155	0.10	5.10
Density-2	4.3	0.671	0.188	0.082	3.57
	4.4	0.774	0.163	0.095	4.75
	4.5	0.771	0.166	0.093	4.71
	4.6	0.762	0.166	0.093	4.60
	4.7	0.805	0.183	0.085	5.14
	4.8	0.661	0.210	0.074	3.46
	4.9	0.725	0.193	0.080	4.17
Set A	4.10	0.515	0.169	0.091	2.10
Surface	4.11	0.591	0.152	0.102	2.77
Density-1	4.12	0.558	0.160	0.097	2.47
Set A	4.13	0.546	0.162	0.096	2.36
Surface	4.14	0.631	0.138	0.112	3.16
Density-2					
Set B	4.15T	0.616	0.165	0.094	3.01
Surface	R	0.741	0.135	0.119	2.03
Density-1	4.16T	0.585	0.226	0.069	2.71
	R	0.738	0.177	0.091	2.02
Set B	4.19T	1.119	0.092	0.168	9.92
Bed Level	R	1.152	0.086	0.186	4.92
Density-1	4.20T	0.917	0.143	0.109	6.66
	R	0.945	0.141	0.114	3.31
	4.21T	1.180	0.118	0.132	11.04
	R	1.207	0.113	0.141	5.40
	4.22T	1.237	0.114	0.136	12.13
	R	1.234	0.114	0.140	5.64

Comparison of Stability for Riprap and Tetrapods

Plotting the points of incipient motion allows a comparison between tetrapods and riprap. Table 4 contains incipient-motion data from Phase 4, Sets A and B, and the calculated stability numbers. Figure 5 is a plot of the stability numbers for tetrapods and riprap. The stability of tetrapods in Figure 5, based on the calculated equivalent length, is higher than the stability of riprap for both the recessed and surface installations. If weight is reintroduced into the stability equation by replacing significant length,

$$W = l^3\gamma_s \quad (3)$$

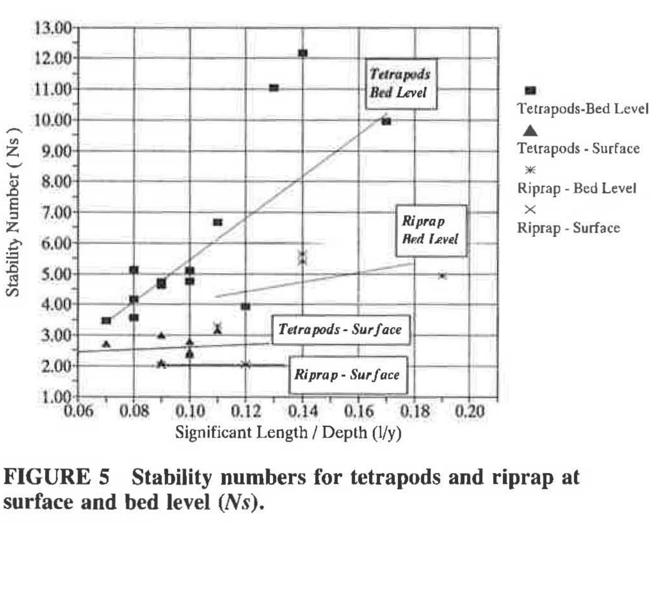

FIGURE 5 Stability numbers for tetrapods and riprap at surface and bed level (*Ns*).

then it can be seen that weight is inversely proportional to the stability number. Tetrapods that are lighter than riprap can provide the same stability. This conclusion is based on the assumption that the significant length of a tetrapod or riprap particle can be represented by an equivalent volumetric sphere. The results, however, are sensitive to the significant length selected. A second limitation is that the materials were tested for a specific situation. They were installed on a level, fixed bed and applied in pad sizes that covered only a limited area of the channel bed.

Table 5 presents results from Phase 4, Set C, in which three densities of material and pad sizes of 1.0*W* and 0.5*W* were tested. The results from Set C indicate that placement density has no significant effect on the stability of tetrapods, but stability appears to increase with the size of the protective pad.

CONCLUSIONS

1. The scour mechanics of upflow play an important role in the effectiveness of scour-protection materials.
2. Installation of mats:
   –Mats should be installed at bed level (top of mat even with the channel bed).
   –Recommended lateral extent of mats is 2.0*W*, where *W* equals the pier width [see Figure 2 (*right*) for explanation of dimensions].
   –Edges of the mat should be toed in below predicted depths for channel degradation, troughs of bedform movements, and local scour holes from debris.

TABLE 5 Set C, Tetrapods

Run Number	Protection Material /Size	No. of Failed Tetrapods	Flow Depth (m)	Average Velocity (mps)	Density[b]
4.23	1.0W	2	0.233	0.430	1
4.24		5	0.224	0.448	
4.25		17	0.265	0.503	
4.26		4	0.293	0.448	
4.27	0.5W	9	0.287	0.354	1
4.28		6	0.279	0.348	
4.29		25	0.293	0.451	
4.30		9	0.323	0.405	
4.31	0.5W	5	0.282	0.366	1.5
4.32		27	0.221	0.448	
4.33		32	0.288	0.460	
4.34		16	0.289	0.460	
4.35	0.5W	8	0.271	0.369	1.75
4.36		12	0.281	0.354	
4.37		110	0.346	0.384	
4.38		12	0.318	0.412	
4.39	1.0W	49	0.171	0.573	1.5
4.40		50	0.171	0.585	
4.41		58	0.213	0.625	
4.42		58	0.221	0.604	

[a] Tetrapods were placed on the surface of the fixed bed.
[b] Density of 1 is equivalent to 3292 tetrapods per square meter.

–The mat must be sealed around the walls of the pier.

3. Installation of grout bags:

–Recommended lateral coverage of grout bags is 2.0*W*, although 1.5*W* may be acceptable, if proper precautions are taken.

–Grout bags should be installed at bed level. If grout bags are installed on the surface, there is slightly less scour, but life expectancy for the project is reduced.

–Filter fabric is an integral part of the system and should be installed.

–Grout bags should not be rigidly connected.

–The sizing of bags should entail a careful comparison of, and balance between, weight and dimensions.

4. Installation of footings:

–A 2.5*W* footing is required to provide complete protection, although a 2.0*W* size is effective if the footing has adequate thickness or can tolerate a minor degree of erosion.

–The footing should be installed level with the channel bed, or lower.

–A lower installation or thicker footing provides some additional measure of scour protection.

5. Tetrapods:

–Tetrapods exhibited a higher stability than riprap, based on calculations using the equivalent spherical diameter of the materials.

–Stability of the tetrapods does not appear to be affected by their placement density.

–Stability of the tetrapods increased with an increase in the lateral extent of their coverage.

ACKNOWLEDGMENTS

Laboratory testing was funded by an FHWA Research Fellowship, whose support is gratefully acknowledged. Special thanks is extended to J. Sterling Jones, FHWA Project Advisor for this study.

REFERENCES

1. Posey, C. J. Some Basic Requirements for Protection Against Erosion. *Proc., Minnesota International Hydraulics Convention*, IAHR and ASCE, Minneapolis, Sept. 1953, pp. 85–88.
2. Koloseus, H. J. Scour Due to Riprap and Improper Filters. *Journal of Hydraulic Engineering*, ASCE, Vol. 110, No. 10, 1984, pp. 1315–1324.
3. *Shore Protection Manual*, Vol. 2. U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Miss., 1984.
4. Jones, J. S. *Laboratory Studies of the Effects of Footings and Pile Groups on Bridge Pier Scour*. Report FHWA-RD-90-035. USGS; FHWA, U.S. Department of Transportation, Oct 1989, pp. 340–360.
5. Fotherby, L. M. *Footings, Mats, Grout Bags, and Tetrapods: Protection Methods Against Local Scour at Bridge Piers*. M.S. thesis. Colorado State University, Fort Collins, July 1992.