Alternatives to Riprap as a Scour Countermeasure

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Riprap is the most common and best documented method of protection against local scour at bridge piers. Alternatives to riprap vary in size, shape, and mass as well as flexibility of design. The overall performance of alternatives such as grout mats and grout bags, extended footings, tetrapods, cable-tied blocks, anchors (used in connection with countermeasures) and high-density particles is evaluated. In general, alternatives are used when riprap is hard to obtain, the size required for high-velocity streams is unreasonable, or riprap is difficult to place, among other reasons. Various tests were performed on all previously mentioned countermeasures with and without a pier on a fixed bed. An obstructed movable-bed condition was also tested to obtain qualitative data for each countermeasure. Recommendations for implementing these alternatives are based on laboratory results and include the effects of filter fabric, lateral extent of the countermeasure, sealing between the face of the pier and the countermeasure, and anchoring. The impact of the drag coefficients on the stability of the countermeasure was also examined. The results of these experiments provide some comparative conclusions among the countermeasures as well as criteria for the design and implementation of these devices in the field. Investigations at an FHWA hydraulics laboratory over several years are summarized, including results of the investigations of riprap and of alternatives to riprap. As a local scour countermeasure, each alternative has its unique attributes that, depending on the application, may provide superior protection over riprap.

State highway agencies are conducting a nationwide evaluation of existing bridges for vulnerability to failure due to scour. Of the 483,000 bridges over water, roughly 39 percent either are susceptible to scour or have unknown foundations. Of the scour-susceptible bridges that have been evaluated, about 17 percent have been identified as scour critical. These require monitoring, repair, or scour protection.

FHWA has dedicated much of the research activity in the Turner-Fairbank Highway Research Center hydraulics laboratory in support of the nationwide scour evaluation program. In particular, this laboratory has been a focal point for investigating the feasibility of various techniques for protecting bridge piers from local scour.

Rock riprap is the standard material that historically has been used to protect bridge piers from local scour, but it is not always readily available in sizes required to protect piers, nor is it always a practical option. FHWA initiated a graduate research fellowship study in 1991 that intended to look at various options for protecting bridge piers; these options ranged from rock riprap to the built-in scour arresting capability of footings and pile caps. Fotherby first reported on the use of alternatives to riprap as a local scour countermeasure in her original graduate research project (*1*). However, the investigation continued far beyond what was envisioned for Fotherby's study. This paper summarizes all tests conducted since the study began.

The study tested the following techniques for providing pier protection:

- Grout bags,
- Grout mats,
- Extended footings,
- Tetrapods,
- Cable-tied blocks,
- Anchors (used in conjunction with mats and cable-tied blocks),
- High-density particles, and
- Rock riprap with various apron sizes.

Grout mats and grout bags are fabric shells filled with concrete. The mat is a single continuous layer of fabric with pockets, or cells, filled with concrete; grout bags are individual pieces that, collectively, form a protective layer when placed side by side (Figures 1 and 2). The advantage of the grout mats is that the fabric between the cells acts as a filter, but the small-scale models used in these experiments were poor representations of the grout mats because the fabric, which was essentially the prototype fabric, overwhelmed the concrete cells.

Footings are often placed near the stream bed and appear to provide a measure of scour protection by protecting the sediment from the turbulence generated by the pier. Extended footings were investigated in this study to determine conditions necessary for them to provide significant scour reduction.

Tetrapods have long been used for shore protection because of their effectiveness in dissipating the energy of waves along shorelines. These tetrapods have four arms that are 120 degrees equilateral to each other. These devices have never been applied to fluvial systems or served as protection for bridge pier scour. A model tetrapod is shown in Figure 3.

Cable-tied blocks are composed of precast concrete blocks that are interconnected to form a continuous protection layer (Figure 4). Cable-tied blocks offer an advantage over riprap because the blocks subjected to the highest dynamic forces are stabilized by the surrounding blocks so that they act as a system rather than as individual particles.

Anchors are often recommended for mats and cable-tied block systems as a means of stabilizing the leading edge, at which failure is most likely to occur. Prototype anchors supplied by one of the manufacturers were tested for their resistance to uplift forces when placed in a fully saturated bed material (Figure 5).

High-density particles are individual armoring particles placed around a pier as a scour countermeasure. High-density particles can provide a stable protective layer around a pier without being much larger than the particles in the underlying bed material. Advantages

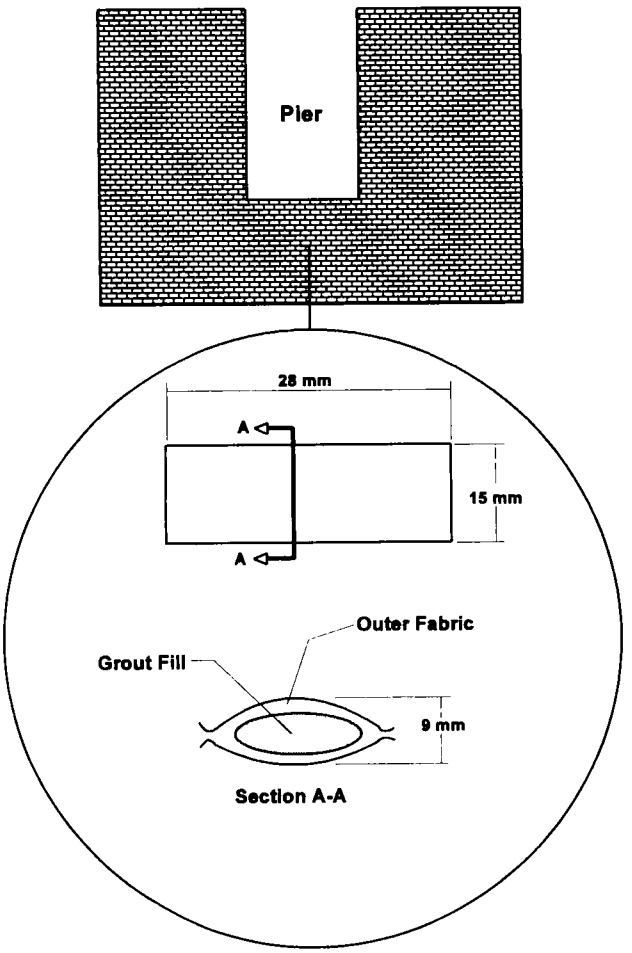

FIGURE 1 Grout mat plan view (*top*) and individual element detail (*bottom*).

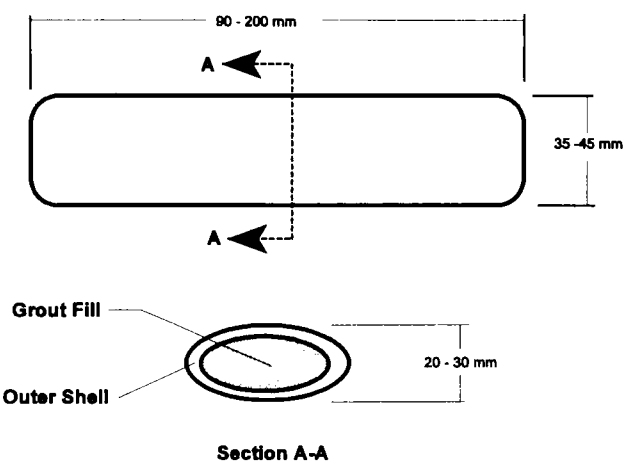

FIGURE 2 Grout bag detail.

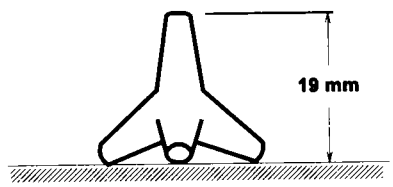

FIGURE 3 Model tetrapod.

over riprap include a reduced need for a filter layer and the possibility that the particles could be manufactured.

Framework for Experiments

Model experiments were conducted in a tilting flume 21.3 m long and 1.8 m wide equipped with a sediment recess (1.32 m long and 0.51 m deep), where the models were installed, located 9.3 m from the upstream end. The fixed bed upstream and downstream of the sediment recess consisted of a fine sand (D_{50} = 0.43 mm) glued to the flume deck (plywood), which helped establish a uniform surface roughness. The setup for the movable-bed experiments is shown in Figure 6. Most experiments were conducted under clear water conditions. Scour countermeasures can be modeled under clear water conditions because they are not the size particles that are normally transported by the stream.

The countermeasures were subjected to four basic tests:

- Scour reduction at incipient motion velocities for the underlying bed material,
- Scour reduction at higher velocities up to three times the incipient motion velocity,
- Failure criteria for the countermeasures when placed in unobstructed flow, and
- Failure criteria for the countermeasure when placed around a bridge pier in obstructed flow.

For the failure criteria, the flume was modified by covering the movable-bed section with a glued sand surface. This setup is shown in Figure 7 (*top*). The high-velocity experimental setup is shown in Figure 7 (*bottom*).

Most tests were allowed to run for 3.5 hr to accommodate two tests per normal work day. A 3.5-hr test duration is sufficient to ascertain the stability of countermeasures and establish a relative percentage scour re-

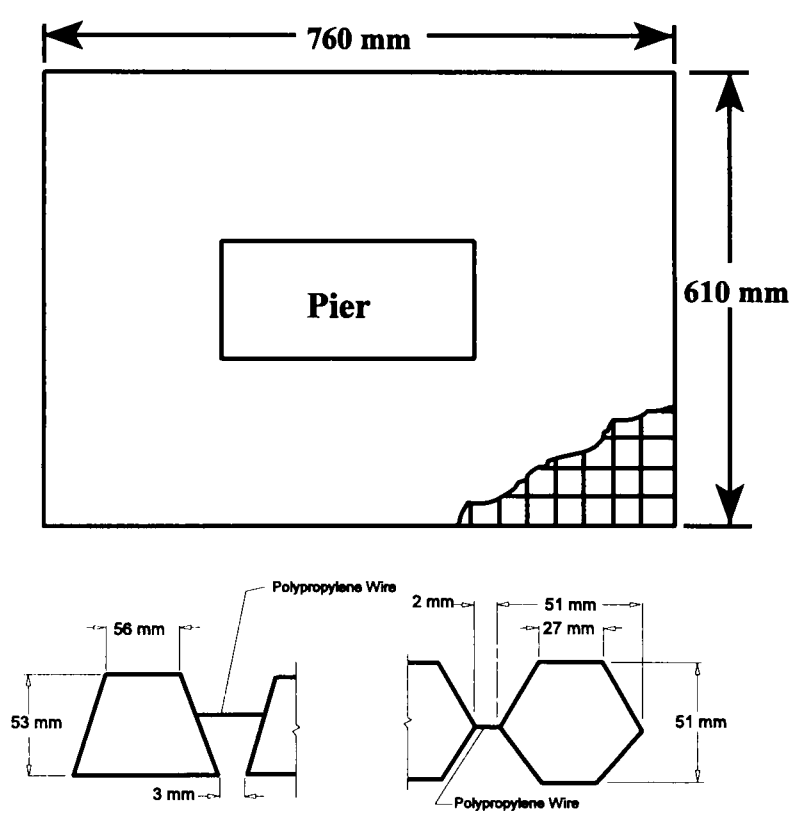

FIGURE 4 Cable-tied block plan view (*top*) and individual detail (*bottom*) for (*left*) trapezoidal and (*right*) hexagonal blocks.

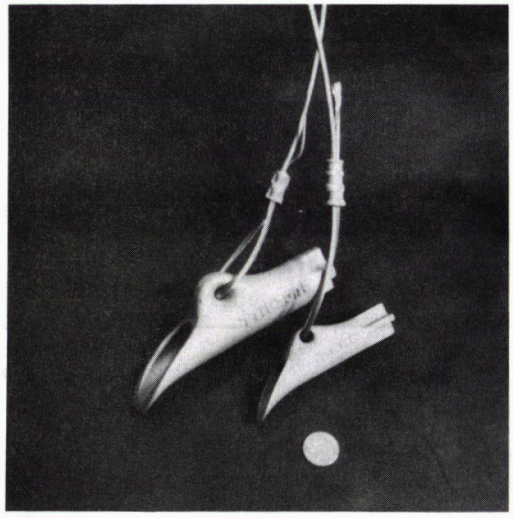

FIGURE 5 Prototype anchors tested for dislodging force.

duction. Some 24-hr tests were conducted throughout the research to evaluate the variation of scour over time.

Stability Paradigms

In designing scour countermeasures, the stability of the device in relation to the fluid forces imposing on it becomes the determining factor. The criteria that can be used to characterize the stability of a countermeasure depend in part on the failure mode that is envisioned. If the failure mode is overturning along the leading edge, the simplest way to characterize stability criteria is to specify an experimental drag coefficient. If, however, the failure mode is particle erosion or uplift on the internal parts of the apron, the most common ways of characterizing stability criteria are either Shields' shear velocity framework or Isbash's sediment number approach.

Shields Framework

A commonly used hydraulic characteristic for evaluating particle stability is shear stress. The shear stress on the channel bed due to the kinematic forces of the fluid can be defined as

$$\tau = \gamma_w y S_e \tag{1}$$

where

τ = shear stress due to fluid force (N/m^2),
γ_w = unit weight of water (9789 N/m^3 at 20°C),
y = depth of flow (m), and
S_e = energy slope.

For uniform flow, the energy slope can be calculated using Manning's equation as follows:

$$S_e = \frac{V^2 n^2}{y^{4/3}} \tag{2}$$

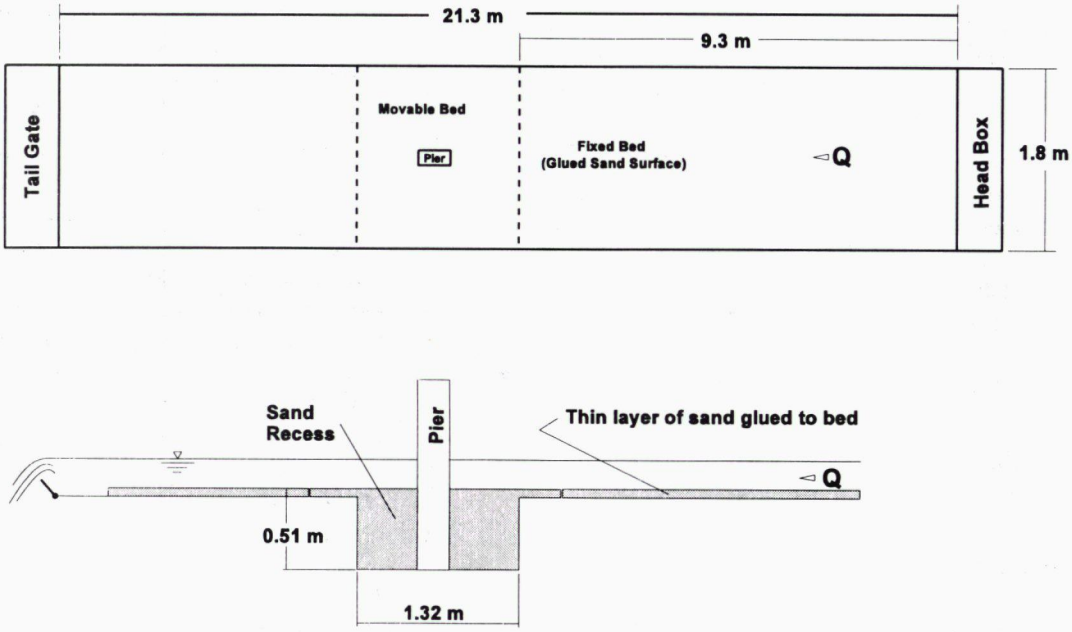

FIGURE 6 Sketch of flume plan view (*top*) and side profile (*bottom*) for movable-bed experiments.

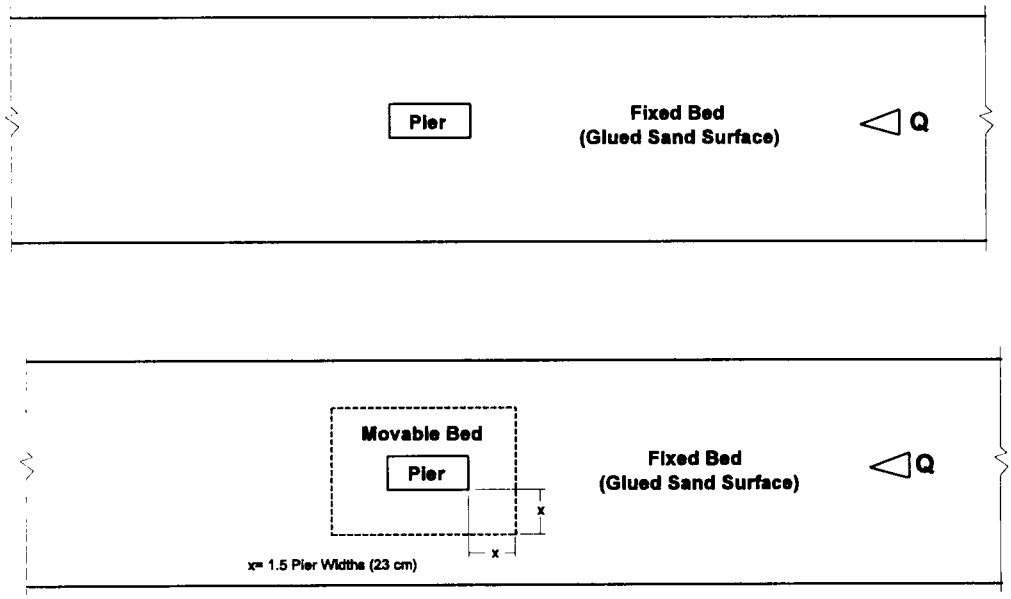

FIGURE 7 Flume setup for fixed-bed obstructed and unobstructed experiments (*top*) and for high-velocity movable-bed experiments (*bottom*).

where V equals velocity in meters per second and n equals Manning's n.

Shield's criteria for the shear stress, τ_c, required to move a particle can be represented as

$$\frac{\tau_c}{\rho_w g(\mathrm{SG} - 1)D_{50}} = \mathrm{SP} \tag{3}$$

where

ρ_w = density of water (kg/m^3),
SG = specific gravity of particle,
g = gravitational acceleration (9.81 m/sec^2), and
SP = Shields' parameter, which could be a function of Reynolds number or Froude number of approaching flow.

Shields represented the Shields parameter as a function of the Reynolds number only, but Kilgore observed that discrepancies in the Shields' parameter noted by various researchers can best be described by a Froude number relationship (*2,3*).

An alternative arrangement of this equation is

$$\frac{U_{*,c}^2}{g(\mathrm{SG} - 1)D_{50}} = \mathrm{SP} \tag{4}$$

where $U_{*,c}$ is the critical shear velocity in meters per second, or $(\tau_c/\rho_w)^{1/2}$.

Isbash Approach

Another approach is to consider the particle stability as presented by Isbash using the sediment number, N (*4*). The sediment number, also referred to as the stability number, is a dimensionless measure of stability calculated as follows:

$$N = \frac{V^2}{gD_{50}(\mathrm{SG} - 1)} = 2E^2 \tag{5}$$

where

V = average approach velocity (m/sec),
D_{50} = median armor unit size (spherical D_{50} is used to calculate spherical stability number) (m),
E = Isbash's coefficient (0.86 for stones that will not move at all and 1.20 for stones that can roll slightly until they become "seated").

The biggest challenge for applying the Shields or Isbash criteria for countermeasures other than rock riprap is selecting a representative D_{50}. This is handled for tetrapods and blocks by using an equivalent sphere diameter in lieu of D_{50}. The spherical diameter is a rough estimation for the diameter of a sphere that would have the same mass and specific gravity as the particle. The grout bags are more difficult because of their elongated shape, and attempts to represent them by a D_{50} gave a distorted comparison between grout bags and other countermeasures. For lack of a better choice, the height of the grout bags was selected for D_{50} in applying the Shields and Isbash criteria.

Overturning

The Shields and Isbash approaches provide a criterion for defining particle motion. However, for some coun-

termeasures the mode of failure is not erosion or uplift but an overturning induced by the protrusion of the countermeasure into the flow field. This type of failure can not be modeled using particle movement criteria. Another criterion for determining the characteristics of stability is to determine the drag coefficient, C_D, associated with overturning. This approach provides a criterion for the failure of various countermeasures, taking into account their geometries and relative positions in the flow field. The drag coefficient is derived by determining the force at which the device begins to overturn. This relation is given as

$$F_D = C_D A_o \rho \frac{V^2}{2g} \tag{6}$$

where

F_D = drag force (N),
C_D = drag coefficient,
A_o = area of obstruction (m^2), and
V = approach velocity (m/sec).

Here, the drag force, F_D, is assumed to act at the centroid of the device. Figure 8 shows an illustration of the forces acting on a grout bag oriented perpendicular to the flow. Calculating the drag force from Equation 8 will result in a drag coefficient for overturning the grout bag. Drag coefficients for the grout bags and cable-tied blocks are presented in Table 1.

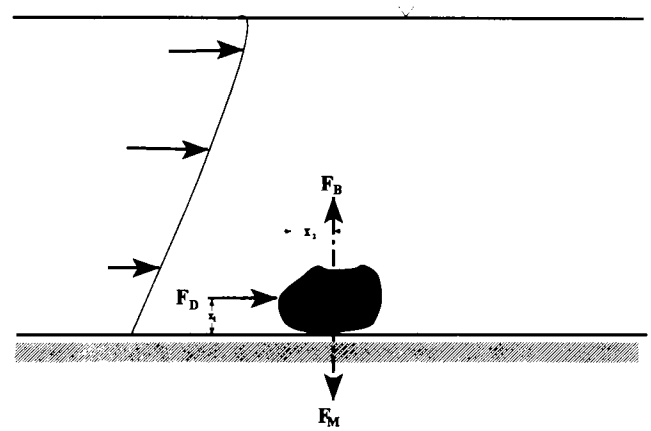

FIGURE 8 Forces acting on grout bag oriented perpendicular to approach flow.

Pier Model

The pier model used in this study was a 152- × 305-mm rectangular wooden column. Because the study is limited to one pier shape, the rectangular shape (as a conservative approach) was modeled because it tends to experience more severe scour than round-edged or circular piers. Two pier models were constructed for the experiments: one was a simple rectangular pier and the other was a special pier used only for the extended footing simulation. The pier for the extended footing had an 89- × 89-mm wooden support to allow for the lowering and raising of the pier (and its footing).

Unprotected Pier Scour

The flow conditions and resulting scour were examined for various sand and riprap configurations around a pier. Sand with a D_{50} of 0.43 mm was used to simulate local scour around the pier. Six unprotected experiments were conducted at incipient velocity conditions for 3.5 hr each. The maximum scour averaged 169 mm for the six experiments. These test results served as a reference standard for the evaluation of riprap alternatives.

TABLE 1 Drag Coefficients

Block Type	Configuration	Overturning Velocity (m/s)	Velocity at Mid- Block Height (m/s)	Flow Depth (mm)	Drag Coefficient C_d
Trapezoidal	3 Abreast	1.053	.890	237	3.96
Hexagonal	3 Abreast	.647	.578	320	1.40*
Grout Bag (A-size)	Perpendicular	.479	.398	308	3.21
Grout Bag (A-size)	Parallel	1.269	1.147	204	1.79

* Hexagonal blocks had a much lower apparent drag coefficient because of the small moment arm for the gravity forces tending to resist overturning.

As a point of reference, the laboratory-measured scour can be compared with an empirical scour equation based on laboratory data. For comparison, the Colorado State University (CSU) pier scour equation was used (*5*):

$$\frac{y_s}{y_1} = 2.0\ K_1K_2K_3\left(\frac{W}{y_1}\right)^{0.65} \mathrm{Fr}_1^{0.43} \tag{7}$$

where

y_s = scour depth (m),
y_1 = flow depth just upstream of pier (m),
K_1 = correction for pier nose shape (1.1 for square nose),
K_2 = correction for angle of attack of flow (1.0 for no skew),
K_3 = bed form factor,
W = pier width (m),
Fr_1 = approach Froude number = $V_1/(gy_1)^{0.5}$,
V_1 = average velocity just upstream of pier (m/sec).

Equation 7 predicts scour to be, on average, 203 mm for the unprotected pier experiments. This equation predicts the ultimate scour depths, and it is necessary to adjust for the duration of the experiments to compare measurements with predictions. For example, the scour depths for these tests were, on average, 169 mm, which corresponds to 83 percent of the ultimate scour predicted by Equation 7. Using Laursen's relationships between scour and time, in clear water conditions, the average scour depth of 169 mm after 3.5 hr corresponds to 80 percent (*6*). Extrapolating the results of the 3.5-hr experiments using Laursen's relationship yields a maximum scour depth of 211 mm. This value compares favorably with Equation 7. The effect of experiment duration should not change the relative results for these experiments.

Riprap Experiments

Many studies have examined the use of rock riprap for channel protection. Maynard et al. conducted a key study that is the basis for current U.S. Army Corps of Engineers riprap design procedures (*7*), and Wörman investigated the relationship between riprap layer thickness and filter requirements (*8*).

The pivotal study for use of riprap for bridge pier protection was done by Parola (*9*). Parola observed that riprap procedures developed for unobstructed channel flow could be used to size riprap for obstructed flow around bridge piers if the approach velocity is adjusted to account for vorticity and accelerations around a pier. The simplest expression derived by Parola is based on the Isbash equation to yield

$$\frac{(KV)^2}{g(\mathrm{SG} - 1)D_{50}} = 4.88 = 2(1.2)^2 \tag{8}$$

where K equals 1.7 for rectangular piers and 1.5 for round nose piers.

Parola's experiments were limited to full aprons that extended at least two pier widths on each side of the piers. He did not study the effect of reduced apron widths. Because the apron width was a variable for the alternative countermeasures included in this study, additional riprap tests were conducted to determine the scour reductions associated with various apron widths.

There was no scour when the riprap apron extended 1.5 to 2.0 times the pier width. For smaller aprons, scour occurred at the perimeter of the riprap apron, but it was much less severe than the maximum scour that would occur at the base of an unprotected pier. For example, the maximum scour depth at the perimeter of a riprap apron that extended only half a pier width on all sides was 58 mm, compared with 169 mm for the unprotected pier. The half-pier-width extension reduced the scour by 34 percent.

Grout Mats and Grout Bags

Various grout mats and grout bag configurations were evaluated for their effectiveness in protecting against pier scour. Both the mode of failure and degree of scour were observed.

The aim of these experiments was to determine the threshold of movement of the grout mat and the grout bags and then observe their effect on scour. Failure can be defined to be the point at which the device moves or "rolls" and the degree of scour that occurs underneath the device. Figure 9 shows a grout bag installation after a movable-bed experiment.

Grout Mats

The unobstructed incipient motion tests for the model grout mats exhibited two different failure modes at two ranges of bed shear stress. Grout mats placed loosely on the fixed bed failed by rolling up when the shear stress reached 0.17 N/m^2. The same mats, "toed in" at the upstream edge, required a greater shear stress, averaging 3.7 N/m^2, to induce failure. This greater shear stress is the result of the leading edge of the mat not being exposed to the flow field, thus creating a more stable device. These results demonstrate the effects of the bed shear stress. The mode of failure for these toed-in runs was for the mats to be "lifted up" off the bed,

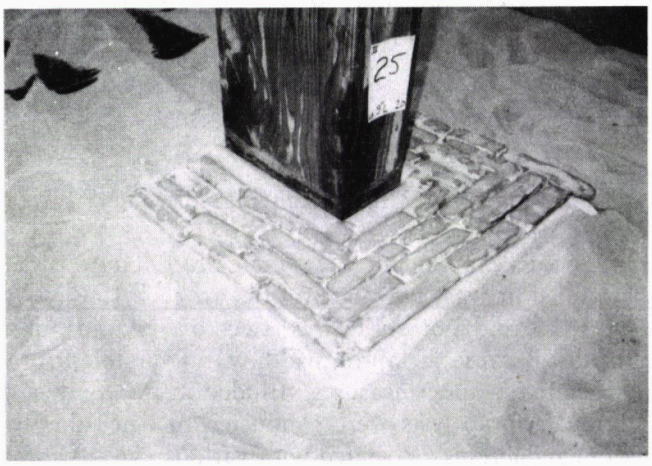

FIGURE 9 Results of movable-bed grout bag test.

presumably by a low-pressure zone above the mats. The leading edge of the mat (the toed-in section) did not fail at all.

Obstructed fixed-bed incipient tests were also performed on the grout mat. The mats were placed around a rectangular pier on the surface of a fixed bed. The approach velocity was increased incrementally until failure occurred. Failure was obtained when the mat began to roll or flip up at the front edge. After this failure, velocity profiles and flow depths were recorded in the approach section. The mats failed by rolling up when the shear stress reached 0.18 N/m^2, which compares to the unobstructed failure bed shear stress of 0.17 N/m^2. Thus, this type of failure for the grout mat is independent of the obstruction created by the pier for the fixed-bed condition.

Scour with Grout Mat Protection

On the basis of the maximum scour depths for the grout mat experiments, the difference in scour depths between the runs appears to be due to the placement of the mat around the pier. That is, the proximity of the mat to the sides of the pier (tightness of fit) contributes greatly to the effectiveness of the mat. From the experiments, one of the runs had the highest velocity of all the runs but showed one of the lowest scour depths. This is primarily due to the subjective manner in which the mat was placed around the pier. Placement appears to be the difference between a successful and an unsuccessful protective measure. Approach velocity is a factor, but it is the placement of the protective grout mat that is the primary factor, assuming the lateral extent of this device is at least two pier widths. A silicon seal between the face of the pier and the grout mat was used for several runs, which reduced the scour depth at the face of the pier to zero. In the absence of such a seal, some runs showed significant scour (or undermining) beneath the mat. Similarly, when the mat was tucked up against the pier face, the resulting scour hole was less than if it was not tucked.

Observations

The grout mats provide a barrier through which flow cannot penetrate. The leading edge can sag when undermining occurs. This flexibility appears to provide protection against scour and to increase the mat's stability. Wider grout mats result in less sagging because the lateral extent is beyond the predominant near field vortices being shed by the pier. As with riprap mats, grout mats extending 1.5 pier widths provide significant protection for bridge piers.

Grout Bags

Unobstructed incipient motion tests were performed on various sizes of grout bags by placing the bags perpendicular and parallel to the approach flow. Similar to previous experiments, the velocity was increased slowly until failure was observed. Failure was obtained when the bags oriented perpendicular to the flow rolled over. Failure for the bags oriented parallel to the flow occurred when they moved or rolled in any direction, which required a much higher velocity.

Grout bags perpendicular to the flow failed by rolling over at an average bed shear stress of 0.5 N/m^2, and the grout bags oriented parallel to the flow failed at an average bed shear stress of 3.5 N/m^2. For the bags oriented parallel to the flow, failure appears to be independent of the bag length based on the similarities of the failure approach velocities for several different grout bag lengths.

Obstructed fixed-bed experiments were also performed using a grout bag apron around a rectangular pier. The mode of failure here was the displacement of any of the bags from around the edges of the pier; failure appears to depend on the positioning of the grout bags. That is, local positioning at the face and corners of the pier is an important part of their stability. The grout bags were tested using several placement techniques. Most were oriented parallel to the approach flow. Figure 10 demonstrates the placement of the bags around the pier. Failure of the grout bags at the edge of the pier appeared to depend on the position relative to the front corners of the pier, where the vorticity is the most intense. The positioning of the grout bags at the face of the pier dictates the stability of the individual bags relative to each other—when a bag overlapped the edge of the pier, it was less likely to fail than a bag that was aligned with the edge of the pier. The leftmost con-

figuration in Figure 10 has the highest probability of failure because its position coincides with the highest vorticity levels shed by the pier.

Scour with Grout Bag Protection

Failure with the grout bags usually occurred at the pier's leading edge, where a scour hole formed into which a grout bag would roll. For the higher-velocity experiments, the leading edge was not allowed to scour, causing the bags to fail by rolling because of the fixed-bed surface surrounding the pier. Experiments without filter fabric simply allowed flow to pass between bags and create a scour hole.

Grout bags depend on a filter fabric to prevent the underlying soil from seeping through the large voids between the bags. Experiments without filter fabric did not demonstrate any scour-reduction characteristics. A comparison of two similar experiments (one with and one without filter fabric) showed that without filter fabric, the scour is four times greater than it is with a filter.

Observations

The incipient motion experiments showed that the stability of a grout bag on a fixed bed depends on its position relative to the approach flow. However, from the practical standpoint of a movable bed with an obstruction, this positioning does not appear to be a factor. Typically, grout bags will be anchored to each other and to the bed, which will ensure stability. These experiments showed that their effectiveness as a scour countermeasure is dependent on the use of filter fabric, tightness of fit to the face of the pier, and lateral extent or width of the protective apron.

No conclusive comparative results can be made for grout mats and grout bags when tested on a fixed-bed surface because of their obvious differences in scale relative to the pier. Although the grout bags are more stable, on the basis of the bed shear stress, the incipient motion is an indicator not of its scour-reduction potential but of its measure of resistance to overturning.

Figure 11 provides a scour depth–to–velocity comparison for the grout bags and grout mats. The maximum scour depth with protection (d_s) over the maximum measured pier scour without protection (d_{so}) is plotted versus the average approach velocity (V_a) over the incipient failure velocity of the countermeasure (V_i). Figure 11 shows the reduction or increase in scour for the grout mats and grout bags at various ratios.

Extended Footings

The experimental setup consisted of a 152- × 305-mm rectangular pier placed on a rectangular footing installed over the sediment recess. Both footing width and footing location (elevation relative to the channel surface) were varied to determine the effect on scour. The footing width describes how far the footing extends from the pier in any direction. The height describes the vertical dimension of the footing, and the top location describes the elevation of the top of the footing relative to the sand surface. The setup for these experiments is shown in Figure 12. A total of 91 runs were performed at various footer widths, heights, and thicknesses for 3.5 hr each. The depth-averaged approach velocity was kept fairly constant within a range of 0.29 to 0.35 m/sec and a depth of 305 mm was maintained for all but two runs, which had depths of 152 mm.

Failure for extended footing runs is defined as the formation of a scour hole. Two types of local scour were identified for these experiments. The first was induced by the vertical position of the footing in the flow

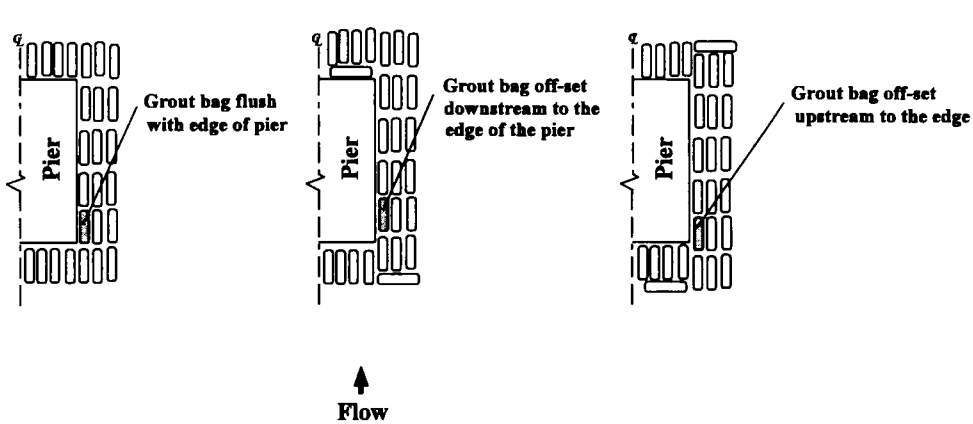

FIGURE 10 Test configurations for placement of grout bags relative to pier on obstructed fixed-bed surface.

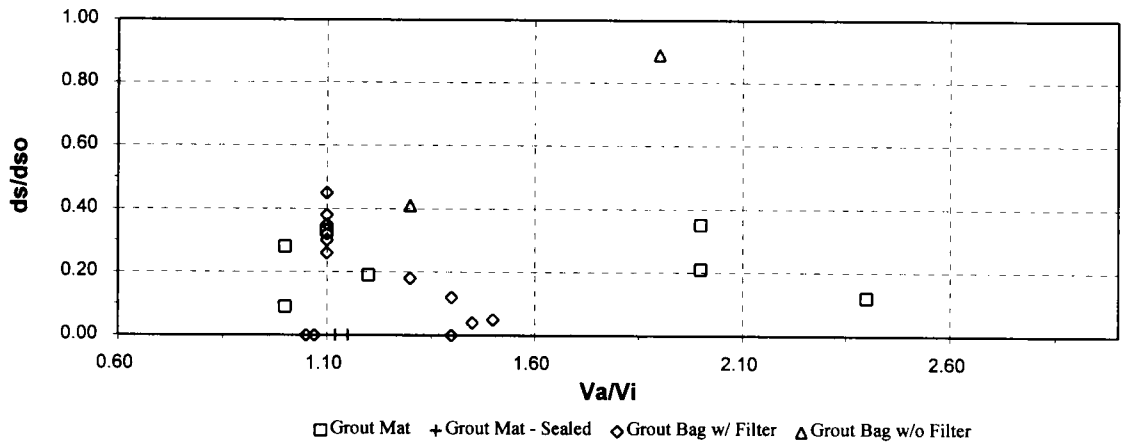

FIGURE 11 Scour reduction for grout bags and grout mats.

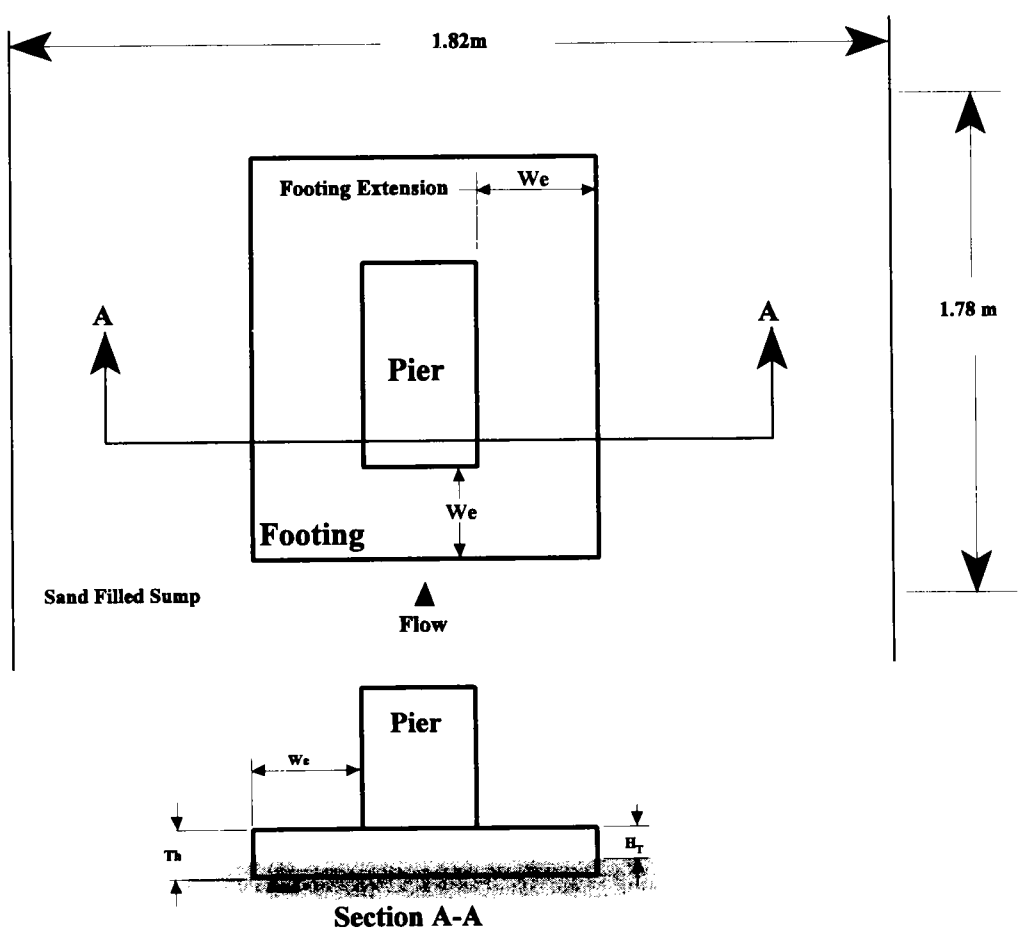

FIGURE 12 Configuration for extended footing experiments.

field. The scour depth was generally not as great for the deeper footing locations because the footing did not protrude high enough into the flow field. However, as the footing was raised, it protruded farther into the flow field, causing flow to be redirected down the face of the footing and resulting in greater scour. As the footing continued to be raised, a channel scoured out below the footing providing relief for the flow directed down the face of the footing, thus resulting in lower scour depths. The second type of scour was created by the near-field vortices being shed by the pier. For this case, the scour is related directly to the footing width. That is, the smallest footing width (76 mm) did not appear to extend far enough to provide protection against the local vorticity. The largest footing width (229 mm) showed no significant scour.

Tetrapods

The geometry of the tetrapod is believed to enhance its ability to resist movement and in turn increase its scour protection characteristics. The interlocking capability of the tetrapod is thought to account for greater stability than riprap. The results of these experiments show that tetrapods may exhibit a higher degree of stability, but the increase was slight and was within the scatter of riprap data.

Experimental Setup

A number of experiments were performed with various riprap and tetrapod configurations. In the first group of tests, conditions for tetrapod incipient motion were determined for unobstructed flow (no pier). The test section dimensions were 203 × 152 mm, and both recessed and surface placements of tetrapods were evaluated on a fixed bed.

There is a significant difference between placement of armor units on the surface and that on recessed. For riprap, the average Shields parameter for recessed placement is 0.096 versus 0.043 for surface placement. For tetrapods, the result is similar, with the recessed placement yielding an average Shields parameter of 0.075 and the surface placement, 0.042.

A comparison of tetrapods and riprap using the stability number versus relative roughness (D_{50}/y) for the recessed placement showed no obvious correlation. The riprap data of Parola and Neill are included to supplement these riprap data (*9,10*). Inspection reveals significant scatter in the data and no clear distribution in performance between the tetrapods and riprap.

Figure 13 summarizes a comparison of tetrapod and riprap data using the Shields parameter versus the Froude number for the recessed data only. The data from Neill and Parola are included in this comparison as well. The Shields parameter for tetrapods is higher, on average, than the riprap for a given Froude number. In addition, none of the tetrapod runs was conducted at Froude numbers greater than 0.8. The Pennsylvania Department of Transportation (PennDOT) is sponsoring additional research to expand this data base. However, there is enough scatter in the data to question whether the interlocking capability of the tetrapods represents a true increase in stability.

Obstructed Flow

Failure of the tetrapod armoring in obstructed flow runs typically occurred at the perimeter of the mats rather than at the pier. This suggests that the tetrapods are less vulnerable to diving currents at the pier than are other independent armoring units with less interlocking cap-

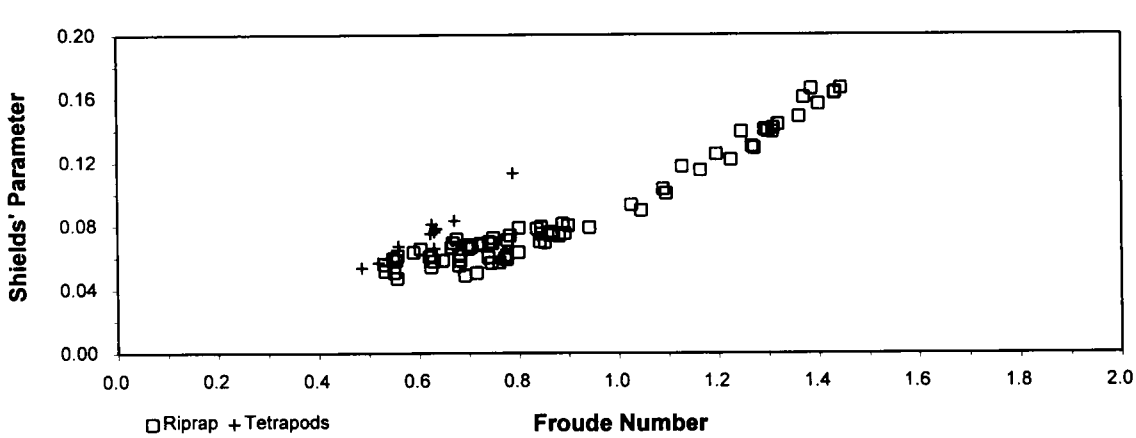

FIGURE 13 Shields parameter for riprap and tetrapods.

ability. However, the general turbulence in the flow field caused by the pier contributes to tetrapod failure.

For these tests, two mat widths were tested. As expected, the wider mat width (the pier width; 152 mm) resisted greater shear stress before failing than did the narrower width (76 mm). No runs were made with wider mats because there were insufficient tetrapod models and the PennDOT study was expected to expand on the experiments.

Results

Three tetrapod concentration variations were also evaluated. The lowest concentration of 3,300 tetrapods per square meter (or approximately a single layer) provided less protection than the medium concentration (4,900 tetrapod per square meter) for both mat widths. Greater concentrations, and therefore more opportunities for interlocking arms, apparently contribute to greater stability as well as less entrainment area for the flowing water. However, the highest concentration tested (5,700 tetrapods per square meter) resulted in earlier failure than the medium concentration for both mat widths. One explanation for this is that the higher concentration protruded farther up into the flow field, resulting in earlier failure. The higher-concentration experiments also had a higher percentage of the tetrapods that were not interlocking efficiently. That is, when a second layer of tetrapods is placed on top of the first, it will interlock better than a third layer on the second layer because there are fewer voids to allow interlocking. This situation caused the tetrapods to roll more easily.

The approach shear resisted by tetrapods in the obstructed cases should be less. In a comparison of the obstructed versus the unobstructed runs, the average shear stress was 2.4 N/m^2 for the 76-mm mat and 3.4 N/m^2 for the 152-mm mat. The unobstructed average shear stress was 5.4 N/m^2. For the obstructed runs, it is unclear if a larger mat would continue this trend and approach the unobstructed level of stability. Although no obstructed runs were conducted in a recessed test section, primarily because of time constraints, it is intuitive that tetrapods would demonstrate higher stability. Further experimentation would be required to verify this case. The fact that most failure is at the mat perimeter suggests that it would approach the unobstructed level.

Cable-Tied Blocks

Cable-tied blocks are continuous scour protection devices placed on the bed surface. This scour countermeasure consists of concrete blocks connected or joined by reinforcement cables. The blocks were evaluted for their stability on a fixed bed for both obstructed and unobstructed flow conditions and on an obstructed movable bed. High-velocity tests were performed for various sediment sizes to simulate live-bed conditions. Trapezoidal and hexagonal geometries were tested, and single trapezoidal and hexagonal blocks were also tested for their drag coefficients. These countermeasures are illustrated in Figure 4.

Trapezoidal Cable-Tied Blocks

Movable-bed experiments using the trapezoidal cable-tied block mats were performed under obstructed flow conditions. The first runs used the setup shown in Figure 6. The high-velocity runs, shown in Figure 6 (*bottom*), consisted of a movable bed underneath the mat in order to observe the performance of the mat at a high shear stress ratio, thus avoiding general bed scour. The mat was placed flush with the surrounding fixed bed. The mat used a filter fabric to prevent water entrainment. Here, no clear trend for scour depth versus velocity is apparent. The controlling factor appears to be the tightness of fit of the mat around the pier. Several experiments were performed at high velocities using a silicon seal between the face of the pier and the countermeasure. This scenario resulted in no scour.

The critical shear stresses, which represent incipient motion conditions, are considerably higher than the shear stresses for the unprotected sand experiments. This indicates that the cable-tied blocks are more stable than unprotected sand and could, therefore, mitigate scour in a live-bed situation. This finding is verified by the increased-velocity experiments, which show that approach velocities up to 3.4 times greater than the incipient motion velocity of the sand reduce scour even after equilibrium conditions are reached. The critical difference between significant scour and no scour regardless of the approach velocity appears to be the seal between the face of the pier and the countermeasure. Although some scour reduction is achieved without using a seal, sealing will greatly improve the effectiveness of the countermeasures.

Hexagonal Cable-Tied Blocks

Hexagonal cable-tied blocks are similar to the trapezoidal cable-tied blocks because they are interconnected by a network of plastic wire. Like the trapezoidal block experiments, hexagonal blocks were tested for their incipient motion as well as their scour-reduction capabilities.

The hexagonal cable-tied blocks were tested up to 2.5 times the incipient velocity motion of the sand. This indicates that the hexagonal blocks will remain effectively in place during flood events of that magnitude. The approach velocity and bed shear stress are greater for the unobstructed conditions than for the obstructed test conditions, which indicates that the incipient motion of the mat is partially dependent on the obstruction that the pier creates.

Results

The effectiveness of a cable-tied block mat in preventing scour depends on the surface roughness characteristics, its tightness of fit around the pier, and the lateral extent of the mat around the pier. The rougher surface of the cable-tied block mats provides better scour resistance, and the better fit of the mat around the pier reduces the scour potential. Regardless of the type of material, the most influential scour prevention characteristic is the lateral extent of the countermeasure and the tightness of fit. Securing the edges of the protective countermeasure to the river bed by using an anchoring system will decrease the countermeasures' natural tendency to overturn or flip up during large flood events. (Anchors and their application are discussed in greater detail in the next section.)

The use of filter fabric for such countermeasures is essential to their overall effectiveness. Without filter fabric, the erosive currents induced by the pier will penetrate between each block and eventually cause scour. Several experiments without filter fabric were performed, and observation indicated that the local scour progressed as if the mat were not there. This eventually led to a scour depth equal to that of an unprotected pier.

For the fixed-bed unobstructed incipient motion experiments, the trapezoidal block mat overturned at a lower bed shear stress than the hexagonal block mat. This occurrence indicates that the hexagonal blocks are more stable than the trapezoidal blocks. One observed phenomenon was that the calculated drag coefficients for the three-abreast hexagonal block experiments were lower than those for the trapezoidal three-abreast experiments. However, for the single block experiments this phenomenon appears to be reversed. One conclusion may be that stream-lining between the hexagonal blocks is more efficient than the trapezoidal blocks, thus creating a slightly more stable cable-tied block mat.

For the obstructed fixed-bed experiments, no clear advantage between either cable-tied block mat is evident. The bed shear stresses required to overturn the hexagonal and trapezoidal cable-tied block mats are 1.47 and 1.46 N/m^2, respectively. This similarity indicates that the incipient motion of an obstructed fixed-bed surface is dependent on the pier. That is, the stream-lining or local velocity gradients surrounding the pier dominate the stability of the mat.

From the results, it appears that the hexagonal and trapezoidal cable-tied blocks compare favorably to each other on the basis of their overall scour reduction potential. However, the incipient motion experiments showed that the hexagonal cable-tied block mat is slightly more stable for the unobstructed experiments. The stability of the countermeasure does not appear to control its scour reduction potential. The controlling factor for scour reduction appears to be how the countermeasure is anchored down and the tightness of fit between the face of the pier and the countermeasure. For example, two experiments were performed using a silicon seal between the face of the pier and the countermeasure. The result was no scour. When no seal was present, the scour depth increased proportionally with the velocity and as a function of the tightness of fit. This is based on both inductive reasoning and the fact that all of the observed scour throughout this research occurred at the face of the pier.

The trapezoidal cable-tied blocks are more stable than the hexagonal cable-tied blocks. This finding is verified by the trapezoidal block's lower drag coefficient and higher shear stress, which may be because the trapezoidal block has more surface area in contact with the bed surface, thus establishing a higher moment arm needed to overturn it. However, for a movable-bed situation, some attributes of the hexagonal blocks may be desirable—that is, the stability of a countermeasure does not necessarily dictate its scour protection potential. Assuming that the cable-tied block mat is stable relative to the underlying sediment, during a sizable flood event, the stream-lining between the individual blocks will most likely contribute to overall effectiveness against scour. The inherent shape of a hexagonal block will allow for channeling or diverting of the approach velocity forces between the blocks as opposed to the trapezoidal block mat, which may divert flow downward instead of around it. However, when used in conjunction with a filter fabric, this characteristic may not be a significant factor.

Anchors

Anchors are often recommended as an auxiliary device that adds stability to the leading edge of a countermeasure. They will improve the overall performance of the countermeasure for scour protection by anchoring to the bed. The anchor is designed to be prototypical in size and is to be implemented with various scour protection countermeasures. The anchor's cable is attached to the countermeasure at the surface and the anchor is

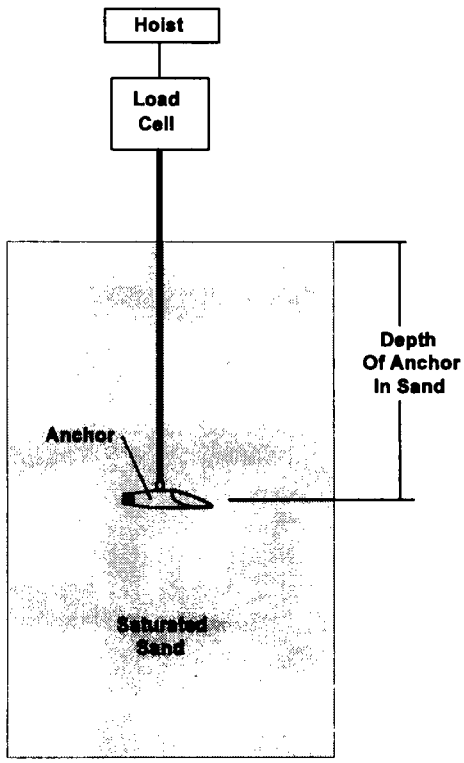

FIGURE 14 Configuration for anchor test.

driven into the bed to an appropriate depth. The setup for the experiments is shown in Figure 14. Intuitively, it can be seen that the anchor may work best with continuous scour devices such as the grout mat and cable-tied block mats.

These experiments were designed to determine the maximum force that an anchor, buried in sand, can withstand without being dislodged. This maximum resisted force becomes critical when the fluid forces acting on the anchor are equal to or greater than its resistance. The resistant forces of the anchor are reported as a function of the depth of the anchor embedded in the sand.

The large forces associated with dislodging the anchors for the different experiments vary considerably. These differences were due to inconsistencies in the sand settlement and saturation percentages. The force required to dislodge the anchor from the sand appears to be dependent on the location of the anchor within the barrel as well as the amount of time the sand had to settle between experiments. The compaction of the sand changed from one experiment to another.

An alternative design for an anchor might be one that is "duck-billed" on both ends. This design would enable the anchor to be driven into the bed material much easier. More important, it would provide a larger surface area when the anchor is in its horizontal position (i.e., once the anchor is in place, the force required to pull up the anchor would be greater since the obstruction area to uplift the anchor is greater). With respect to using anchors in conjunction with a countermeasure, the force required to dislodge the anchor from the bed can be combined with the force required to overturn the countermeasure: the drag force required to overturn the countermeasure can be recalculated using a larger force holding down the countermeasure. This can be used in sizing countermeasures for large flood events. The procedure for sizing the anchors and countermeasure would entail estimating the desired approach velocities and, in turn, the drag forces allied to the countermeasure for a large flood. The appropriate anchor can be determined from the drag force for a specifically sized countermeasure.

The experiments revealed that the performance of the anchor is dependent on soil characteristics such as consolidation and compaction. This conclusion is corroborated by the fluctuation of anchor strength from the first run to the second for the same depths. As can be expected, the larger anchor is more resistant to dislodging than the smaller for the same depth. Figure 15 summarizes the results for these experiments. Furthermore,

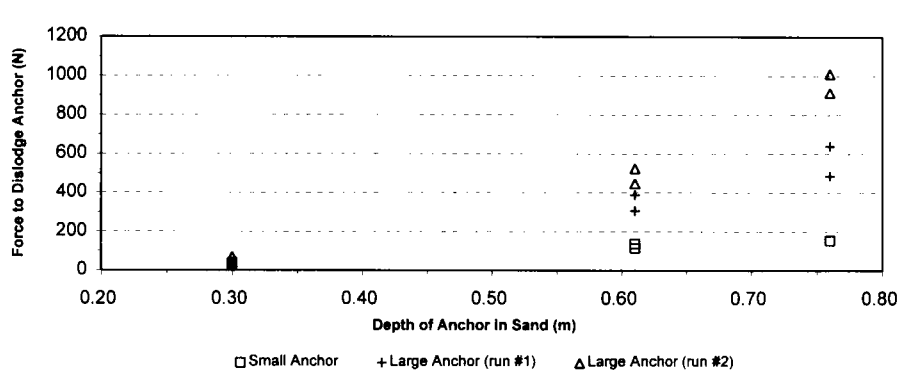

FIGURE 15 Anchor depth versus pullout force.

the resistance to dislodging increases as the sand consolidates. The influence of soil characteristics on the stability of the anchor is beyond the scope of this study. The performance, or pullout force, can be increased greatly by a design modification. Making the anchor duck-billed on both ends would significantly increase the resistance area and make installation easier.

High-Density Particles

High-density particles were tested for their performance as a local scour countermeasure. These particles may be less prone to turbulence around the pier because of their reduced size and their higher specific gravity. High-density particles are more than four times as dense as conventional riprap.

The purpose of these experiments is to evaluate this alternative to riprap as a scour countermeasure. Intuition suggests that high-density particles may provide a better protective apron around a pier than conventional riprap. These experiments are designed to give some insight into how high-density particles will perform as a local scour countermeasure.

Two sizes of high-density particles were tested. The particles were made from lead, were cylindrical in shape, and had diameters of 2.3 and 6.3 mm. Each particle size was tested on the high-velocity movable-bed surface shown in Figure 7 (*bottom*). A layer thickness of two to three diameters was used for the tests. No filter was used. The approach velocity averaged about 0.7 m/sec. Each experiment was allowed to run for about 4 hr, at which time the experiments were stopped and the scour depths recorded.

Although this countermeasure will provide an adequate protective layer, the size and specific weight of the high-density particles appear to have an important impact on its effectiveness. There appears to be a point at which these particles need to be sized according to the underlying bed material size. That is, if the high-density particles are smaller than the bed material that they are trying to protect, this type of countermeasure is inappropriate. When filter fabric is not used, the size of the particle must be larger than the bed material but small enough to close the spacing between each particle. In this manner, the water currents are prevented from entraining between the gaps, thus causing scour.

In general, high-density particles appear to be a more stable scour countermeasure, on the basis of their relative mass and size, than riprap. One advantage of high-density particles is the reduction in the size particles required to provide protection. Along with the size reduction are decreases in void size and the need for filters. Although the riprap experiments scoured less, these experiments were performed near incipient motion, whereas these tests achieved a velocity of 2.6 times that of the incipient motion of the underlying sediments. An increase in the velocity of about 500 percent was observed for these conditions, indicating the need for a thicker apron. With the riprap experiments, typically a two-layer-thick apron was used, which increased the ability of the countermeasures to withstand scour.

Conclusive results to validate this type of countermeasure could not be obtained because of the limited number of experiments performed. However, the Shields criteria and sediment number relations would apply for this type of protection if the appropriate specific gravity were used. Further research would enhance the understanding of this scour countermeasure.

Lead was used for these experiments only for convenience. The authors do not recommend using this countermeasure because of its environmental impact. A material that is more environmentally sound should be used instead.

Summary

The riprap experiments indicate that the protection increases substantially as the riprap apron width increases to 1.5 pier widths beyond the edge of the pier. From these experiments, the two-pier-widths extension criterion currently recommended in FHWA's Highway Engineering Circular 18 (*5*) is adequate.

Grout mats and grout bags also provide substantial protection, especially when they extend at least 1.5 pier widths. The grout mats and grout bags performed comparably to the riprap mats.

Footing configuration can have a profound effect on scour. Wide footings with the top of the footing level with the bed surface provide substantial protection against the strong near-field vortices being shed by a pier. Narrower footings might not extend far enough from the pier to provide protection against these vortices. As general bed scour occurs, the top of the footing is raised into the flow field and the flow is redirected down the face of the footing into the bed, increasing scour. As the footing continues to rise (or scour increases), a channel may be scoured out under the footing. This channel provides relief for the redirected flow and results in scour equilibrium being reached. The maximum protection is provided with wide footings (at least 1.5 pier widths) level with the bed surface, although this configuration does not appear to provide as much protection as equally wide riprap mats, grout mats, or grout bags because footings are rigid and cannot settle or roll into a scour hole. Another reason may be that the riprap sheds off, or breaks up, some of the dominating vortices that are present, whereas the extended footing only transfers them outward. The front

of the footing can also generate scouring vortices when raised into the flow field.

For both unobstructed and obstructed (pier) flow conditions, riprap and tetrapods behaved comparably when both stability number and spherical stability number were compared. These experiments also show that fixing the perimeter and varying the number of layers of tetrapods may affect stability. Therefore, economics should have a major role in choosing between riprap and tetrapods.

A direct comparison between the alternative protection measures is possible, but it must be done with care. The main reason is that the riprap, grout bags, grout mats, tetrapod models, high-density particles, and cable-tied blocks do not necessarily scale up to comparable prototype dimensions; equal scaling between the various models relative to the pier size could not be achieved. A measure such as the Shields parameter can reduce the importance of scaling for measures such as riprap and tetrapods but does not have the same utility for a continuous grout mat. The second problem in making direct comparisons derives from the unknown degree to which the presence of a protection measure changes local scour potential. This may be an issue in terms of both the location of the measure (i.e., whether it is extended into the flow field) and the extent to which the measure changes surface roughness locally (i.e., whether enough to change the flow field energy slope).

The countermeasures that act as a continuous apron can be compared. These include grout mats, grout bags, cable-tied blocks, and high-density particles. Figure 16 shows the effectiveness of these countermeasures relative to each other. The scour reduction ratio (d_s/d_{so}) versus the velocity ratio (V_a/V_i) is examined. Overall, the alternatives that used a seal between the pier and the countermeasure showed little or no scour regardless of the velocity ratio. None of the countermeasures appears to dominate in terms of its scour reduction capacity but the overall trend is that the scour increases proportionally with the velocity. The variability in scour for similar countermeasures at similar velocities may reflect the manner in which they were placed before the experiment. If, for instance, the grout mat was not tight enough around the pier, greater scour could result. From these experiments, there does not appear to be any correlation between the stability of a countermeasure and its scour reduction capability. The critical shear stress to overturn a hexagonal cable-tied block mat (1.9 N/m^2) on a fixed bed is almost 10 times that of a grout mat (0.2 N/m^2). However, from Figure 16, the grout mat experiments compare favorably to the hexagonal cable-tied block experiments.

Although comparing the scour protection alternatives is difficult at best, some relative comparisons are made from the perspective of inherent countermeasure stability and scour protection. The resisting critical shear stress and Shields parameter are measures of the resistance of the alternative to movement in a flow field. Since the Shields parameter is dimensionless, it is independent of scale. However, shear stress has units of force per area and is, therefore, scale dependent. Uniform sand with a D_{50} of 0.43 mm resists a shear stress of approximately 0.2 N/m^2 or less, and a sand with a D_{50} of 2.4 mm resists a shear stress of approximately 1.2 N/m^2. Any measure designed to protect the sand from scour should have a higher degree of resistance. This is true for all measures, except for grout mats laid

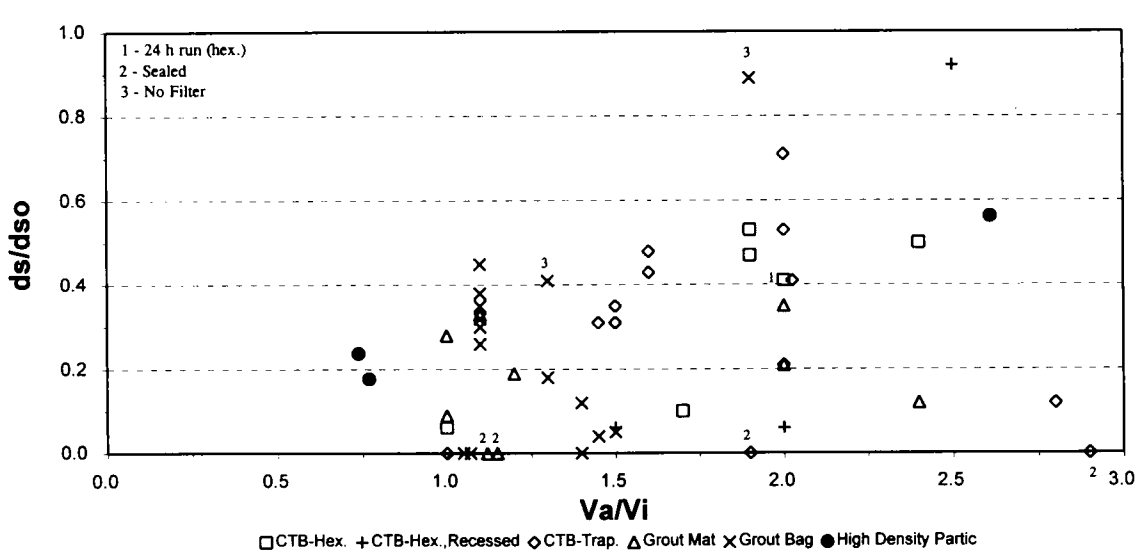

FIGURE 16 Combined scour reduction for countermeasures.

flat on the bed surface. It is also observed that the method of installation affects stability (compare grout mats laid flat and those toed-in, and tetrapods recessed and on the surface).

Another way to evaluate the countermeasures is to compare their effectiveness in scour protection. This is a function of both inherent stability and the ability to stop the base material from moving while underneath the countermeasure. The results show the range of scour allowed by each measure (as a percentage of the unprotected scour) and notes where that scour takes place. The riprap tests reduced maximum scour from 14 to 20 percent of the unprotected scour for a mat width of 152 mm and to 0 percent (no scour) for a mat width of 305 mm. Equally important is that the scour that did take place was found at the mat perimeter rather than at the pier and is, therefore, less of a threat. As expected, the other countermeasures show that a wider mat width improves scour protection. The results show that the installation technique for grout mats and grout bags affects not only the degree of scour, but also the location of scour.

Conclusions

This study provided some valuable insight into the overall behavior and effectiveness of various scour countermeasures. Two main areas of concern emerged: the first corroborated previous recommendations to extend at least two pier widths laterally from the pier in order to provide adequate protection from local scour, and the second addressed the use of filter fabric and sealing between the pier and countermeasure. Although each countermeasure has its own characteristics, the common bond between them is their ability to act as a continuation of the pier much like an extended footing. The following is a list of conclusions drawn from this study for each countermeasure:

- Countermeasures tested in this study are remedial measures to arrest local pier scour at existing bridges.
- Countermeasures were evaluated in terms of failure modes and techniques for analyzing expected stability. All of the alternatives to riprap merit another level of scrutiny for practicality and cost-effectiveness.
- Two techniques determined to be appropriate for analyzing stability were (a) particle displacement criteria patterned after Shields and Isbash incipient motion formulas and (b) drag coefficients to characterize overturning forces. Both of these techniques involve dimensionless parameters that can be transferred from laboratory to full-size conditions.
- Loose particle countermeasures such as rock riprap, tetrapods, or other precast concrete particles and high-density particles can be analyzed by particle displacement criteria and can be compared with one another by using an equivalent spherical diameter as a characteristic size.
- High-density particles can be formed into near-spherical shapes from scrap metal and crushed automobile bodies to serve as an effective countermeasure. Although they may pose environmental problems, they were tested because they are stable in much smaller diameters and in some situations can serve as their own filters for the underlying bed materials.
- Interconnected mats such as cable-tied blocks and grout mats have two failure modes. The first is overturning and rolling up the leading edge if it is not adequately anchored or toed in. The second usually occurs at much higher velocities if the leading edge is adequately anchored; it is uplift of the inner portion of the mat. This process is analogous to particle displacement.
- Anchor strengths of full-size, commercially available duck-billed anchors were measured in the laboratory by the forces required to dislodge them from a barrel of saturated sand. The forces depended on the depth of penetration and size of the anchor and varied from 200 N for the small anchors to 1000 N for the large anchors at 0.75-m penetration.
- Interconnected mats must be fitted around a pier and require a good seal between the mat and the pier to avoid being undermined by the diving currents along the upstream face of a pier.
- Grout bags formed into oblong shapes can be analyzed by particle displacement criteria, but the equivalent spherical diameter, which worked well for riprap, tetrapods, and high-density particles, was not an appropriate way to characterize the size of the grout bags. The authors selected the grout bag height as a characteristic size dimension.
- Extended footings can serve as scour arresters under favorable conditions, but they can become a major contributor rather than an arrester to scour if they are located above the stream bed.

Recommendations

The experiments reported in this paper provide valuable insight into some of the issues surrounding design and implementation of pier scour protection measures. However, additional model experimentation and field verification are necessary to produce defensible guidance for use in the field. More research is needed to address some of the issues that could not be resolved in these experiments of relatively small scale. These issues include

- Practical methods for placing filter fabric under water,

- Development of filter criteria for various prototype protective measures,
- Evaluation of the long-term integrity of cables and polyethylene ropes for cable-tied block systems,
- Evaluation of the long-term integrity of the fabric for grout mats,
- Performance of anchors used in conjunction with countermeasures,
- Consideration of environmental problems associated with the potential erosion of countermeasures and the corrosion of high-density particles,
- General verification testing at larger scales, and
- Evaluation of practical techniques for sealing countermeasures to piers on existing bridges.

Once their effectiveness is demonstrated, issues of cost, availability of materials, and installation will determine which measures are applied in the field.

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