

# Sizing Riprap to Protect Bridge Piers from Scour

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## ABSTRACT

Equations recommended for determining riprap size to protect bridge piers are compared to experimental results from small-scale model studies conducted in laboratory flumes. Adjustments to the equations are recommended from the analysis of laboratory data, as are uses of the equations to protect circular and rectangular bridge piers from scour.

## INTRODUCTION

The leading cause of bridge failure over waterways has been the scouring of foundation material by floodwaters (Makowski, Thompson, and Yew 1989). Bridge piers obstruct flow and induce local secondary currents that take the form of strong eddy systems which have a much higher capacity for eroding bed material than unobstructed flow. As a result, local scour holes tend to form in unprotected alluvial streambeds surrounding bridge piers. Often local scour holes develop to the extent that the pier foundation is undermined causing settlement and, in some cases, the collapse of supported bridge spans.

One of the most common methods for protecting piers is the placement of a riprap apron to armour the streambed influenced by the secondary currents. The rock sizes required to protect the streambed tend to be much larger than normally required for unobstructed flow conditions. Small-scale laboratory

experiments have been conducted to relate the rock sizes required to protect bridge piers to local flow conditions (Quazi and Peterson 1973, Parola 1990). This paper compares the data of those small-scale experiments to the current equations for sizing riprap to protect bridge piers suggested by the Federal Highway Administration (FHWA), and proposes equations based upon experimental data.

## CURRENT FHWA METHOD

FHWA published a Technical Advisory to provide guidelines for evaluating and designing bridge foundations in waterways (FHWA 1989). The advisory includes a method for sizing rock to protect the streambed surrounding bridge piers. The method involves determining the local average velocity just upstream of the pier such that the pier does not directly influence the flow. This velocity,  $V$ , is multiplied by a factor,  $f$ , which can range from 1.5 to 2.0. The increased velocity is then used in the equation proposed by Isbash (1935) for determining the stability of rocks dumped into flowing water. The equation recommended for sizing rock protection at piers can be written as

$$D_{50} = 0.347 \frac{(f V)^2}{g (S_g - 1)} \quad (1)$$

where

$D_{50}$  = the nominal sieve size for which 50 percent of the rock is finer by weight (ft)

$S_g$  = specific gravity of rock material

$V$  = local average velocity (ft/s)

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$g$  = gravitational acceleration  
(ft<sup>2</sup>/s)

$f$  = 1.5 to 2.0, factor to account for pier turbulence

The value of  $f$  used in the equation is left to the designer's discretion.

Equation 1 was recommended based on the suggestions of Breusers, Nicollet, and Shen (1977), Neill (1973), and unpublished velocity measurements collected in the vicinity of model bridge piers at the Turner-Fairbank Highway Research Center in McLean, Virginia.

Through comparison of the rock sizes recommended to protect streambeds conveying unobstructed uniform flow to the rock sizes recommended to protect piers in similar flow conditions, the dramatic increase in rock size required to protect bridge piers is apparent. The equation (US Department of Transportation 1989) recommended for determining rock sizes to protect a streambed conveying uniform flow is

$$D_{50} = 0.387 \frac{V^3}{Y^{1/2} g^{3/2} (Sg-1)^{3/2}} \quad (2)$$

where

$V$  = average velocity (ft/s)

$Y$  = flow depth (ft)

An important difference between Equation 1 and Equation 2 is that the rock sizes in Equation 1 are much larger than those predicted by Equation 2 for the same flow conditions. In addition, the rocks sizes predicted by Equation 2 are dependent on flow depth,  $Y$ , unlike the rock sizes predicted in Equation 1.

Both equations can be written in non-dimensional form by dividing each side of each equation by the flow depth,  $Y$ , and by the substitution of Froude number,  $F = V/(gY)^{1/2}$ . Equation 1 can be rewritten as

$$\frac{D_{50}}{Y} = 0.347 \frac{(f F)^2}{(S_g - 1)} \quad (3)$$

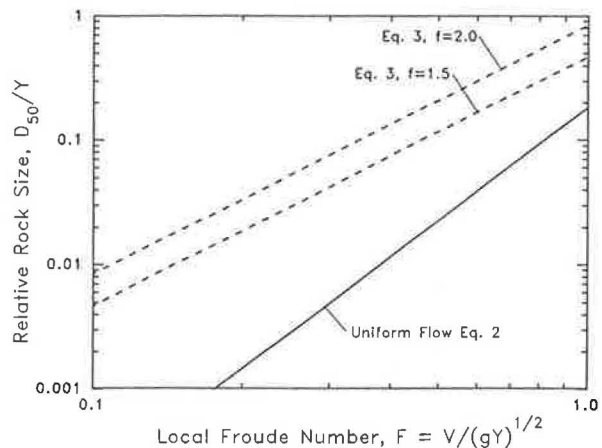
and Equation 2 can be rewritten as

$$\frac{D_{50}}{Y} = 0.387 \frac{F^3}{(S_g - 1)^{3/2}} \quad (4)$$

Equation 3 with  $f = 1.5$  and  $f = 2.0$  and Equation 4 are compared graphically in Figure 1 with the assumption that the specific gravity of the rock material is 2.65. The difference in the slope of each line is a result of the dependence of  $D_{50}$  on flow depth in Equation 4 and the non-influence of flow depth in Equation 3. The relative rock sizes,  $D_{50}/Y$ , predicted by each equation can be compared for a given flow condition (Froude number). Note also that the size differences between the uniform flow equation and the pier equations decrease with increases in Froude number.

**MODEL STUDY RESULTS AND COMPARISONS**

Small-scale model studies were conducted in laboratory flumes to relate the rock sizes required to protect pier foundations to local flow conditions (Quazi and Peterson 1973, Parola 1990). Quazi and Peterson (1973) conducted experiments in a 4.0 ft wide flume using a 0.13 ft round-nosed pier model with rock placed flush with the surrounding streambed elevation. Parola (1990) conducted experiments in a 6.0 ft wide flume using a 0.375 ft rectangular-nosed pier model where rock was mounded around the pier in some



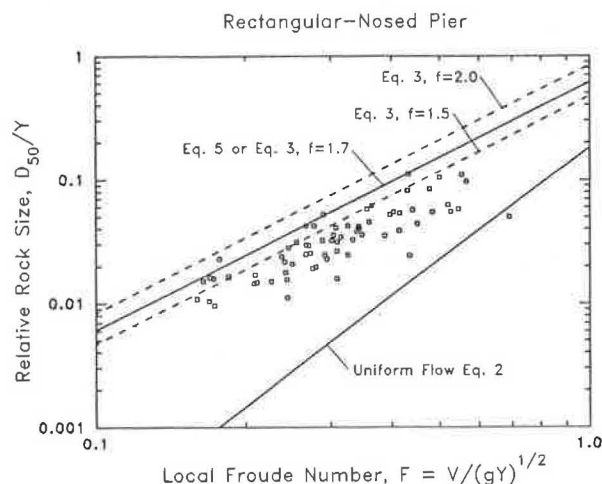
**FIGURE 1 Comparison of Currently Recommended Uniform Flow and Pier Protection Rock Sizing Equations**

test runs, and was placed within preformed scour holes of various depths in other runs. A cylindrical 0.375 ft diameter pier model with rock mounded around the pier was also tested. All of the experiments were conducted using uniform gravel to model riprap under subcritical flow conditions with a Froude number range from 0.2 to 0.6. Quazi and Peterson (1973) defined failure as the first displacement of a single rock particle, while Parola (1990) defined failure as the removal of the top layer of gravel resulting in the exposure of the second gravel layer.

Based on the data from the rectangular-nosed pier experiments, the following conservative equation is proposed

$$\frac{D_{50}}{Y} = 1.0 \frac{F^2}{(S_g - 1)} \quad (5)$$

The data from the rectangular-nosed pier experiment, Equation 5, and Equation 3 with  $f = 1.5$  and  $f = 2.0$  are plotted in Figure 2. A specific gravity of 2.65 is assumed.



**FIGURE 2 Comparison of Rectangular-Nosed Pier Data With the Proposed Eq. 5 and the Currently Recommended Equations for Pier and Uniform Flow Protection**

Equation 5 is equivalent to Equation 1 or Equation 3 with  $f = 1.7$ . The data scatter is large because data were included from several different experiments where the level of the riprap was varied from well-below the streambed to a mounded

condition above the streambed. Analysis of data collected under laboratory conditions in which the streambed was fixed showed that a reduction of approximately 50 percent in rock size could be realized if the rock was placed to a depth of 0.7 pier widths below the streambed. However, in an actual riprap placement, a general lowering of the streambed may occur that would reduce the depth of the protection with respect to the streambed, creating a highly unstable situation; therefore, the size rock as predicted in Equation 5 is recommended without reduction for the depth of placement.

Based on the data from the round-nosed pier (Quazi and Peterson 1973) and cylindrical pier (Parola 1990) experiments, the following conservative equation is proposed

$$\frac{D_{50}}{Y} = 0.61 \frac{F^2}{(S_g - 1)} \quad (6)$$

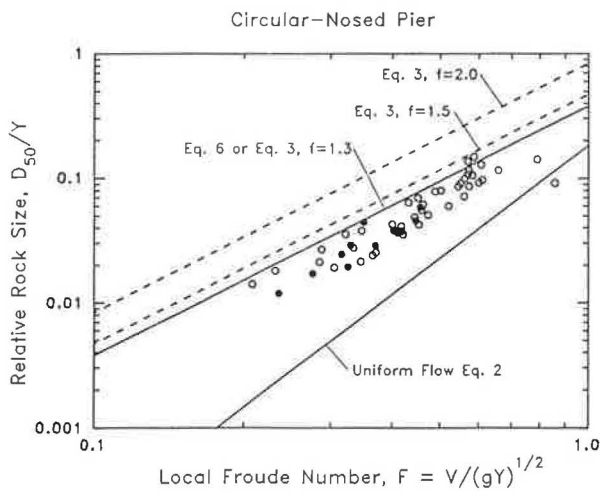
The data from the round-nosed pier experiment, cylindrical pier experiment, Equation 6, and Equation 3 with  $f = 1.5$  and  $f = 2.0$  are plotted in Figure 3. A specific gravity of 2.65 is assumed. Equation 6 is equivalent to Equation 1 or Equation 3 with  $f = 1.3$ . Direct comparison of Equation 5 and Equation 6 shows that the rock sizes required to protect round-nosed and cylindrical piers are 40% smaller than those required to protect rectangular-nosed piers.

The results of the model studies indicate that the form of Equation 1, with slight adjustment to the values of  $f$  to compensate for the increased turbulence at the piers, is useful in determining the rock size necessary to protect bridge piers from scour.

As is implied by Equation 1, the rock size required to protect piers was not found to be dependent on flow depth,  $Y$ , unlike the rock sizes predicted by the equation for uniform flow conditions.

#### RECOMMENDED APPLICATION

The small-scale model studies were conducted using model piers of simple



**FIGURE 3 Comparison of Round-Nosed Pier Data and Cylindrical Pier Data With Proposed Eq. 6 and the Currently Recommended Equations for Pier and Uniform Flow Protection**

geometry and uniform rock sizes. Although some older bridge piers may have rectangular-shaped noses, most modern piers have rounded or pointed noses and are supported on rectangular spread foundations or rectangular pile caps. Equation 1 with  $f = 1.3$  is applicable for use with round-nosed piers that are fairly aligned with flow, that are not subjected to ice jams or debris accumulation, and that are located in bridge openings where the general bed elevation is expected to remain above the rectangular pile cap or spread footing. Equation 1 with  $f = 1.7$  is recommended for piers in which the square foundation is expected to be above the general bed elevation, or for piers that are founded on square footings which are likely to be exposed by general scour throughout the bridge opening. Experiments on pointed-nosed piers or piers skewed to the flow have not been performed, although Equation 1 with  $f = 1.7$  should provide a conservative estimate of rock protection size for these conditions. A safety factor should be applied to the rock sizes obtained.

The laboratory experiments were conducted using uniform gravels in at least three layers. Ettema (1976) has shown that for clear-water local scour, well-graded bed material tends to scour less than uniform material. Based on this research, a speculation is made that well-graded riprap with  $D_{50}$  equal to the uniform rock

sizes recommended for pier protection in this paper will be conservative. As a design criteria for failure of a protective mat, the layer thickness of the protection is recommended to be at least three times  $D_{50}$ , as was used in the model experiments. Further research should be conducted to determine the effects of riprap gradation and layer thickness.

## CONCLUSIONS

A comparison of the results of small-scale laboratory studies indicates that the equation recommended by FHWA with slight adjustment to the factors used to accommodate pier turbulence are well suited for determining rock sizes to protect rectangular-nosed, cylindrical, and round-nosed bridge piers from scour. Factors to account for pier turbulence were recommended based on the results of the small-scale model studies. Recommendations for the application of the equations were provided.

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