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SUMMARY
The use of riprap to protect bridge piers against scour is considered. The four mechanisms of failure of riprap at bridge piers, i.e. shear failure, winnowing failure, edge failure and bed-form undermining, are discussed. A new design method for selecting riprap size is presented. The method, which is derived from many laboratory data, is based on the assumption that riprap failure occurs when the local scour depth at a riprap-protected pier exceeds 20% of the scour depth at the unprotected pier. The new method is compared with existing methods. The design of riprap protection at the Hutt Estuary Bridge in Wellington, New Zealand is discussed also. A physical model study was used as part of the design process for riprap protection at the Hutt Estuary Bridge.

1 INTRODUCTION

The most commonly employed method of protecting bridge piers against scour is the use of a layer of riprap around the piers. A U.S. field study reported 6000 cases of the use of riprap at bridge piers. The principle behind the use of riprap as a scour countermeasure is that large stones that are heavier than the river bed grains should be able to withstand the elevated shear stresses that occur around a bridge pier.

1.1 Riprap Failure Mechanisms

Four failure mechanisms of riprap layers at bridge piers can occur, as follows:

- Shear failure, where the riprap stones are entrained by the flow. Shear failure occurs where the armour units are unable to resist the hydrodynamic forces induced by the flow.
- Winnowing failure, where the finer underlying bed material is eroded through voids between the riprap stones under the action of turbulence and seepage flows. Winnowing is more likely to occur in sand-bed rivers than in coarser-bed materials. A filter layer, beneath the riprap layer, is often recommended to resist winnowing failure.
- Edge failure, where scouring at the periphery of the riprap layer undermines the armour stones. Riprap is vulnerable to edge failure if there is insufficient lateral extent of the protective layer.
- Bed-form undermining, where the riprap layer is undermined and settles with the migration past the pier of the trough of large dunes. Recent research (Melville, Lauchlan and Hadfield [10]; Lim and Chiew [9]; Parker, Toro-Escobar and Voigt [12]) indicates that bed-form undermining is the controlling failure mechanism at bridge piers founded in river beds subject to migration of dunes, especially sand-bed rivers. The settling of the riprap layer associated with bed-form undermining is significantly reduced with initial riprap placement at a depth of the order of the minimum expected trough level. With reduced settling of the riprap, the riprap layer remains reasonably intact. Conversely, a significant degree of settling is associated with destabilisation of the riprap layer due to the effects of the other failure mechanisms.

2 RIPRAP DESIGN FOR PIER PROTECTION

2.1 Stone Size

Most of the available methods for sizing riprap to protect bridge piers against scour can be expressed as follows:

$$\frac{d_{r50}}{y} = \frac{X}{(S_s - 1)^{\alpha}} Fr^{\beta} \tag{1}$$

where d_{r50} is the median size of the riprap stones; Fr is Froude Number of the approach mean flow = $V/(gy)^{0.5}$; V is mean velocity of flow; y is flow depth; g is acceleration of gravity; S_s is specific gravity of riprap stones; and X, α and β are coefficients. Amongst the various methods, α varies from 1 to 1.5, while β varies from 2 to 3. Some of the equations include factors for the effects of other influences on riprap stability, such as pier shape, pier size relative to riprap size and position of the pier in the channel.

The published equations are compared in Figure 1 over the range Fr = 0.2→0.6, with coefficients adopted for round-nose piers and S_s = 2.65. The methods of Chiew [5] and Parola [15] include an influence of the riprap size (d_{r50}) relative to the pier size (b). The methods by Austroads [1], Breusers et alia [3] and Croad [6] give very large riprap size, while that of Breusers and Raudkivi [4] gives very small riprap size. The Austroads [1] method is strongly dependent on the velocity factor, K_v, which varies with both the position of the pier in the channel and also whether the bridge is sited at a bend or otherwise. The values plotted in Figure 1 apply to a pier near the bank of a straight channel (K_v = 0.81) and a pier at the outside of a bend (K_v = 2.89). Chiew's [5] method can lead to both very large and very small riprap, depending on b/d_{r50}.

The remaining methods give riprap sizes within much narrower ranges, e.g. d_{r50}/y ranges from about 0.03→0.08 at Fr = 0.3, and from about 0.07→0.13 at Fr = 0.5, amongst the various methods. Lauchlan's

[8] method, which is plotted with the thick line, includes a parameter for the level of placement (Y_r) of the riprap within the sediment bed, which her study showed to be very significant. Given the lack of consistency amongst the methods, it is prudent to select a method that leads to conservatively large riprap relative to the other remaining methods. On this basis, the methods of Parola [14, 15], Richardson and Davis [18] and Lauchlan [8] are preferred. The method by Parola [14, 15], however, includes a significant influence of the pier size relative to the riprap size, b/d_{r50}, which is not present in the live-bed scour data measured by Lauchlan [8]. The expression presented by latter, given by the following equation, is recommended for selecting suitable riprap for bridge pier protection:

$$\frac{d_{r50}}{y} = 0.3S_f\left(1-\frac{Y_r}{y}\right)^{2.75} Fr^{1.2} \qquad (2)$$

where S_f is factor of safety, with a minimum recommended value of 1.1. Equation (2) is based on laboratory data using a failure criterion whereby the riprap was adjudged to have failed when the local scour depth at a protected bridge pier exceeded 20% of that at the same pier without riprap protection. The relation in equation (2) for the effect of placement level, i.e. $(1-Y_r/y)^{2.75}$, was determined also from laboratory data using the same failure criterion. Curves for different values of Y_r, based on equation (2), are given in Figure 2. It is demonstrated in Figure 2 that equation (2), with $Y_r = 0$ (i.e. riprap laid at bed level), is an envelope to many other published data. It should be noted that different failure criteria were applied amongst the various sets of data plotted, including failure defined by complete disintegration of the riprap. The "20% scour-depth" criterion adopted by Lauchlan [8] is the most rigorous criterion, consistent with her equation enveloping the other data.

2.2 Riprap Placement

Other important factors relating to riprap design are the thickness (t_r), horizontal extent, and placement level (Y_r) of the riprap layer. Figure 3 shows recommendations for these factors, based principally on recent studies by Lim and Chiew [9] and Lauchlan [8]. Parker, Toro-Escobar and Voigt [12] have shown that the use of a synthetic filter (or geotextile), placed below the riprap, is advantageous because the effects of winnowing failure are minimised. Their experiments demonstrate, however, that the synthetic filter should have lateral extent limited to about 75% of that of the riprap. With a full-coverage geotextile, edge failure of the riprap stones can result in roll-up of the edges of the geotextile leading to subsequent failure of the riprap layer. Typical recommendations for riprap grading, e.g. Croad [6], are as follows:

$$0.5d_{r\max} < d_{r50} < 2d_{r15} \qquad (3)$$

where $d_{r\max}$ is the largest stone size, and d_{r15} is the stone size for which 15% of the stones are finer by weight.

3 HUTT ESTUARY BRIDGE

3.1 Background

The design of riprap protection at the piers of the Hutt Estuary Bridge, near Wellington, New Zealand, is discussed in the following. The 5-span bridge is 179 m long and is sited about 1 km from the river mouth in Wellington Harbour. The bridge has a history of scour problems due to significant bed degradation, which occurred until recently, the degradation arising from uncontrolled gravel mining at several sites upstream. The piers are rectangular (1.1 m wide, 16.4 m long) with slab footings, the footings having been encased with steel caissons (5.5 m wide, 16.4 m long). The approximately 7.6 m deep caissons were installed to protect the piers against the bed degradation. Bed material is a coarse sand with median size d_{50} = 2 mm. Flood levels are controlled by associated sea levels at the river mouth. For the 1% AEP design flood, the flood level is 1.86 m above mean sea level (MSL). The general scour depth under the design flood was estimated, using the Blench [2] equation, at 4.1 m below MSL or 5.96 m below flood level. The corresponding flow velocity is V = 3.6 m/s. With a flow depth of y = 5.96 m following general scour, the tops of the caissons would be about 2.3 m above the scoured bed level. The method by Melville and Raudkivi [11] for local scour depth, predicts a total scoured depth of 13.1 m below flood level. On the basis of these calculations, it was recognised that the bridge would be seriously endangered in the design flood. A cross-section of a pier, showing the calculated scour depths, is given in Figure 4.

3.2 Model Study

A model study was undertaken to assess the requirements for riprap protection at the piers. The model comprised one pier, built to a scale of 1:20, and was tested in a 1.52 m wide laboratory flume using Froudian scaled flow parameters and a uniform sand of median size 0.8 mm. During preliminary testing, the model results were found to confirm the local scour depth calculations for the unprotected pier.

Riprap was selected based on the Lauchlan [8] equation (2) with $Y_r = 0$. For V = 3.6 m/s and y = 5.96 m, d_{r50p} = 724 mm, equivalent to a model size of 36.2 mm. Two sizes of riprap were used in the model, having median sizes, d_{r50m} = 35 mm and 28 mm, and grading satisfying the criteria of equation (3). Note that subscripts 'p' and 'm' refer to prototype and model, respectively. The riprap was placed according to the recommendations in Figure 3 (end radii = 1.5b, width = 3b), with the top surface flush with the undisturbed bed. Tests were conducted with the pier both aligned with the flow and also skewed at angle $\theta = 10°$ to the flow. Two thickness arrangements were tested. One arrangement featured $t_r = 2d_{r50}$ throughout the layer. For the other arrangement, the thickness of the riprap layer was increased to $3d_{r50}$ for the section of riprap upstream of the pier where it was observed that the worst scour occurred.

The results are shown in Table 1, which gives the percentage reduction in local scour depth, from that at the unprotected pier, afforded by the different riprap arrangements.

Test	d_{r50} (mm)	t_r	θ (°)	Percentage Scour Reduction (%)
1	35	$2d_{r50}$ throughout	0	71
2	35	$3d_{r50}$ upstr./ $2d_{r50}$ elsewhere	0	97
3	35	$2d_{r50}$ throughout	10	77
4	35	$3d_{r50}$ upstr./ $2d_{r50}$ elsewhere	10	88
5	28	$3d_{r50}$ upstr./ $2d_{r50}$ elsewhere	10	76

Table 1 Results for Model Tests of Riprap Protection at Hutt Estuary Bridge

For all tests, the scour reduction was significant. The riprap configuration for Test 4 was recommended. The riprap comprises a 1400 mm thick layer of 700 mm riprap thickened to 2100 mm upstream of the pier. The local scour depth is reduced 88% when the flow is skewed 10° to the axis of the pier. The recommended riprap configuration is illustrated in Figure 4.

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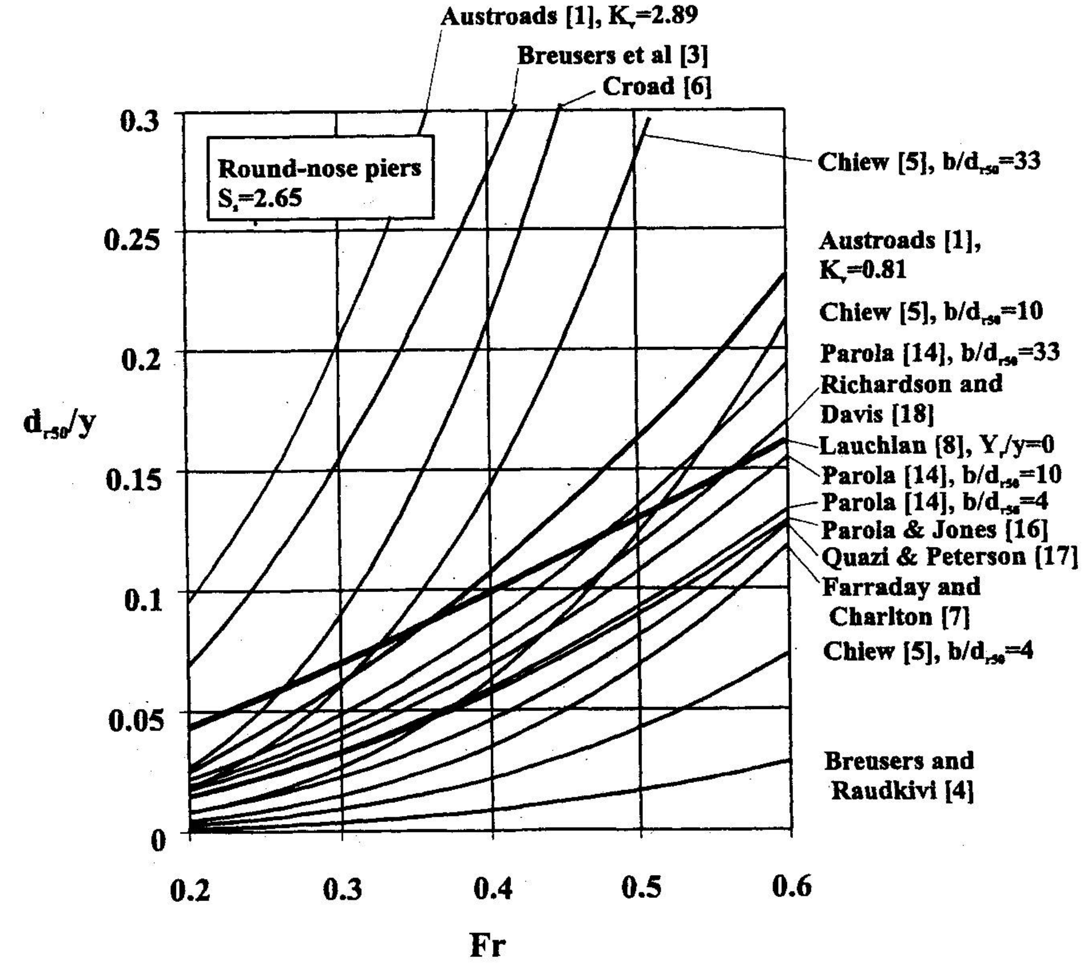

Figure 1 Comparison of Available Methods for Selecting Riprap Size at Bridge Piers

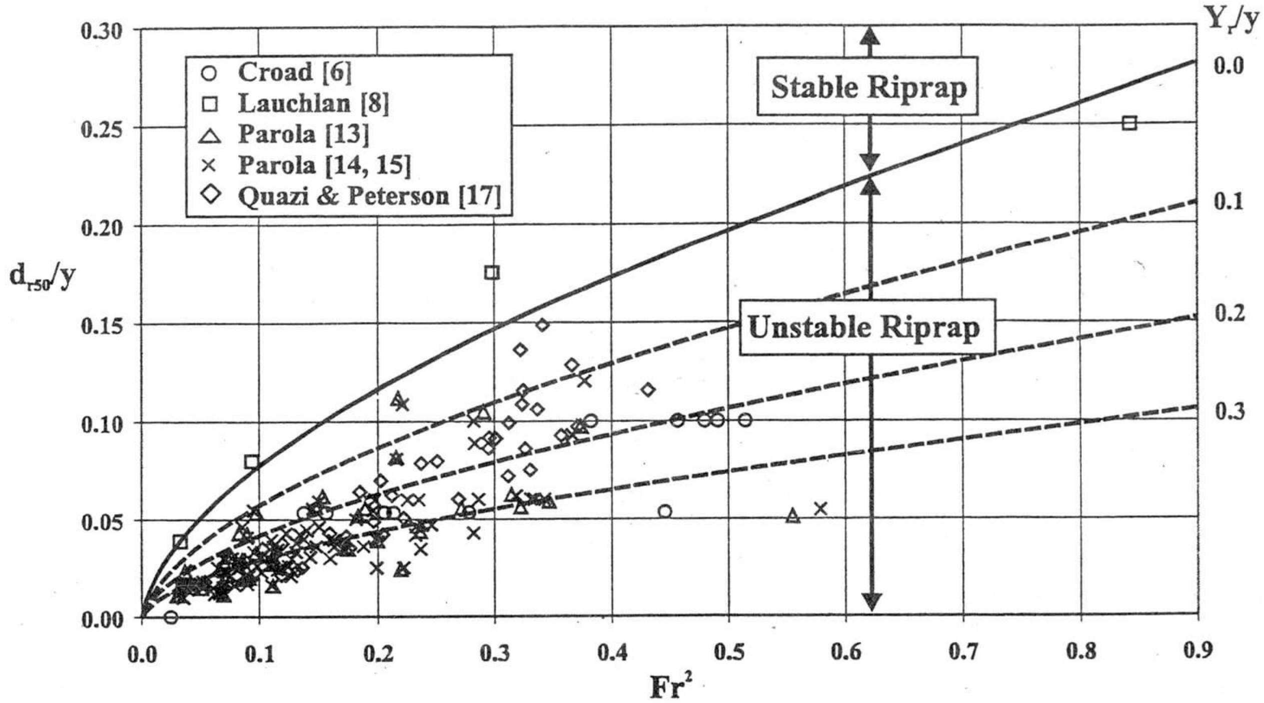

Figure 2 Design Curves for Riprap Size by Lauchlan [8]

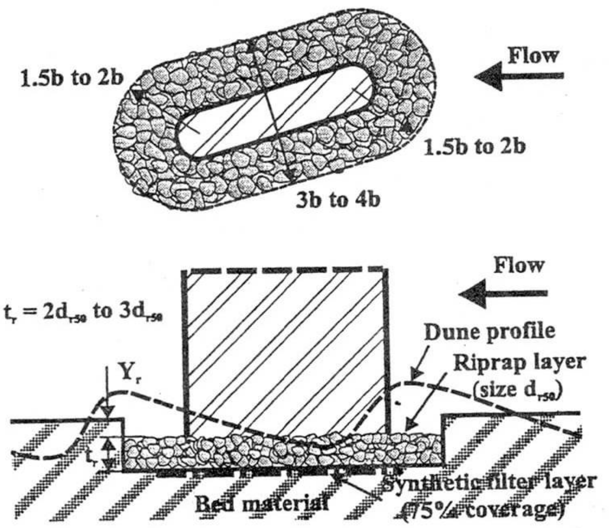

Figure 3 Riprap Placement Recommendations

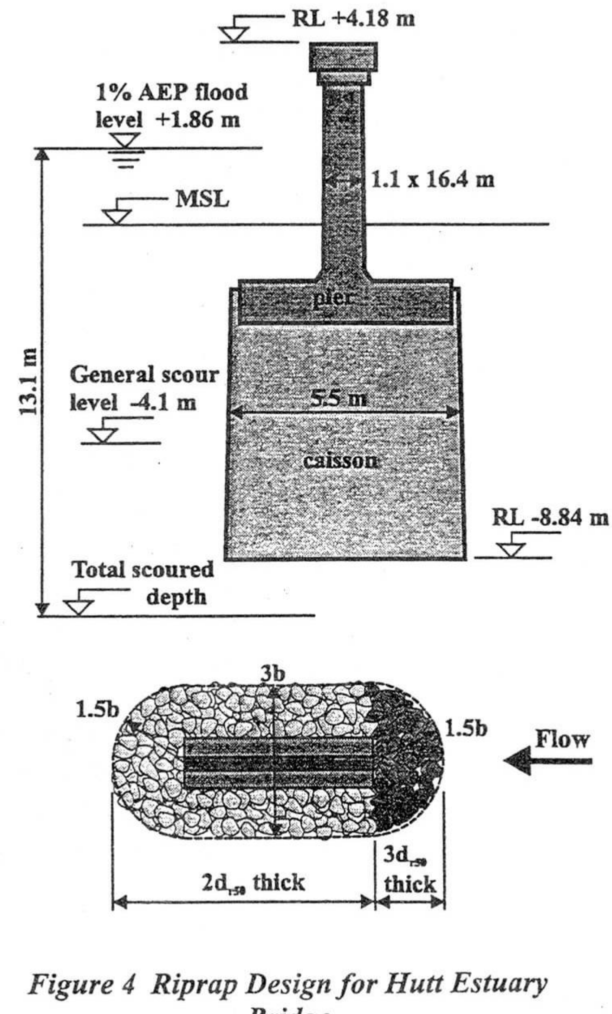

Figure 4 Riprap Design for Hutt Estuary Bridge