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Countermeasures for Scour at Spill-Through Bridge Abutments

By

Bruce Melville[1], Stephen Coleman[2], David Hoe[3]

ABSTRACT

Experimental data for the use of riprap and cable-tied blocks to protect the fill material at spill-through bridge abutments are presented, including data by Eve (1999) for riprap, and by Hoe (2001) for cable-tied blocks. The experiments were undertaken under clear-water conditions, which are relevant to bridge abutments situated in the floodplain.

Eve (1999) studied the use of riprap at spill-through bridge abutments under clear-water scour conditions. She determined that riprap is an effective protection for spill-through abutment fill material. A particular focus of the project was the use of an apron of riprap to protect the toe of the spill-through slopes. Based on her observations of progressive failure of the abutment embankments, she developed a relation for determining the extent of protection.

Hoe (2001) undertook similar investigations to those of Eve, using cable-tied blocks in place of riprap. The same experimental flume and abutment and flow configurations were used in both studies. Hoe determined that, although cable-tied blocks can offer protection to spill-through abutment fill material, the technique is probably inferior to the use of riprap.

INTRODUCTION

Protection of bridge abutments from scour includes countermeasures that alter flow and scour patterns and those that armour the bed, bank, floodplain and embankment slopes, such as riprap and cable-tied blocks. Armour protection frequently includes the coverage of susceptible portions of embankment slopes. Many design guidance documents recommend that an apron be constructed around the toe of the embankment slope. Armour aprons can protect vertical-wall abutments founded on spread footings. Filters have been recommended below the protection to prevent piping of soils through the armour layers. The filters also may be beneficial to prevent winnowing of soils from beneath aprons especially where the armour layer is used to protect embankments under live-bed conditions.

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Riprap as a Scour Countermeasure

Riprap is a commonly used technique to protect bridge abutments and bridge approach embankments from scour. The increased weight of the riprap stones enables them to resist the increased turbulence caused by the presence of the abutment and approach embankment structures in the flow, and thereby provide an armour layer protection to the underlying sediments. Interlocking forces between adjacent stones also act to stabilise the riprap layer. Typically, the riprap is placed on the embankment slopes to protect the embankment material from scour. Riprap can also be placed in an apron, sometimes referred to as a launching apron, to fall onto the sides of a developing scour hole. This riprap acts to reduce the scour depth, and protect the abutment foundation from undermining.

Riprap is subject to certain failure mechanisms, dependent on where it is placed in respect to the bridge abutment. Riprap placed in the apron is subject to similar failure mechanisms as riprap placed about a bridge pier, whereas riprap placed on the embankment slopes is subject to not only dislodgement by the flow, but also slump and slide failures where the riprap moves down the embankment slope.

Parola (1993), Chiew (1995) and Lauchlan (1999) identify four failure mechanisms for riprap placed in an apron, viz. shear failure, winnowing failure, edge failure, and bed-form undermining. Similarly, Blodgett and McConaughy (1985) identify the principal failure modes for riprap placed on sloping embankments. These are particle erosion failure, translational slide failure, and slump failure.

Equations for selecting the size of riprap for bridge abutment protection have been proposed by Simons and Lewis (1971), Croad (1989), Brown and Clyde (1989), Pagan-Ortiz (1991), Austroads (1994), Atayee et al. (1993) and Richardson and Davis (1995), among others. Many of these equations can be arranged into the form

$$\frac{D_{50}}{y} = \frac{C}{(S_r - 1)} Fr^2 \tag{1}$$

where D_{50} is median stone size, y is flow depth, S_r is specific gravity of the riprap stones, Fr is Froude Number of the approach flow and C is a coefficient.

A graphical comparison of the various equations for $S_r = 2.65$ is shown in Figure 1. It can be seen that the various equations give a wide range of recommended riprap sizes for a given flow. The equations given by Croad (1989) and Richardson and Davis (1995) give larger riprap sizes in comparison with the other equations, whereas the equations given by Brown and Clyde (1989) and Pagan-Ortiz (1991) give relatively smaller riprap sizes.

Cable-Tied Blocks as a Scour Countermeasure

Cable-tied blocks consist of concrete blocks or slabs interconnected with metal or non-metallic cables. The cables used can be fabricated from steel, copper or synthetic materials, such as polypropylene (Przedwojski et al, 1995). An example of cable-tied blocks is given in Figure 2.

A key feature of cable-tied blocks is the interconnecting of small units, which may be unstable as individual blocks, into a framework capable of withstanding much higher flow velocities. The term "cable-tied blocks" typically refers to relatively small units. Articulated concrete mattresses, which rely on the same principles, are larger units commonly used for bank protection.

Previous studies and experiments on the use of cable-tied blocks for scour protection of bridge foundations are limited and are focussed on bridge piers (McCorquodale et al., 1993; Bertoldi et al., 1996; Jones et al., 1995; Parker et al., 1998).

Parker et al. (1998) identify three possible failure mechanisms:

- Overturning and rolling-up of the leading edge, which is exacerbated if the edge is not anchored
- Uplift of the centre of the mat, which can occur where the mat edge is inadequately anchored
- Winnowing of sediment between the mat and the bridge pier, if the mat is not sealed tightly to the pier.

EXPERIMENTS

The experimental studies were conducted to investigate the use of riprap and cable-tied blocks to protect spill-through abutments against scour under clear-water conditions. In particular, the use of an apron to extend the protection beyond the toe of the spill-through abutment slope (as shown in Figure 3 for riprap experiments) was investigated. The experiments were conducted in a 2.4 m wide, 0.30 m deep and 16.5 m long wooden-sided recirculating flume. A sediment recess section, 0.45 m deep, is located 7.2 m from the upstream end of the channel. A uniform-bed sediment, with median size, $d_{50} = 0.85$ mm, was used in all experiments.

Full details of the experimental technique are given in Eve (1999) and Hoe (2001) for riprap and cable-tied block experiments, respectively. The spill-through embankment shape was constructed from the bed sediment using a mould of sheet metal. The sand was packed inside the mould, which was then removed. Two approach embankment mould lengths of 975 mm and 1175 mm were used for the riprap experiments, while only the shorter length was used for the cable-tied block experiments. The spill-through slopes had a rounded frontal section of 375 mm radius, were 250 mm tall, and featured side slopes of 1:1.5 (H:V).

The median sizes, D_{50}, of the three uniform riprap sizes used in the riprap experiments were 16.3, 21.5, and 27.8 mm. The riprap was placed on the embankment slopes to a thickness of $2D_{50}$. An apron of the dimensions required was placed on the bed around the embankment. Commercially-manufactured ceramic bathroom tiles, of dimensions 25 mm x 25 mm and 5 mm high, were used to represent the cable-tied blocks. A synthetic filter fabric was used in most of the cable-tied-block tests, Figure 4. All tests were conducted at the same flow depth (y = 150 mm), under clear-water conditions on the approach flow bed, with $V/V_c < 1.0$ (where V is mean velocity of flow and V_c is the mean velocity of flow at the threshold condition for sediment movement on the approach flow bed). For the riprap experiments, V/V_c was set at 0.73, while for the cable-tied block experiments, V/V_c varied from 0.66 to 0.98. The experiments were run for a maximum of 24 hours, if the abutment did not fail before this. Once a test was completed, the scour hole was profiled with string, laid at 50 mm intervals of depth, for photographic purposes.

Assessment of failure – riprap tests

The abutment and fill slopes were assessed for failure at the end of each riprap test. Criteria were developed to assess the failure, based on the ability of the abutment to continue to support a bridge foundation. The abutment was adjudged to have failed if the side slopes of the embankment fill material had shifted in any way. The three types of failure for riprap protection were:

- Total failure, where large-scale movement of sediment and riprap had occurred on the slopes of the fill material, the slope of the embankment having slumped, and large areas of embankment material having been exposed with no riprap protection.
- Partial failure, where riprap and sediment movement had been initiated in one part of the embankment, but a change in the embankment slope as a whole had not resulted. Typically partial failure was observed at the water level, with small numbers of riprap stones displaced a small distance down the embankment slope, and at the base of the embankment, if undermining of the toe had occurred.
- No failure, where no change could be seen in the embankment slope, and the sediment and riprap on the embankment slope had maintained their original position.

EXPERIMENTAL RESULTS

The configurations for the experiments, as well as the assessment of failure for each test, are summarised in Tables 1 and 2, for cable-tied block and riprap tests, respectively.

Riprap tests

For each riprap size, initial tests were carried out with an apron width of 300 mm, equal to $2y$, as recommended by most guidelines. The guidelines inherently assumed θ and ϕ values of zero, where θ and ϕ represent apron extent reductions on the downstream and upstream sides respectively, as shown in Figure 3. The apron width, W, was then reduced until a failure was observed. For the minimum apron size for which a failure did not occur, the apron coverage, in terms of θ and ϕ, was reduced until a full or partial failure was observed.

All riprap-protected abutments that failed exhibited the same failure mechanism. Undermining of the embankment toe lead to translational slide failure, where a mass of riprap stones moved down the embankment slopes. This resulted in a gentler slope, which eventually became stable. Tests conducted using the two smaller riprap materials also exhibited particle erosion failure, where the flow was able to entrain single stones from the riprap layer. Riprap stones displaced into the scour hole would be temporarily entrained by the strong turbulence in the scour hole region and moved small distances downstream. In this manner riprap stones were displaced to positions nearer to the position of maximum depth, thus slowing the development of the scour hole.

Reductions in scour depth of 38% to 63% were achieved by protecting the abutment with riprap, compared to the expected scour depth at an unprotected abutment, as estimated using the method of Melville and Coleman (2000). The scour depth decreased with increasing apron width and increasing riprap size. The greater the width of the apron, the greater the decrease in scour depth for an increase in riprap size. The position of the point of maximum scour depth also moved progressively away from the abutment with increasing apron size and riprap size.

For a riprap apron of W = 0.3 m, no abutments failed. A typical test result is shown in Figure 5. This would indicate that an apron width of twice the flow depth (2y) is adequate for abutment protection under clear-water conditions, and within the limits of these tests. However, the results show that this is a conservative solution. The apron width can be reduced, and the extent of the apron in terms of θ and ϕ can be reduced also. The results suggest that there is a relationship between the total area of apron and degree of protection. The suggested form of this relationship is shown in Figure 6, which shows a clear zone of partial failure. Note that the values for the tests using a 0.3-m apron have been omitted, to allow the remainder of the data points to be seen more clearly.

The variable on the y-axis of Figure 6 is $\left(\frac{A_u + A_d}{A_*}\right)\left(\frac{b-L}{b}\right)$, where A_u is the area of riprap protection of the apron on the upstream side of the abutment, and A_d is the equivalent area on the downstream side. A_* is the area of riprap protection as recommended by current guidelines ($W = 2y$), with θ and ϕ equal to zero. These areas exclude the riprap area on the embankment slope. The first term in this expression can be expressed in terms of the parameters W, y, θ, ϕ, and an additional parameter r, which is defined as the radius of the toe of the spill-through abutment. The second term is the contraction ratio (β) for the channel. The line shown in Figure 6, defining the failure limit, can then be expressed as

$$\frac{W}{y}\left(\frac{0.5W + r}{y + r}\right) = \left(0.5 - 1.82\frac{D_{50}}{y}\right)\frac{1}{\beta}\left(\frac{180}{180 - (\theta + \phi)}\right) \tag{2}$$

which reduces to the following expression for $\theta = \phi = 0$

$$\frac{W}{y}\left(\frac{0.5W + r}{y + r}\right) = \left(0.5 - 1.82\frac{D_{50}}{y}\right)\frac{1}{\beta} \tag{3}$$

Expressions (2) and (3) are presently limited to $0.1 < D_{50}/y < 0.2$.

Cable-tied block tests

For the cable-tied block experiments, the standard layout used in all experiments is shown in Figure 7. This layout did not provide adequate protection for flow conditions approaching $V/V_c = 1.0$. In an attempt to improve the protection, additional cable-tied blocks were added for the final three experiments of $V/V_c \to 1.0$, as shown in Figure 8.

The additional cable-tied block mat areas are defined in Table 1 in terms of their radial extent measured from the bridge axis, namely α_u (upstream extent) and α_d (downstream extent). These additional apron areas did improve the level of protection afforded by the cable-tied block mats.

The failure mechanisms that were observed for cable-tied block experiments involved one or more of the following types:

- Undermining of the outer edge of the apron as scour developed, leading to slumping of the fill material (translational slide failure) and potential failure (settlement) of the abutment. This was the predominant failure mechanism.
- Lateral movement of the cable-tied mat protecting the embankment slopes on the upstream side, exposing the fill material to surface erosion. Attaching the edge of the cable-tied block mat to the flume wall prevented this movement from occurring.
- Undermining of the upstream edges of the cable-tied block apron, leading to overturning (role-up) of the upstream edge and accelerated erosion of the underlying sand bed material.
- Winnowing of fill material through the gaps between blocks in the mat. The presence of the filter layer significantly reduced this loss of fill material.

The scour depth reductions achieved with the cable-tied blocks were significantly less than those achieved with riprap protection. In some cases, as shown in Table 1, the maximum scour depth increased in relation to that for an unprotected abutment. In all cases, however, the position of the point of maximum scour was deflected away from the abutment by the presence of the cable-tied block mats. The reason for the increases in scour depth is that the cable-tied block mats settled into the developing scour holes, rendering them larger flow obstructions than the equivalent unprotected embankments (Figure 11). In doing so, the cable-tied block mats maintained their overall shape. Conversely, the ability of riprap stones to settle and change their relative positions allowed the riprap protection to armour the developing scour holes and thus limit the overall scour development. This inability of cable-tied block mats to adjust, in the manner of riprap, as scour develops is perceived to be a significant limitation to their potential use. The possibility of employing cable-tied block protection to all or part of the fill slope, together with a protective apron of riprap, is worthy of further consideration.

The relative performance of riprap and cable-tied blocks is highlighted by comparing the results for riprap-Test 17 and cable-tied block-Test 4. For these tests, the experimental conditions were similar, the velocity ratios being 0.73 and 0.66, respectively. The scour depth reductions for these two tests were 42% and –11%, respectively. The scour developed in each of these tests is shown in Figures 9 and 10.

The level of protection required using cable-tied blocks increased with increasing flow velocity. The effect of increasing flow velocity is seen by comparing Tests 5 and 6, for which V/V_c = 0.80 and 0.86, respectively. Test 5 (Figure 11) was adjudged to be a success, because the fill material did not slump near the top of the fill slope and an abutment structure would not have failed. Conversely, Test 6 (Figure 12) was a failure because the fill material slumped near the crest.

CONCLUSIONS

The following conclusions are drawn from this study:

1. Riprap is an effective protection for spill-through abutment fill material under moderate clear-water scour conditions, pertinent to abutments situated on the floodplain. The ability of a riprap layer to settle into a developing scour hole and armour the base of the scour hole, is an important factor in the protection afforded.
2. Cable-tied blocks can offer protection to spill-through abutment fill material. This study has shown, however, that the technique is probably inferior to the use of riprap. The design of a protection system involving a combination of cable-tied blocks and riprap may lessen the disadvantages of the former technique.
3. Armour protection of bridge abutments and approach embankments, using either of these techniques, should extend around the end of the embankment and include an apron placed on the floodplain to protect the toe of the fill material.

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Table 1 - Experimental set-up and assessed failure for cable-tied block experiments

Test ID	**V/V_c (-)**	**L (mm)**	**Filter[1]**	**α_u (°)**	**α_d (°)**	**Failed[1]**	**Scour reduction (%)**
1	0.80	863	N	0	0	Y	-10
2	0.80	863	Y	0	0	Y	NA
3	0.66	863	N	0	0	N	-15
4	0.66	863	Y	0	0	N	-11
5	0.80	863	Y	0	0	N	27
6	0.86	863	Y	0	0	Y	22
7	0.86	863	Y	10	55	N	13
8	0.98	863	Y	10	55	Y	2
9	0.98	863	Y	55	55	Y	12

[1] Y = yes, N = no.

Table 2 - Experimental set-up and assessed failure for riprap experiments

Test ID	***V/V*$_c$ (-)**	***L* (mm)**	***D*$_{50}$ (mm)**	***W* (m)**	**θ (°)**	**ϕ (°)**	**Failed[1]**	**Scour reduction (%)**
16	0.73	863	16	0	0	0	Y	38
19	0.73	863	16	100	0	0	P	48
24	0.73	863	16	200	90	45	Y	49
22	0.73	863	16	200	90	0	N	52
23	0.73	863	16	200	45	45	N	55
21	0.73	863	16	200	60	0	N	41
20	0.73	863	16	200	45	0	N	42
18	0.73	863	16	200	0	0	N	42
17	0.73	863	16	300	0	0	N	42
10	0.73	863	22	0	0	0	Y	38
26	0.73	863	22	100	45	45	Y	41
25	0.73	863	22	100	45	0	P	55
14	0.73	863	22	100	0	0	N	49
15	0.73	863	22	200	0	0	N	55
13	0.73	863	22	300	0	0	N	49
1	0.73	863	28	0	0	0	Y	52
34	0.73	863	28	100	45	45	P	55
33	0.73	863	28	100	0	0	N	54
8	0.73	863	28	300	0	0	N	63
30	0.73	1063	16	100	45	0	Y	57
29	0.73	1063	16	100	0	0	P	56
28	0.73	1063	22	100	45	0	P	55
27	0.73	1063	22	100	0	0	N	55
32	0.73	1063	28	100	45	0	N	60
31	0.73	1063	28	100	0	0	N	60

[1] Y = yes, P = partial, N = no.

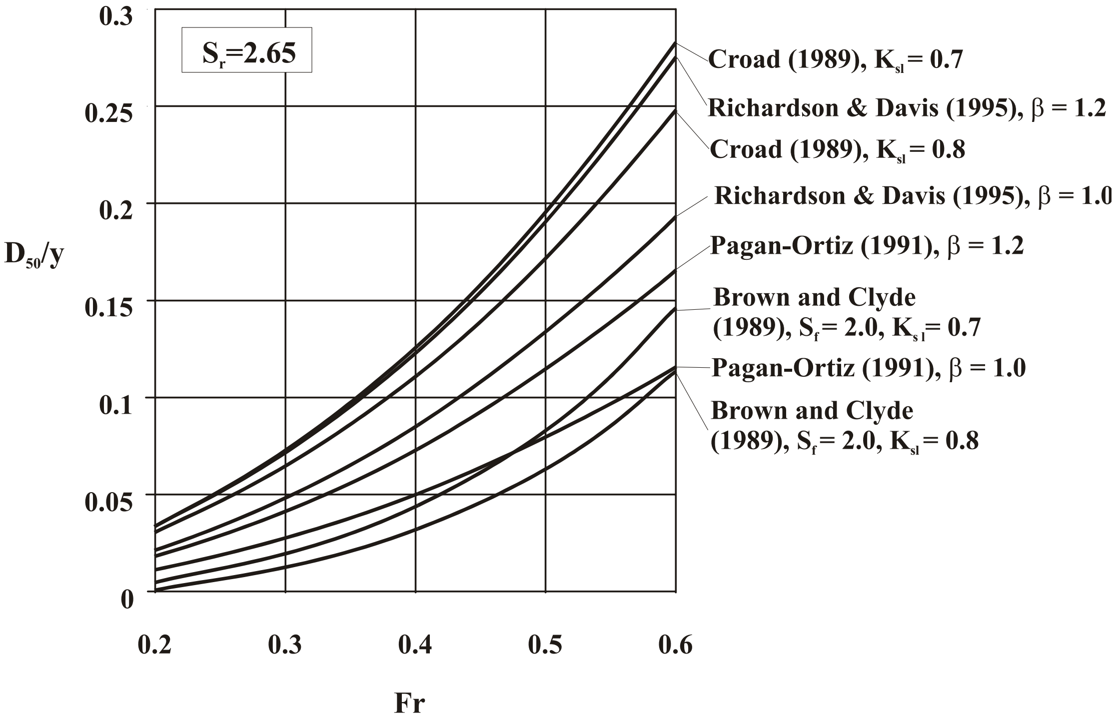

Figure 1 - Comparison of equations for riprap sizing at bridge abutments

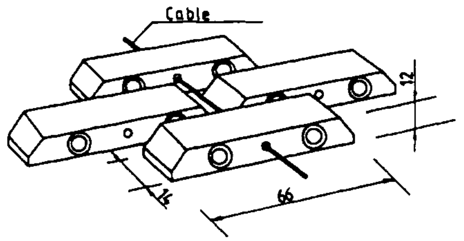

Figure 2 - Cable-tied blocks used as bank protection (Przedwojski et al, 1995)

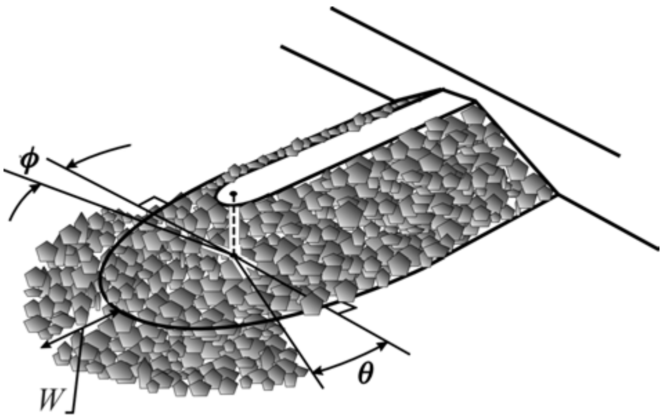

Figure 3 – Variables defining the geometry of a spill-through abutment and riprap layer

Figure 4 – The filter fabric placed over the sand embankment ready for placement of cable-tied blocks

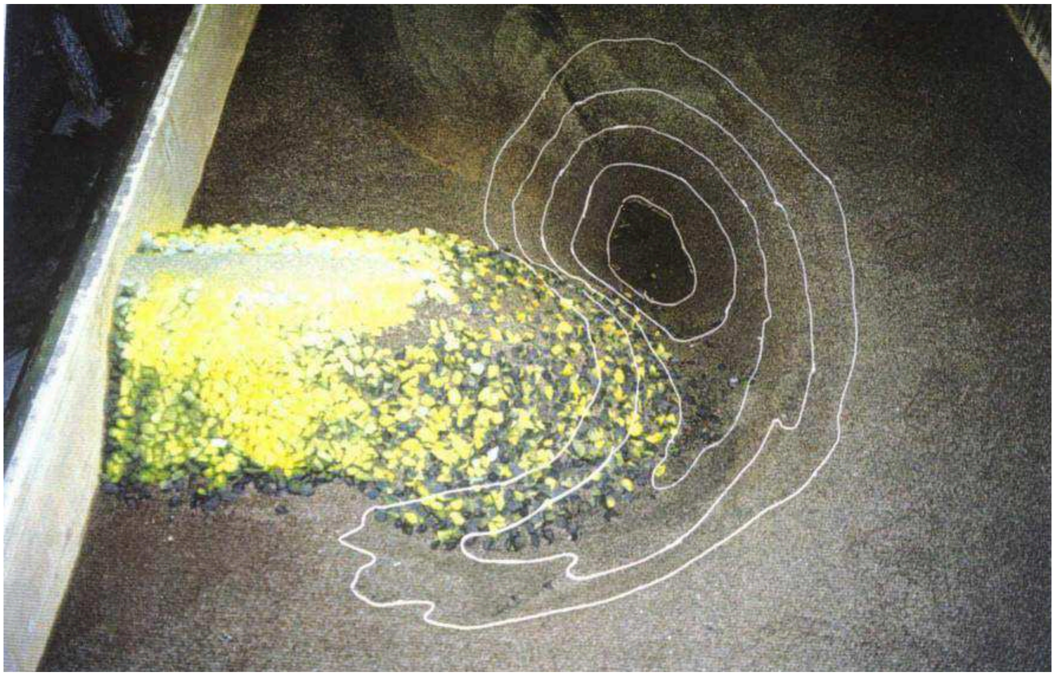

Figure 5 – Typical scour hole developed at an abutment (of no failure) with riprap protection, viewed from downstream

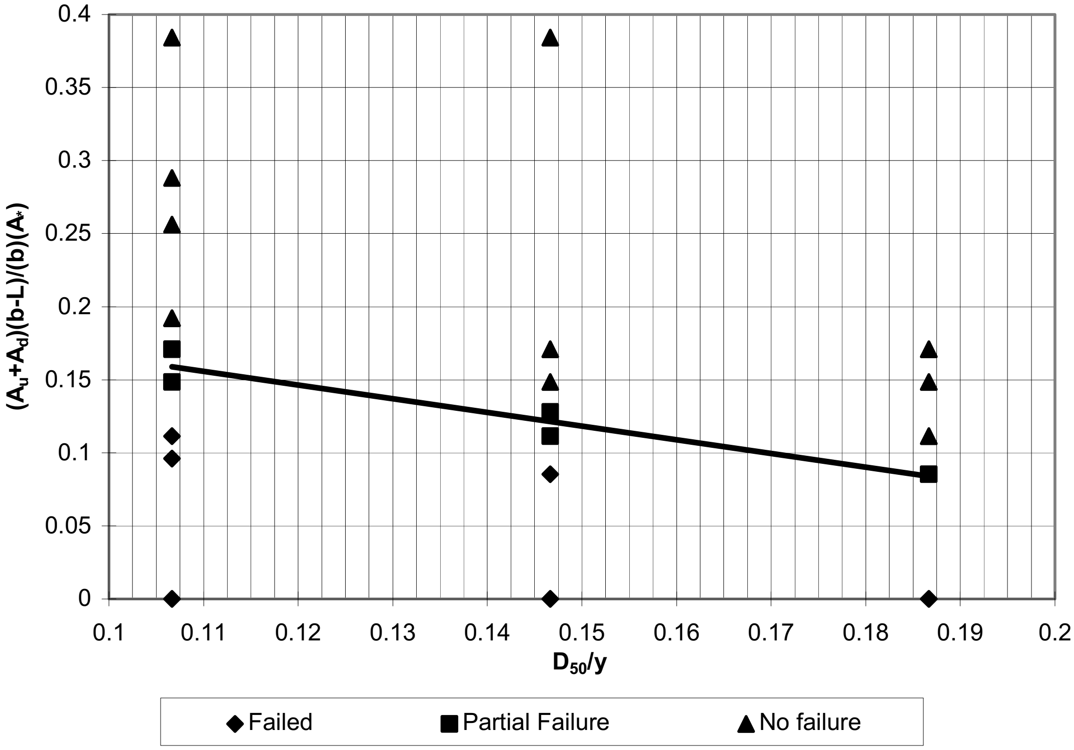

Figure 6 - Relationship between apron extent and riprap size.

Figure 7 – The standard apron used in all cable-tied block tests

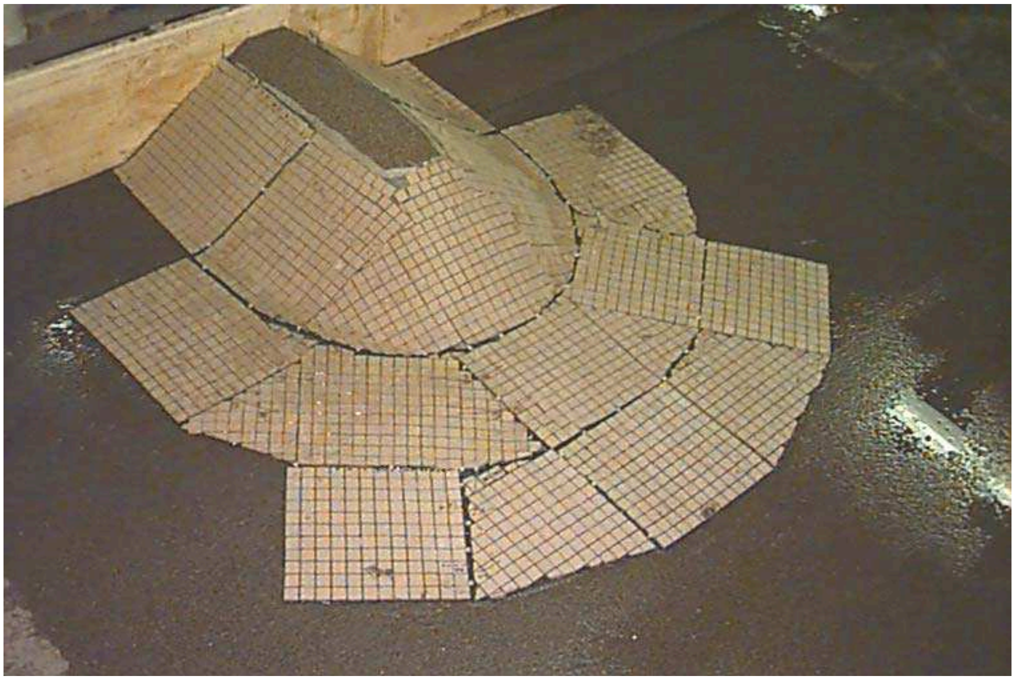

Figure 8 – Additional cable-tied block apron protection, for $V/V_c \rightarrow 1.0$

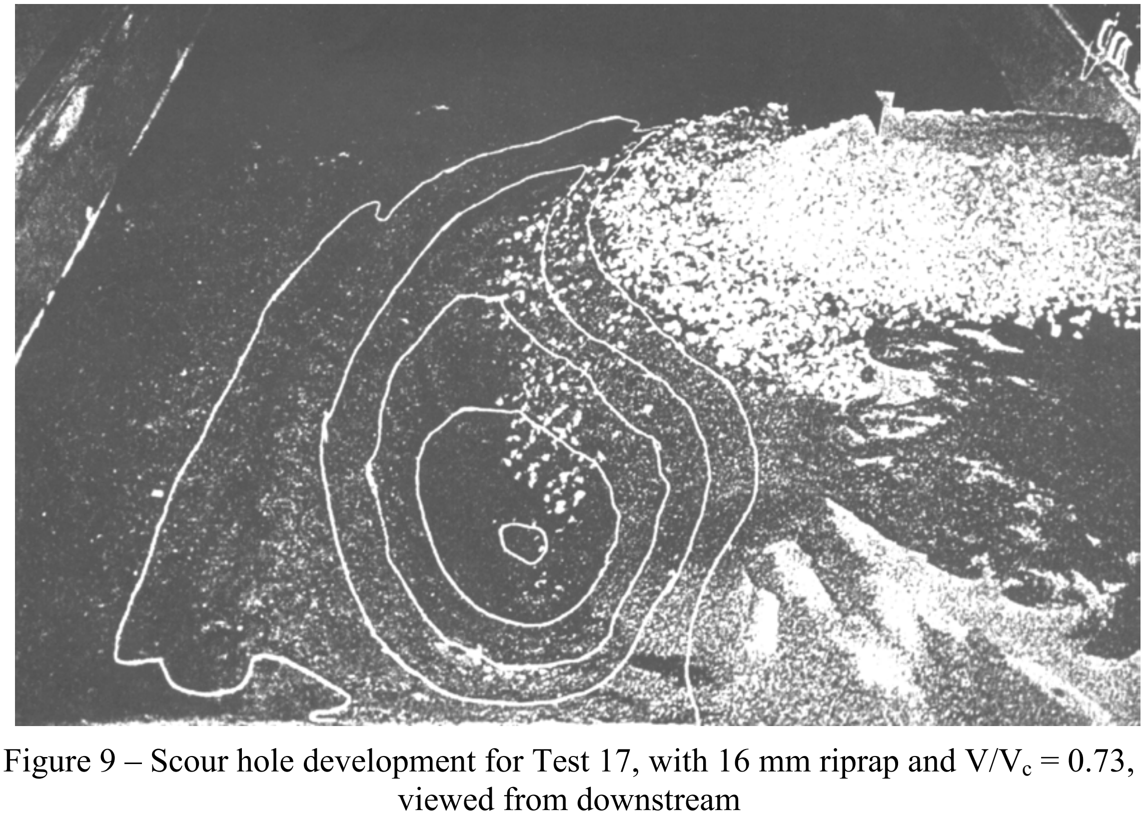

Figure 9 – Scour hole development for Test 17, with 16 mm riprap and $V/V_c = 0.73$, viewed from downstream

Figure 10 – Scour hole development for Test 4 using cable-tied blocks, with $V/V_c = 0.66$, viewed from downstream

Figure 11 – Typical scour hole development for cable-tied block protection (Test 5), viewed from downstream. In this test, the protection was deemed not to have failed

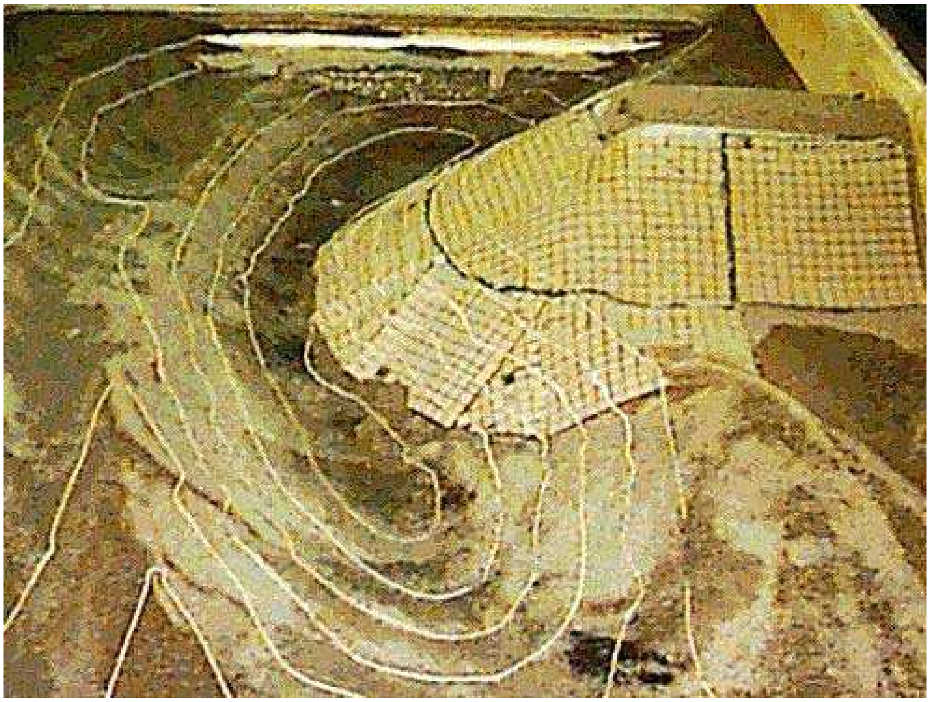

Figure 12 - Typical scour hole development for failed cable-tied block protection (Test 6), viewed from downstream. The failure was due to slumping of the fill material near the top of the embankment