RIPRAP AND CABLE-TIED BLOCK PROTECTION FOR SPILL-THROUGH ABUTMENTS *

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An experimental study of scour countermeasures for spill-through abutments situated on the flood plain of a compound channel is reported. The purpose of the study was to determine the variations in the scour hole geometry under clear water conditions, by varying the compound channel and abutment geometries, and the level and type of armoured scour countermeasure protection provided. This approach avoids one of the inherent difficulties in conducting scour countermeasure experimental work, that is the subjectivity of determining whether the countermeasure used in the experiment is a success or a failure. Riprap and cable-tied block countermeasures are incorporated.

The results show that for most cases, as the countermeasure apron width is increased, the scour hole is deflected further away from the abutment and reduces in size. However, for abutment and compound channel configurations where the scour hole forms close to the main channel bank, the size of the scour hole is relatively unaffected by apron width. With increasing flood plain width, the scour hole increases for most cases, because less flow is diverted into the main channel upstream of the abutment. The results also show that cable-tied block mats allow the scour hole to form closer to the abutment than equivalent riprap aprons, and result in deeper scour holes. The project represents an improvement on the current, rather-simplified practice of providing aprons of fixed width equal to twice the flow depth. The results enable determination of the local equilibrium scour formation for an abutment in question, for any level and type of armoured scour countermeasure protection.

1 Introduction

Scour countermeasures are used to protect bridge foundations from scour, mainly by inhibiting scour development at bridge piers and abutments. Rock riprap is the most common type of scour protection used at bridge abutments and approach embankments. Despite the widespread use of rock riprap, the guidelines for its use are based on limited research. Numerous alternative scour countermeasures now exist; one of the more recent developments being cable-tied blocks. Cable-tied blocks comprise concrete blocks interconnected by stainless steel cable, giving a flexible concrete mattress. As a scour countermeasure, they have the advantage of ease of construction, minimal encroachment into the river channel, and a lower tonnage than riprap per unit area covered.

2 Present Study

One of the difficulties in conducting scour countermeasure experiments is the subjectivity of determining whether the countermeasure used in the experiment is a success or a failure. A series of experiments was conducted in a 2.4-m wide flume to measure the equilibrium scour hole formation at an abutment with countermeasures in place, Figure 1. The extent of protection, W, the length of the abutment and bridge

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approach embankment, L, and the width of the flood plain, B_f, were systematically varied. The scour hole geometry, which varied according to the type and extent of protection around the abutment, was analysed in terms of the following equation by Melville and Coleman (2000) for the scour depth at an unprotected bridge abutment

$$d_s = K_{yL} K_I K_d K_s K_\theta K_G K_t \tag{1}$$

where the K's are empirical expressions accounting for the various influences on scour depth: K_{yL} = depth-size; K_I = flow intensity; K_d = sediment size; K_s = abutment shape; K_θ = abutment alignment; K_G = channel geometry; and K_t = time.

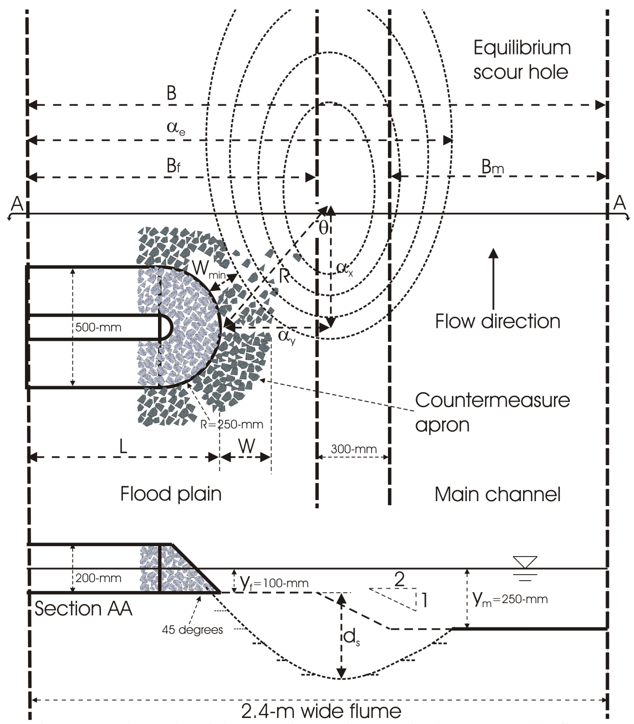

Figure 1. Schematic of the experimental set-up in the 2.4-m-wide flume.

Uniform flow was established along the length of the flume with a flow depth of 100-mm on the flood plain, and 250-mm in the main channel. The flow field was measured in the test section of the compound channel using a particle tracking velocimetry technique. The flow distribution across the flume was adjusted at the inlet so that there was no net transfer of flow over the main channel bank boundary. Average flow velocity in the main channel was set to the threshold condition for sediment movement, while average velocities on the flood plain were typically about 90% of threshold.

The compound channel comprised a fixed-bed main channel, an erodible sand-bed flood channel and, in the test section, riprap protection to the bank of the main channel. The latter was necessary to prevent erosion of the main channel bank, which would have occurred in the absence of an abutment structure, due to the influence of the bank slope. The sand used for the flood plain, test section and spill-through abutment was uniform-sized with median diameter d_{50} = 0.82-mm and specific gravity of 2.65. Uniform-sized riprap stones (D_{50} = 20-mm) were carefully placed to a thickness of $1.5D_{50}$, equivalent to two riprap layers. A filter fabric with a pore space of 0.2-mm was placed over the tip of the abutment, and covered with riprap or cable-tied blocks. The filter layer was also placed beneath the horizontal apron for cable-tied block protection, but not for riprap protection because this could induce edge failure of the riprap. The cable-tied blocks had the shape of a square truncated pyramid with base dimensions 25x25-mm, height 10-mm and density 2084-kg/m^3. The blocks were glued onto shade cloth matting to simulate the blocks being tied together with cables.

Initially, experiments were run with no apron protection (W = 0). Instead, the spill-slope protection was extended below the surface of the flood plain to a depth greater than the expected scour hole depth to protect the toe of the abutment. Next, experiments were run using a 0.5-m-wide apron (Figure 2), and thereafter the aprons were successively reduced in size by 0.1-m until the edge of the equilibrium scour hole occurred adjacent to the abutment. Thus, all data apply to the case of "no failure" of the abutment and approach embankment. For experiments where the scour hole would encroach on the main channel bank, the riprap stones lining the main channel bank were removed just before they were about to fall into the scour hole. In this way the scour hole formation was not affected by the riprap protection to the main-channel bank.

Figure 2. Experimental set-up of a 0.6-m-long abutment protected by a 0.5-m-wide apron situated on a 1.6-m-wide flood plain. Left; CTB apron. Right; riprap apron.

All experiments were run for 72-hours to ensure that the local scour hole had reached equilibrium conditions. At the conclusion of each experiment, the resulting scour hole formation was contoured in 50-mm increments for photographic purposes. The coordinates of the deepest point of the scour hole α_x and α_y, the depth of the scour hole relative to the flood plain d_s, the position of the outer edge of the scour hole α_e, and the minimum distance between the edge of the scour hole and the abutment W_{min} were measured (Figure 1 and Table 1). In the analysis, the position of the centre of the scour hole is defined by R and θ, which are simply obtained from α_x and α_y. An expression is given below for R, while θ was found to be invariably about 30°.

Table 1. Equilibrium scour hole parameters (in metres).

B_f	L	W	Riprap Protection					Cable-tied Block Protection				
			α_x	α_y	d_s	α_e	W_{min}	α_x	α_y	d_s	α_e	W_{min}
0.8	0.4	0.0	0.62	0.25	0.20	0.98	-	-	-	-	-	-
0.8	0.4	0.1	0.66	0.29	0.19	0.99	0.00	-	-	-	-	-
0.8	0.4	0.2	0.79	0.35	0.19	1.00	0.07	0.48	0.19	0.21	0.95	0.00
0.8	0.4	0.3	0.88	0.43	0.21	1.08	0.17	0.58	0.26	0.24	0.99	0.05
0.8	0.4	0.4	0.96	0.53	0.29	1.23	0.25	0.62	0.38	0.28	1.10	0.10
0.8	0.4	0.5	1.05	0.56	0.28	1.35	0.31	0.69	0.41	0.26	1.15	0.16
0.8	0.6	0.0	0.78	0.32	0.36	1.43	-	-	-	-	-	-
0.8	0.6	0.3	1.00	0.50	0.33	1.60	0.01	-	-	-	-	-
0.8	0.6	0.4	1.04	0.55	0.38	1.73	0.06	0.64	0.46	0.37	1.53	0.00
0.8	0.6	0.5	1.08	0.43	0.37	1.81	0.14	0.74	0.41	0.39	1.62	0.10
0.8	0.8	0.0	0.85	0.44	0.44	2.02	-	-	-	-	-	-
0.8	0.8	0.5	0.90	0.70	0.40	2.20	0.00	0.76	0.46	0.42	2.04	0.00
1.2	0.4	0.0	0.38	0.18	0.16	0.86	-	-	-	-	-	-
1.2	0.4	0.1	0.45	0.26	0.16	1.01	0.04	-	-	-	-	-
1.2	0.4	0.2	0.65	0.29	0.16	1.07	0.12	0.30	0.19	0.19	0.95	0.02
1.2	0.4	0.3	0.78	0.36	0.10	1.12	0.25	0.42	0.28	0.18	1.01	0.06
1.2	0.4	0.4	0.86	0.41	0.08	1.18	0.38	0.53	0.32	0.17	1.10	0.20
1.2	0.4	0.5	1.05	0.41	0.07	1.30	0.47	0.70	0.36	0.13	1.23	0.38
1.2	0.6	0.0	0.50	0.22	0.25	1.26	-	-	-	-	-	-
1.2	0.6	0.2	0.65	0.41	0.28	1.36	0.01	-	-	-	-	-
1.2	0.6	0.3	0.81	0.56	0.30	1.48	0.18	0.38	0.25	0.30	1.31	0.00
1.2	0.6	0.4	0.92	0.60	0.32	1.54	0.28	0.48	0.37	0.32	1.40	0.07
1.2	0.6	0.5	1.03	0.65	0.33	1.61	0.35	0.54	0.48	0.30	1.48	0.13
1.2	0.8	0.0	0.80	0.44	0.32	1.63	-	-	-	-	-	-
1.2	0.8	0.3	0.99	0.55	0.37	1.84	0.01	-	-	-	-	-
1.2	0.8	0.4	1.10	0.69	0.39	2.00	0.13	0.62	0.44	0.38	1.72	0.01
1.2	0.8	0.5	1.12	0.73	0.40	2.10	0.21	0.76	0.51	0.41	1.90	0.09
1.6	0.4	0.0	0.45	0.23	0.21	1.06	-	-	-	-	-	-
1.6	0.4	0.1	0.60	0.29	0.21	1.09	0.01	-	-	-	-	-
1.6	0.4	0.2	0.75	0.44	0.21	1.26	0.07	-	-	-	-	-
1.6	0.4	0.3	0.79	0.44	0.22	1.28	0.17	0.43	0.26	0.22	1.11	0.03
1.6	0.4	0.4	0.87	0.48	0.20	1.35	0.28	0.52	0.35	0.20	1.24	0.15
1.6	0.4	0.5	1.01	0.53	0.21	1.39	0.39	0.64	0.44	0.22	1.31	0.25
1.6	0.6	0.0	0.50	0.27	0.29	1.47	-	-	-	-	-	-
1.6	0.6	0.2	0.79	0.49	0.31	1.60	0.02	-	-	-	-	-
1.6	0.6	0.3	0.83	0.53	0.30	1.68	0.15	0.36	0.28	0.31	1.39	0.00
1.6	0.6	0.4	0.95	0.58	0.27	1.71	0.23	0.53	0.33	0.30	1.50	0.05
1.6	0.6	0.5	1.01	0.72	0.26	1.77	0.35	0.62	0.38	0.28	1.63	0.15
1.6	0.8	0.0	0.61	0.33	0.32	1.69	-	-	-	-	-	-
1.6	0.8	0.2	0.82	0.51	0.33	1.78	0.00	-	-	-	-	-
1.6	0.8	0.3	0.88	0.65	0.38	1.95	0.09	-	-	-	-	-
1.6	0.8	0.4	1.06	0.75	0.40	2.06	0.21	0.40	0.36	0.36	1.80	0.00
1.6	0.8	0.5	1.12	0.78	0.39	2.12	0.32	0.63	0.40	0.35	1.85	0.07

2.0	0.4	0.0	0.47	0.19	0.20	0.96	-	-	-	-	-	-
2.0	0.4	0.1	0.53	026	0.19	1.00	0.00					
2.0	0.4	0.2	0.64	0.31	0.18	1.08	0.11					
2.0	0.4	0.3	0.77	0.37	0.16	1.13	0.25					
2.0	0.4	0.4	0.96	0.38	0.12	1.19	0.38					
2.0	0.4	0.5	1.04	0.40	0.11	1.21	0.48					
2.0	0.6	0.0	0.54	0.24	0.26	1.42	-	-	-	-	-	-
2.0	0.6	0.2	0.63	0.43	0.26	1.51	0.03					
2.0	0.6	0.3	0.72	0.50	0.27	1.61	0.18					
2.0	0.6	0.4	0.81	0.53	0.26	1.70	0.29					
2.0	0.6	0.5	0.88	0.62	0.25	1.75	0.41					
2.0	0.8	0.0	0.58	0.18	0.29	1.72	-	-	-	-	-	-
2.0	0.8	0.3	0.72	0.58	0.30	1.89	0.12					
2.0	0.8	0.4	0.80	0.60	0.30	1.99	0.22					
2.0	0.8	0.5	0.99	0.72	0.31	2.09	0.32					

3 Results

The compound channel geometry was found to have a significant influence on the scour development. Two different cases of scour development were identified, depending on the scour location in relation to the boundary between the main and flood channels:

- Case I: the scour hole formed entirely on the flood plain ($\alpha_e < B_f$), and
- Case II: the scour hole extended beyond the flood plain onto the main channel bank and, in some cases, into the main channel ($\alpha_e > B_f$).

For Case I, the scour hole tends to reduce in size when it forms further away from the abutment, this occurring for wider apron protection and also for relatively smaller B_f. Conversely for Case II, the scour hole is reasonably constant in size, irrespective of where it forms.

Several of the factors in Equation 1 were maintained constant in this study, viz. $K_I = K_d = K_t = 1$ and $K_s = 0.5$, and are therefore excluded from the analysis. In addition, a new factor K_a is incorporated to represent the effects of the extent of the apron protection. Thus, Equation 1 is expressed as

$$d_s = 0.5K_{yL}K_GK_a \tag{2}$$

Generalized expressions for K_{yL}, K_G and K_a are given below, where the former is in the same form as that proposed by Melville and Coleman (2000) and new expressions are proposed for K_G and K_a. The new expression for K_G gives better definition for this factor for the situation where the abutment is sited on the flood plain (between Cases C and D as defined by Melville and Coleman, 2000).

Two other important parameters derived from this study are R and W_{min}. Knowledge of d_s, R, θ and W_{min} allows investigation of the integrity of a spill-through abutment, by undertaking a geotechnical slope stability analysis. A full regression analysis was applied to the data to derive empirical relationships for R, α_e, d_s and W_{min}, in terms of the independent variables L, B_f, B, y_f and W, as follows

$$\frac{R}{y_f} = \left[m\left(\frac{L}{y_f}\right)^n \right] \left(1 + \frac{L}{B_f}\right)^p \left(\frac{B_f}{B}\right)^q \left(1 + \frac{W}{y_f}\right)^r \qquad (3)$$

$$\frac{\alpha_e}{y_f} = \left[m\left(\frac{L}{y_f}\right)^n \right] \left(1 + \frac{L}{B_f}\right)^p \left(\frac{B_f}{B}\right)^q \left(1 + \frac{W}{y_f}\right)^r \qquad (4)$$

$$\frac{d_s}{y_f} = 0.5 \left[m\left(\frac{L}{y_f}\right)^n \right] \left(1 + \frac{L}{B_f}\right)^p \left(\frac{B_f}{B}\right)^q \left(1 + \frac{W}{y_f}\right)^r \qquad (5)$$

$$\frac{W - W_{min}}{W} = \left[m\left(\frac{L}{y_f}\right)^n \right] \left(1 + \frac{L}{B_f}\right)^p \left(\frac{B_f}{B}\right)^q \left(1 + \frac{W}{y_f}\right)^r \qquad (6)$$

Values of the coefficients in Equations 3 to 6 are given in Table 2. The flow depth y_f was chosen to normalize the dependent parameters to be consistent with the scour relationships given by Melville and Coleman (2000). Similarly, the term L/y_f is consistent with the approach adopted by Melville and Coleman (2000). The other terms in Equations 3, 4 and 6 represent, in turn: the encroachment of the abutment across the flood plain ($1+ L/B_f$); the relative width of the flood plain (B_f/B); and the apron extent relative to flow depth ($1+W/y_f$). The parameter ($W-W_{min}$)/W represents the fraction of the apron, which is undermined during the scour process. Equations 3 to 6 are limited by the data to the case where $y_f/y_m = 0.4$, $W/y_f < 5$ and $4 < L/y_f < 8$.

Table 2. Empirical K factors for the various influences on the local scour hole parameters.

Scour hole parameter			K_{yL} $m\left(\frac{L}{y_f}\right)^n$		K_G $\left(1+\frac{L}{B_f}\right)^p\left(\frac{B_f}{B}\right)^q$		K_a $\left(1+\frac{W}{y_f}\right)^r$
			m	**n**	**p**	**q**	**r**
R	CTB		0.96	0.28	-.05	-0.18	0.84
	Riprap		3.48				0.36
α_e	CTB		3.62	0.40	1.13	0.36	0.29
	Riprap		5.27				0.13
d_s	CTB	$\alpha_e<B_f$	2.00	0.50	1.86	0.92	0
		$\alpha_e>B_f$			1.04	0.06	-0.10
	Riprap	$\alpha_e<B_f$			0.78	0.57	-0.08
		$\alpha_e>B_f$			0.64	0.10	0.01
W_{min}	CTB	$\alpha_e<B_f$	0.52	2.29	-7.18	-1.00	-1.67
		$\alpha_e>B_f$		0.91	-0.31	–0.44	–0.83
	Riprap	$\alpha_e<B_f$	0.20	3.20	-10.3	-1.42	-1.75
		$\alpha_e>B_f$		0.93	2.23	–0.32	–1.22

In Equations 3 to 6, the first term in square brackets represents abutment size-flow depth effects (K_{yL}), the second and third terms together represent compound channel geometry effects (K_G, for Cases C and D as above), while the last term represents apron extent effects (K_a). Deliberately, Equations 3, 4 and 6 are written in the same form as Equations 2 and 5, ensuring consistency both within this study and also with the method of Melville and Coleman (2000). As a consequence, it will be possible to incorporate other scour development effects in the set of equations, e.g. for time (K_t) and alignment (K_θ) effects.

In the case of a rectangular channel ($B_f = B$), the channel geometry factors tend to unity for L/B_f very small, to be consistent with Case C of Melville and Coleman (2000). For $W \rightarrow 0$, $K_a \rightarrow 1$. For $W = 0$ (or an inadequate apron extent, i.e. W_{min} negative), Equations 3 to 5 were derived from experiments in which the spill-slope protection was extended below bed level, as noted above.

Referring to Equations 3 and 4, R and α_e both increase with L and W. Increasing W deflects the scour hole further away from the abutment and out towards the main channel, while increasing L causes the scour hole to be larger as well as being deflected further towards the main channel. R decreases slightly with increasing B_f and α_e increases slightly with increasing B_f, because larger scour holes form for equivalent abutments on wider flood plains as discussed below. When cable-tied block aprons are used, the scour hole forms closer to the abutment (compared to equivalent riprap aprons), decreasing R and α_e. The difference in behaviour is attributed to the capacity for riprap to continue to afford protection after the edge of the apron is undermined. This deflects the deepest point of scour further away from the abutment.

Equation 5 shows that d_s increases with L as expected. For Case I ($\alpha_e < B_f$), d_s increases with B_f and decreases with W. The latter trend is expected due to the greater protection afforded by a wider apron, while the increase with B_f is due to a compound channel geometry effect. The flow velocity at the abutment tip was observed to be higher for the same abutment situated on wider flood plains. With a narrow flood plain, part of the flow on the flood plain that is obstructed by the abutment is diverted much further upstream from the abutment towards and into the main channel, than for the equivalent abutment on a wider flood plain (van Ballegooy et al, 2004). This compound channel effect of increasing d_s with increasing B_f for the case where $\alpha_e < B_f$, can be interpreted as being consistent with the work of Sturm et al. (1994). Because cable-tied block aprons allow the scour hole to form closer to the abutment, less protection is provided compared to equivalent riprap aprons, resulting in deeper scour holes, as discussed above. For Case II ($\alpha_e > B_f$), d_s decreases with B_f, and is relatively unaffected by W and protection type. The former effect is a consequence of the abutment being further from the main channel bank.

Referring to Equation 6, W_{min} decreases with increasing L. This effect arises because longer abutments cause larger scour holes to form, causing more riprap from the outer edge of the apron to fall into the scour hole, or more material to be undermined from beneath the cable-tied block aprons. Also, W_{min} increases with increasing W, because the scour hole is deflected further away from the abutment. For Case I ($\alpha_e < B_f$), W_{min} decreases with increasing B_f, because larger scour holes form for equivalent abutments on wider flood plains, undermining more material from beneath the aprons.

For Case II ($\alpha_e > B_f$), W_{min} increases with B_f because the abutment is set back further from the edge of the main channel bank. For both cases cable-tied block aprons allow the scour hole to form closer to the abutment, reducing W_{min} considerably compared to equivalent riprap aprons.

When the value of $W_{min} < 0$, insufficient apron protection has been provided for the given abutment geometry. If the toe of the abutment is not sufficiently protected below the bed of the flood plain, the scour hole that is formed will undermine the abutment, causing the material from the abutment to slump into the scour hole. When $W_{min} > W$, the edge of the scour hole forms next to the apron, and the condition is reached for which the resultant scour hole no longer erodes the outer edge of the apron. Further increase in apron width will deflect the scour hole further away from the abutment, by a similar distance. The scour hole will also become smaller until eventually the apron is wide enough that all scour has been eliminated locally at the abutment.

4 Application

Equations 3 to 6 are the basis of a method for assessment of the integrity of spill-through bridge abutments. The method enables determination of the local equilibrium scour formation for an abutment, for a given level and type of scour countermeasure protection. A geotechnical slope-stability analysis can be undertaken using the scour hole position and geometry (along line ‘R’ in Figure 1) to assess the structural integrity of the abutment. This method has the advantage that the countermeasure protection can be designed to be site specific for each bridge abutment. Abutments with deep foundations may not require much countermeasure protection, because larger scour hole formations closer to the abutment may be tolerable. Conversely, for abutments with shallow foundations, the designer may require more countermeasure protection, because scour hole formations in close proximity to the abutment would compromise the structural integrity of the bridge.

If the level of protection provided predicts an undesirable scour hole formation locally at the abutment, the designer can increase the level of protection provided or change the type of protection provided, until the expected scour hole at the abutment is tolerable.

5 Conclusions

The conclusions from this experimental study are:

- The maximum scour depth for spill-through abutments situated on the flood plain of a compound channel can be predicted by (6).
- Cable-tied block mats allow scour holes to form closer to the abutment than equivalent riprap aprons and result in deeper scour holes.
- The scour depth generally increases with abutment length and flood plain width, and decreases with apron width.

- The minimum distance between the edge of the scour hole and the abutment can be predicted by (7), and generally increases with apron width and riprap protection, and decreases with abutment length, flood plain width, and cable-tied block protection.

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