Conference Paper, Published Version

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Verfügbar unter/Available at: https://hdl.handle.net/20.500.11970/100051

Vorgeschlagene Zitierweise/Suggested citation:
Melville, Bruce W.; Fletcher, L. G. (2006): Riprap Protection of Spill-through Abutments on Laterally Sloping Floodplains. In: Verheij, H.J.; Hoffmans, Gijs J. (Hg.): Proceedings 3rd International Conference on Scour and Erosion (ICSE-3). November 1-3, 2006, Amsterdam, The Netherlands. Gouda (NL): CURNET. S. 452-460.

Riprap Protection of Spill-through Abutments on Laterally Sloping Floodplains

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Experimental data of local scour at spill-through abutments on laterally sloping floodplains are presented. The experiments extend an earlier study of riprap protection at bridge crossings featuring wide flood channels. This study applies to situations where the flood channel slopes laterally towards the main channel (rather than being rectangular) and the bridge crossing is skewed (rather than being perpendicular to the river channel); both equilibrium and non-equilibrium scour data are presented. Comparisons with existing design equations are given and recommended modifications to these equations are suggested to predict scour depths. Minimum apron widths to avoid failure are also given. Tests were conducted under clear-water conditions. The data show that equilibrium scour depth increases with increasing abutment length. Typically wider riprap aprons deflect scour further downstream from the abutment toe. Laterally sloping floodplains encourage riprap apron erosion with larger apron widths necessary for a given scour depth than for non-sloping floodplains of the same scour depth. Skewed abutment data show increased scour depth with increasing skew angle. This study is discussed in relation to previous data and suggested design equations and experimental limitations are also outlined.

I. INTRODUCTION

Protection of abutments through armoring and stabilization of the abutment slope, or by re-aligning the flow upstream of the abutment, is a necessary part of abutment and bridge approach design.

Riprap protection is one of the most common methods of protecting bridge abutments as it is readily available in many areas and therefore an economic solution for scouring problems. Riprap protection comprises an apron or layer of broken rock that is either dumped or placed in position as a preventative measure against scour. Typically riprap is used on the embankment side-slopes and ideally apron protection is placed at the toe of the abutment; riprap from the apron falls into the scour hole inhibiting further scour and deflecting the scour away from the abutment.

The large sizing of riprap and increased weight compared with the bed material means that increased flow velocities and turbulence created by the presence of the abutment are resisted. Riprap aprons are easy to construct, have the advantage of flexibility if settlement occurs, are easily repaired and maintained, and are durable. Individual riprap stones are recoverable should the need arise [6].

There are many design guidelines for the use of riprap as a scour countermeasure [1, 11, 16], including rock sizing, stable embankment slope, and protective apron width. These criteria are designed to prevent the common failure modes of abutments described as:

- erosion of riprap particles as a result of insufficient sizing, uniform gradation, or steep embankment side-slopes.
- riprap translational slide down the embankment because of channel scour, excess pore water pressure or steep embankment side-slopes.
- slump failure of riprap, due to channel scour, excess pore water pressure or steep embankment side-slopes.
- slump failure of the abutment due to excess pore water pressure or non-uniform material creating failure planes.

These failure mechanisms can be avoided by ensuring the riprap stones are large and heavy enough to resist movement, providing a riprap layer greater than at least one stone thick, underlying the riprap with a filter fabric to protect the side-slope material, providing a riprap apron in areas prone to scour, and reducing the angle of embankment side-slopes.

Required riprap properties are outlined in [1, 16], which state that the use of hard, durable, dense and angular rock is preferable. The riprap must be able to withstand some movement and weathering and a high density is desirable because, for a given stone size, the riprap will be able to withstand higher flow velocities prior to motion. Angular rocks are more stable on embankment side-slopes and provide a more cohesive protection apron than rounded riprap. Well graded riprap also provides stability and cohesion as the individual stones interlock.

There are many design equations that can be used to find suitable values for these parameters, however these are primarily based upon laboratory experiments or theory and often result in large sizes for individual rocks.

There have been numerous experimental studies relating to riprap protection at bridge abutments. Research on skewed wing-wall abutments was performed by [8] on a plane bed at equilibrium, finding perpendicular abutments had the deepest scour depth of any skew angle for clear-water conditions. Reference [12] studied the effectiveness of scour countermeasures and followed typical construction practice for testing. Laboratory experiments were run under clear-water conditions in an idealized channel geometry. It was found that significant riprap protection is required on the upstream face of an abutment, high velocities damage the abutment structure, and piers adjacent to abutments require special protection as they could be sited in a scour hole. As an extension of this work, [3] conducted experiments under clear-water conditions using square-edged riprap aprons with preexcavated scour holes. Equations for stable riprap size on embankments, and an embankment slope modification factor are derived in [3]. The study of vertical-wall and spill-through abutments to find stable riprap sizes for these abutment types was undertaken by [14]. It was found that the location of the failure zone is at the upstream corner of vertical wall abutments, and downstream of the contraction near the toe for spill-through abutments.

Design procedures for scour protection of bridges, including inspection techniques and installation techniques for countermeasures are presented in [15].

Studies of riprap protection for spill-through abutments on horizontal floodplains [4] were run under clear-water conditions for time periods shorter than equilibrium. It was found that the larger the riprap sizing, the narrower the riprap apron could be to offer sufficient scour protection to the abutment.

Further research on vertical wing-wall abutments of varying lengths under clear-water conditions was performed by [2]. Experiments were run to equilibrium on a plane bed surface with results defining the time to equilibrium relative to both abutment length and flow intensity.

Experiments performed by [18] under clear-water conditions on an idealized channel shape were run to equilibrium using riprap protected spill-through abutments crossing perpendicular to the floodplain and channel. Reference [18] derived design equations for the minimum apron width required for abutment protection and for the expected equilibrium scour depths relative to abutment length, riprap apron width, and floodplain geometry.

These previous studies used idealized channel geometries to introduce scour relationships which may not be applicable for all situations. The aim of this study is to investigate the scouring action at spill-through abutments on laterally sloping floodplains. Scour data, both in terms of scour depth and scour hole geometry are presented and compared with currently used design equations. Previous research on spill-through abutment scour is verified; riprap apron width is evaluated for this channel geometry and the effects of skewness of abutments on scour depth are also discussed [4, 8, 18].

II. EXPERIMENTAL METHODOLOGY

Experiments were conducted in a 2.44m wide and 0.3m deep recirculating flume with flow depths ranging from 0.1m at the abutment to 0.25m at the deepest point. The 13.0m flume test section has a sediment recess 2.8m long and 0.45m deep across the flume. A floodplain and channel slope of 0.07 was used over the entire section and was constructed from quartz silica sand with a median sediment diameter, d_{50}=0.82mm. The sediment is considered to be uniform with a geometric standard deviation, σ_g=1.30.

Abutments were constructed with the same silica sand used for the bed material, and moulds were used to achieve the desired geometry for the spill-through abutments. The moulds allowed for the variation in abutment length whilst keeping the same shape and a side-slope of 1:1. The abutment side-slopes were covered with a filter paper to improve riprap stability with riprap overlaid on the filter paper. The riprap has a median stone size, D_{50},=0.02m and σ_g=1.08 [5]. Riprap sizing was based on [7], which outlines methodology to calculate riprap sizing for these tests based on flow depth, Froude number Fr, and specific gravity S_s, of the riprap. The sediment and riprap parameters are listed below in Table 1.

Riprap was also placed over the bed material near the channel section where velocities were higher than critical for sediment entrainment. The riprap in the channel section inhibited premature scouring. As the scour hole encroaches on the channel section the riprap 'falls' into the scour hole. These riprap stones were promptly removed so as not to hinder the total scour.

Layers of aluminum sheet metal were coated with the same silica sand to provide a comparable roughness to the bed material and were laid upstream of the recessed test section to eliminate upstream scour. After each experiment, the silica sand was smoothed to a flat surface with an accuracy of ±2mm. An inlet tank was designed to provide enough head to distribute flow evenly across the flume and to eliminate excess energy; the downstream tail-gate was used to ensure uniform flow at the required depth during the entire experiment.

The flume was slowly filled to the required flow depth; this eliminated the action of sheet flow generated by insufficient flow depth. Once the required depth was reached the discharge was increased by adjusting the butterfly valves on each of the pipes. Experiments were run for 72hours which was deemed sufficient length of time to reach equilibrium and allowed for comparison with previous research [8], [18].

Measurements were taken every 0.5 hr for the first 4 hours, and every hour for the next 4 hours. Subsequent measurements were taken at 24 hr, 30 hr, and 72 hr.

An initial experiment was run with no abutment present in order to find the pipe and flume settings for uniform flow and to gauge the suitable velocities required for V/V_c of 0.80-0.90, where V is the mean flow velocity and V_c is the critical mean velocity for particle entrainment. Particle Tracking Velocimetry (PTV) analysis was performed. Flow velocities were measured under ultra-violet (UV) light, using fluorescent particles placed upstream of the test section. The particles were recorded on video as they floated downstream.

Several sets of experiments were run during this study. The first experiments were undertaken to verify previous results from [18] and provide additional scour data for the entire duration of the experiments. Equilibrium data are shown in Table II. Previous studies recorded scour depth and scour depth locations at equilibrium [18], whilst this study includes an additional focus on the temporal development of scour. As an extension to previous research, a further 18 experiments were performed using a laterally-sloped floodplain with abutment lengths (L) of 0.4m, 0.6m, and 0.8m and riprap apron widths (W) of 0.0m, 0.1m, 0.2m, 0.3m, 0.4m, and 0.5m. The data are also shown in Table II.

Floodplain setup and measured parameters are shown in Fig. 1.

TABLE I. BED MATERIAL AND ROCK RIPRAP PROPERTIES

Description	**d_{16} (mm)**	**d_{50} (mm)**	**d_{84} (mm)**	**σ_g**	**S_s**
Silica Sand	0.62	0.82	1.04	1.30	2.65
Riprap	18	20	21	1.08	2.65

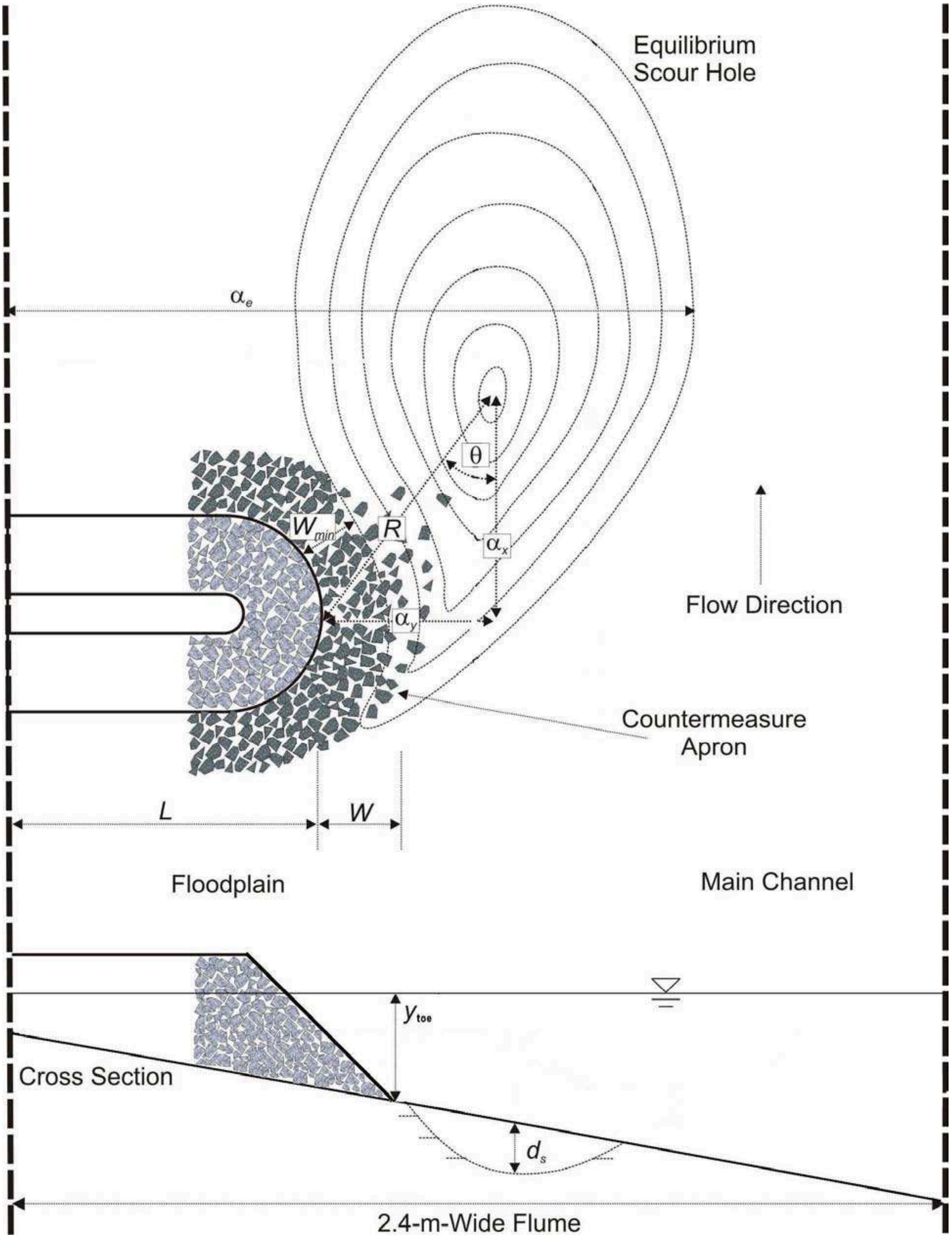


Figure 1. Floodplain setup with scour hole parameters shown. Adapted from [18].

Finally, 8 experiments were conducted with the same laterally-sloped floodplain and L=0.6m and W=0.3m for skew angles, θ, between 30° and 150 from the downstream abutment boundary. Scour data are shown in Table II.

Throughout the experiments transverse profiles of scour depth were recorded using an acoustic depth sounder mounted on a mobile trolley with an accuracy of 0.1mm. At the conclusion of each experiment a series of profiles was taken every 50.0mm across the scour hole enabling construction of a digital contour map of the scour hole. At each measurement the minimum apron width (W_{min}), the transverse (α_y) and longitudinal (α_x) location of the deepest scour from the toe of the abutment, and the outer edge of the scour hole (α_e) were recorded, each with an accuracy of ±5.0mm. From this information the progression of the scour hole was mapped in terms of the resultant distance (R) from the toe of the abutment where

$$R = \sqrt{{\alpha_x}^2 + {\alpha_y}^2} \tag{1}$$

Digital photographs were taken of the abutment layout prior to commencing the experiments and again at equilibrium, with contour lines laid at 50.0mm intervals. The contour lines were constructed using white cotton string laid at the measured depths from a straight edge of the same lateral slope as the floodplain. The contour levels depict the depth of scour from the original floodplain, d_s.

The depth of scour d_s was measured along with the location of the scour hole relative to the abutment toe (α_x, α_y, α_e), and the proximity of the scour to the abutment toe, W_{min}.

III. Discussion / Results

A. Scour Depth

Table II includes equilibrium scour data from this study and scour data for all abutment lengths, L=0.4, 0.6, 0.8m. Maximum scour depths for all apron widths W, are plotted in Fig. 2, with both equilibrium and non-equilibrium data for L=0.4, 0.6, 0.8m. The trendline shown represents the following equation

$$\frac{d_s}{L} = 0.5\left(\frac{t}{t_e}\right)^{0.28} \tag{2}$$

where d_s is the depth of scour below the original floodplain, L is the projected abutment length, t is the time elapsed, t_e is the time to reach equilibrium scour depth, and the coefficients were determined by regression (R^2=0.95). Equation (2) can be simplified for equilibrium scour depth, when t/t_e=1, giving

$$d_s = 0.5L \tag{3}$$

The equation applies to abutments protected with riprap aprons and is limited to the range of parameters investigated in this study.

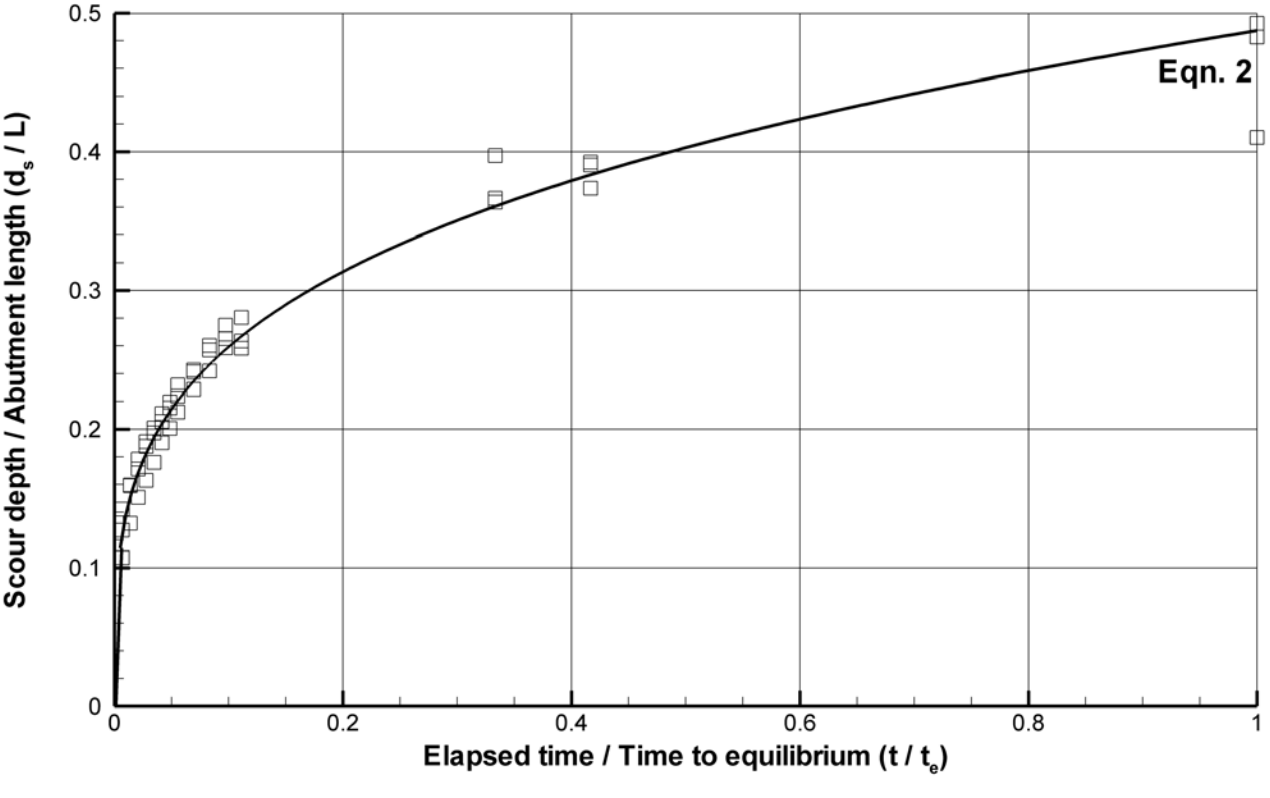


Figure 2. Normalised scour depth as a function of the proportion of elapsed time.

TABLE II. EQUILIBRIUM SCOUR DATA FOR IDEALIZED CHANNEL GEOMETRY, SLOPING FLOODPLAIN GEOMETRY, AND SKEWED ABUTMENTS.

Geometry	L	W	d_s	W_{min}	α_x	α_y	α_e
Non-Sloping B_f							
0.8	0.4	0.2	0.244	0.060	0.750	0.407	1.111
1.2	0.6	0.3	0.273	0.175	0.750	0.448	1.439
2.0	0.8	0.4	0.257	0.235	0.760	0.240	1.201
Sloping							
	0.4	0.0	0.179		0.490	0.204	0.870
	0.4	0.1	0.197	0.048	0.570	0.210	0.958
	0.4	0.2	0.177	0.163	0.710	0.265	0.968
	0.4	0.3	0.198	0.230	0.760	0.348	1.059
	0.4	0.4	0.166	0.373	0.890	0.312	1.040
	0.4	0.5	0.174	0.445	0.910	0.362	1.130
	0.6	0.0	0.277		0.640	0.339	1.317
	0.6	0.1	0.264	0.018	0.700	0.439	1.435
	0.6	0.2	0.290	0.050	0.745	0.406	1.454
	0.6	0.3	0.281	0.125	0.910	0.539	1.554
	0.6	0.4	0.280	0.250	0.880	0.533	1.567
	0.6	0.5	0.269	0.370	1.020	0.541	1.583
	0.8	0.0	0.258		0.710	0.352	1.525
	0.8	0.1	0.329	0.005	0.780	0.303	1.538
	0.8	0.2	0.311	0.038	0.960	0.425	1.668
	0.8	0.3	0.320	0.021	0.950	0.407	1.770
	0.8	0.4	0.307	0.093	1.000	0.504	1.838
	0.8	0.5	0.310	0.248	1.060	0.510	1.843
Skewed θ=							
30°	0.6	0.3	0.269	0.195	0.711	0.485	1.429
45°	0.6	0.3	0.269	0.158	0.740	0.475	1.581
60°	0.6	0.3	0.308	0.154	0.794	0.586	1.660
75°	0.6	0.3	0.275	0.105	0.719	0.518	1.496
90°	0.6	0.3					
105°	0.6	0.3	0.282	0.121	0.961	0.479	1.500
120°	0.6	0.3	0.316	0.115	0.966	0.509	1.610
135°	0.6	0.3	0.291	0.130	1.050	0.511	1.533
150°	0.6	0.3	0.296	0.127	1.319	0.534	1.639

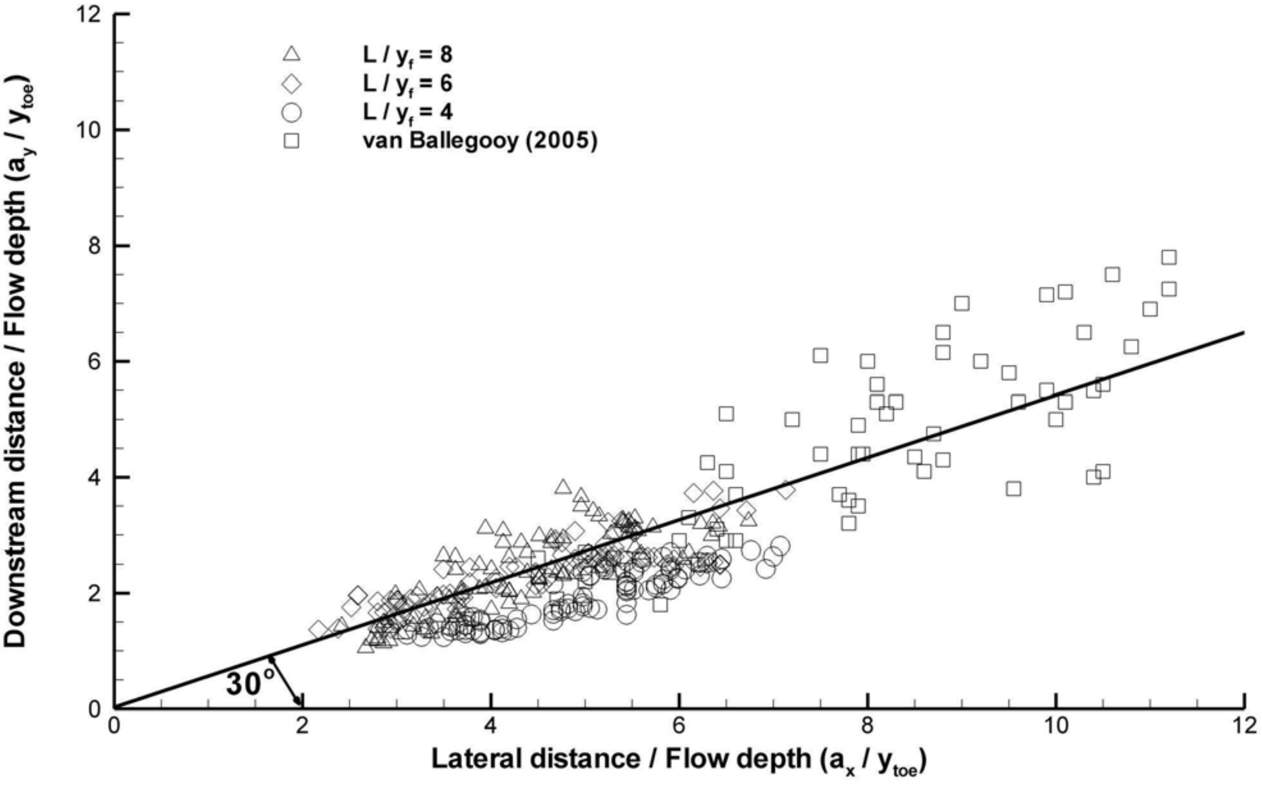


Figure 3. Distance to deepest scour from abutment toe, normalized against flow depth at the abutment toe.

B. Scour Hole Geometry

The proximity of the scour hole to the abutment is important for countermeasure design and was recorded during each experiment. Fig. 3 shows the locations of the deepest scour normalized in terms of the flow depth at the toe of the abutment throughout the development of the scour hole. Equilibrium data from [18] are also plotted for comparison. The plot indicates that the deepest scour is consistently located at θ≈30°; where θ is defined in Fig. 1.

It is noted that for smaller L/y_{toe} (L/y_{toe} =4) the downstream deflection (α_y) of the scour hole is less than that for longer abutments, and produces a smaller resultant angle. This indicates the location of scour is dependent upon the length of the abutment, both in its downstream location and lateral position. It was observed that the velocities are slower at the tip of the abutment for shorter *L*, which in turn lessens the vortex scouring action at the abutment encouraging scour closer to the abutment tip.

The equilibrium distance of the scour hole from the toe of the abutment *R*, is plotted in Fig. 4. The following equation is valid for the data in Fig. 4 (R^2=0.81)

$$\frac{R}{y_{toe}} = 5.73\left(\frac{W_0}{y_{toe}}\right)^{0.23} \tag{4}$$

Equation (4) shows that the position of the scour is directly dependent on W_0, rather than *L*, at equilibrium. However, during the initial stages of tests (*time<24hr*), the scour hole developed further from the abutment toe, and exhibited a dependence on *L*. The higher flow velocities at the tip of longer abutments increased the magnitude of vortex scour action and also increased the range of influence of the vortex, initiating the scour hole further downstream. Once the scour hole was established, *R* followed a similar trend regardless of *L*.

C. Skewed Abutments

Tests with skewed abutments with angles between θ=30° and θ=150° were performed for projected abutment length, *L*=0.6m and *W*=0.3m. Scour results are shown in Table II. The results show that scour depth increases with increasing θ, as found by [10, 17, 19] and others. Conversely, [9] and [8] both found that scour depth decreases when abutments face upstream (θ>90°).

Scour depths are plotted for the various abutment inclinations and are normalized against perpendicular abutment scour depths in Fig. 5. Equilibrium and non-equilibrium scour data for wing-wall and vertical wall abutments are also included from [8, 9] for comparison.

Of particular interest from this study are the higher than expected scour depths obtained at both θ=60° and θ=120°. Velocity analysis using PTV shows no noticeable increase in velocity for these experiments. Stream-traces for θ=60°, 90°, and 120° are shown in Fig. 6. These also show no significant difference between the stream-trace for the perpendicular abutment and the two inclined abutments. Each stream-trace features similar approach angles upstream of the abutment and a similar vortex pattern downstream.

The additional scour experienced at the 60° skewed abutment is attributed to the limitations of the recessed test section. Scour at this angle exposed the edge of the recessed test section and a significant portion of impermeable boundary. Digital photographs taken at equilibrium scour depths indicate significant upstream elongation of the scour hole toward the skewed abutments (θ=60° and θ=120°) compared with the scour hole geometry from the perpendicular abutment.

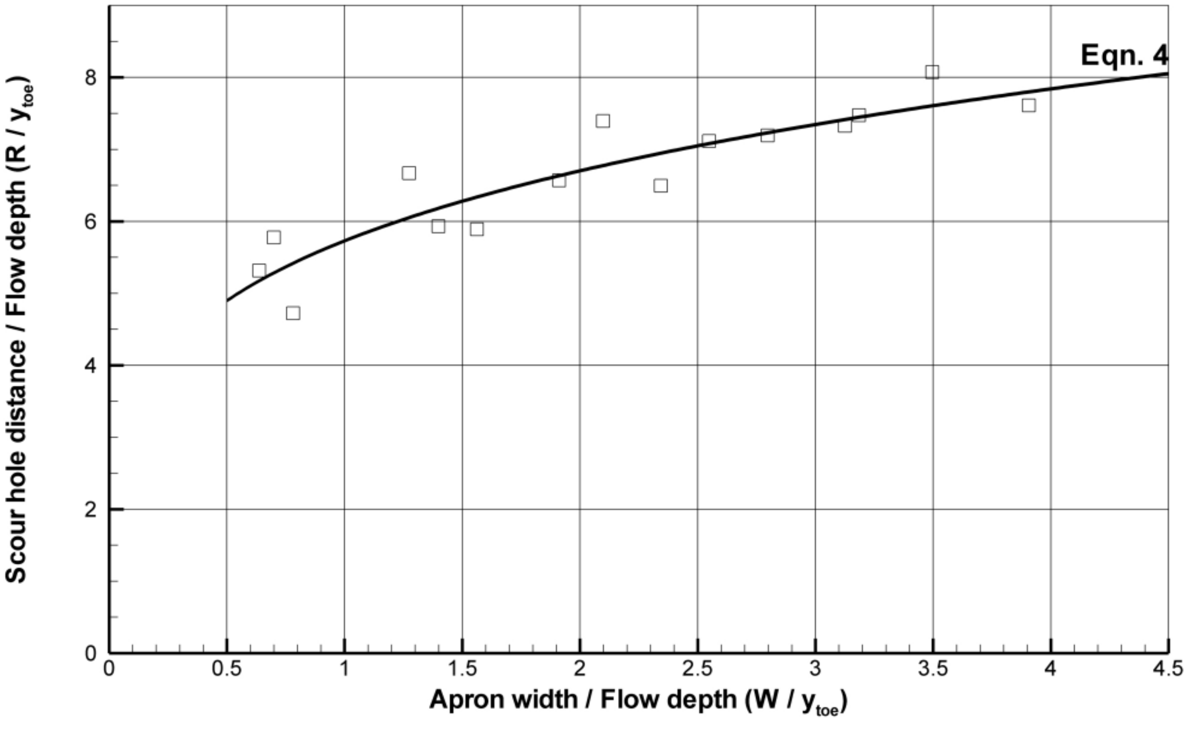


Figure 4. Scour hole position as a function of riprap apron width

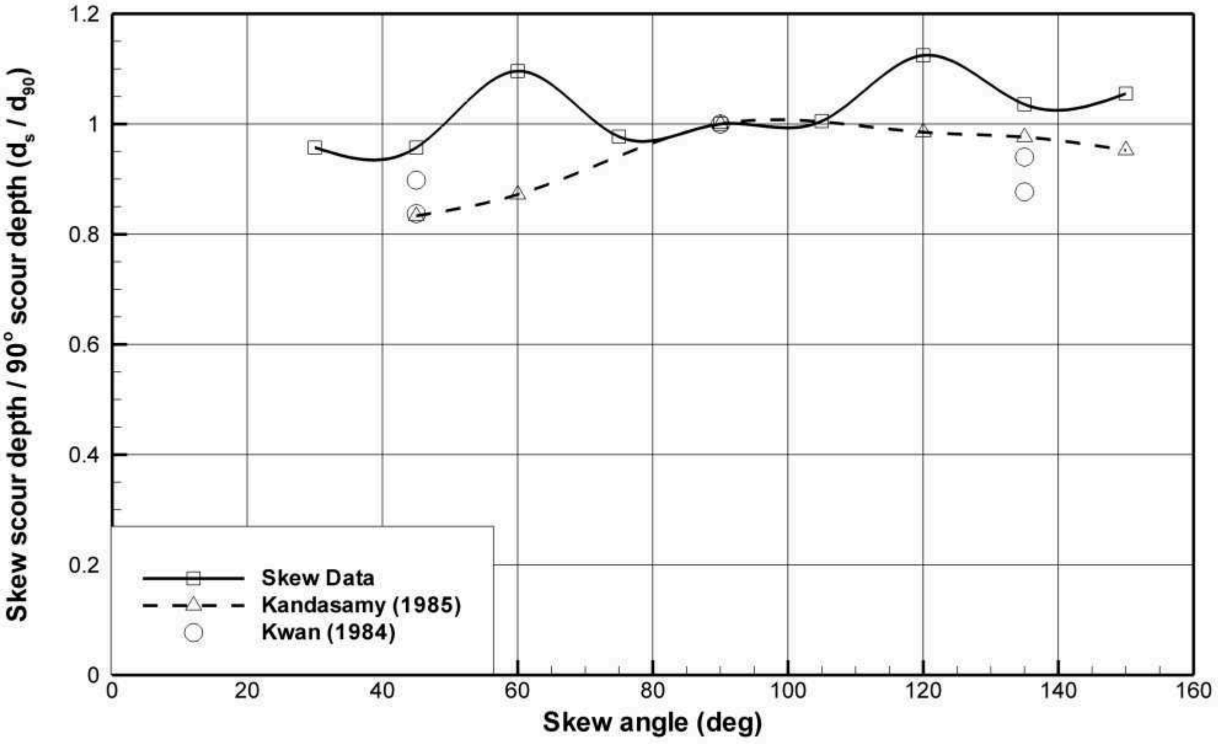


Figure 5. Skewed scour depths proportional to perpendicular scour depth as a function of skew angle.

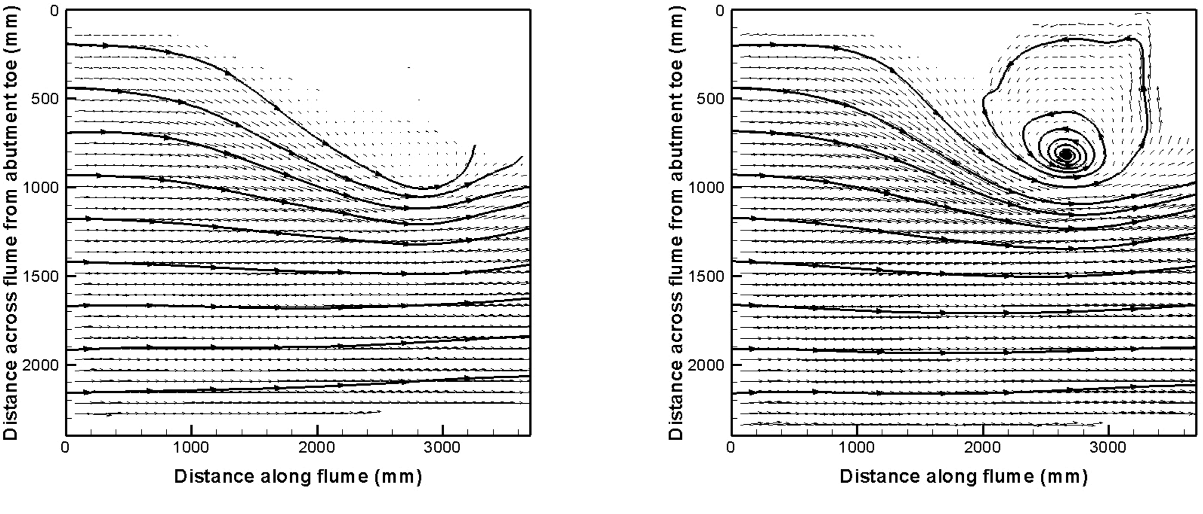
Whilst the experiments produce these anomalies, a slight increase in scour with increasing θ is apparent.

References [8] and [9] noted the development of a secondary scour hole at θ=135° which inhibited d_s. Previous research has shown that at these skew angles (θ>135°) the downflow interferes with the principal vortex creating the secondary scour hole, which reduces the available energy available for scour of the primary scour hole [9]. This was not found to be the case for this data set and the development of a secondary scour hole is assumed to be limited by the presence of the apron.

D. Apron Width

The parameter (W-W_{min}) represents the eroded width of protective apron at equilibrium scour (Fig. 7), where W is the initial protective apron width, and W_{min} is the minimum apron width from the toe of the abutment after erosion.

When W_{min}=0, the apron is just wide enough to prevent undermining of the abutment slope, i.e. the apron erodes to the toe of the abutment. This minimum apron width to protect the abutment is termed W_0. Hence $W \equiv W_0$ when $W_{min}=0$ and $(W-W_{min}) \equiv W_0$. Fig. 7 is a plot of the data in terms of W_0 and scour depth below the floodplain level, d_s. For the case when $W>W_0$, i.e. $W_{min}>0$, the edge of the scour hole is deflected away from the toe of the abutment, and W_0 is approximated by (W-W_{min}). The envelope curve depicted in Fig. 7 has the equation



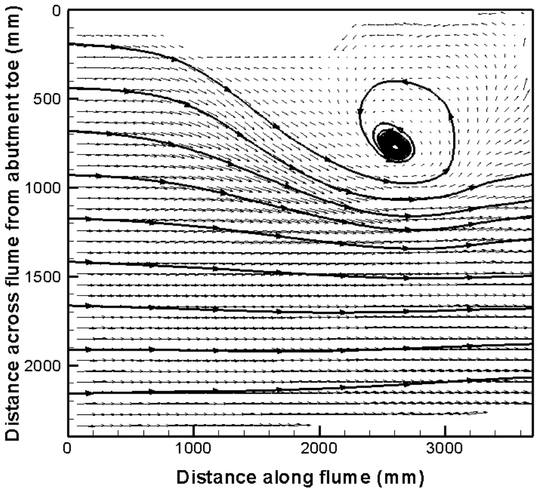


Figure 6. Stream-traces for skewed abutments with *L*=0.6m and *W*=0.3m; previous page from left to right, 60° skewed, and 90° skewed (perpendicular). Above, 120° skewed. Flow is from left to right

$$\frac{W_0}{y_{toe}} = 0.75\left(\frac{d_s}{y_{\text{toe}}}\right)^{1.25} \tag{5}$$

where W_0 is the minimum apron width to ensure failure does not occur, and y_{toe} is the flow depth on the floodplain at the toe of the abutment. Equilibrium and non-equilibrium scour data from this study and from [4, 18] are included in Fig. 7. Equation (5) is valid for all channel geometries studied for both equilibrium and non-equilibrium conditions. An earlier study [18] identified the relationship (6) as an envelope curve to data for non-sloping (level) floodplain experiments.

$$\frac{W_0}{y_f} = 0.5\left(\frac{d_s}{y_f}\right)^{1.35} \tag{6}$$

where the coefficients C_2=0.5 and λ=1.35, y_f is a constant flow depth over a level floodplain. Hence $y_{toe} \equiv y_f$ when y_f is measured at the toe of the abutment [18]. Based on the non-sloping channel geometry used in the earlier study, (6) represents a reasonable envelope. However, the

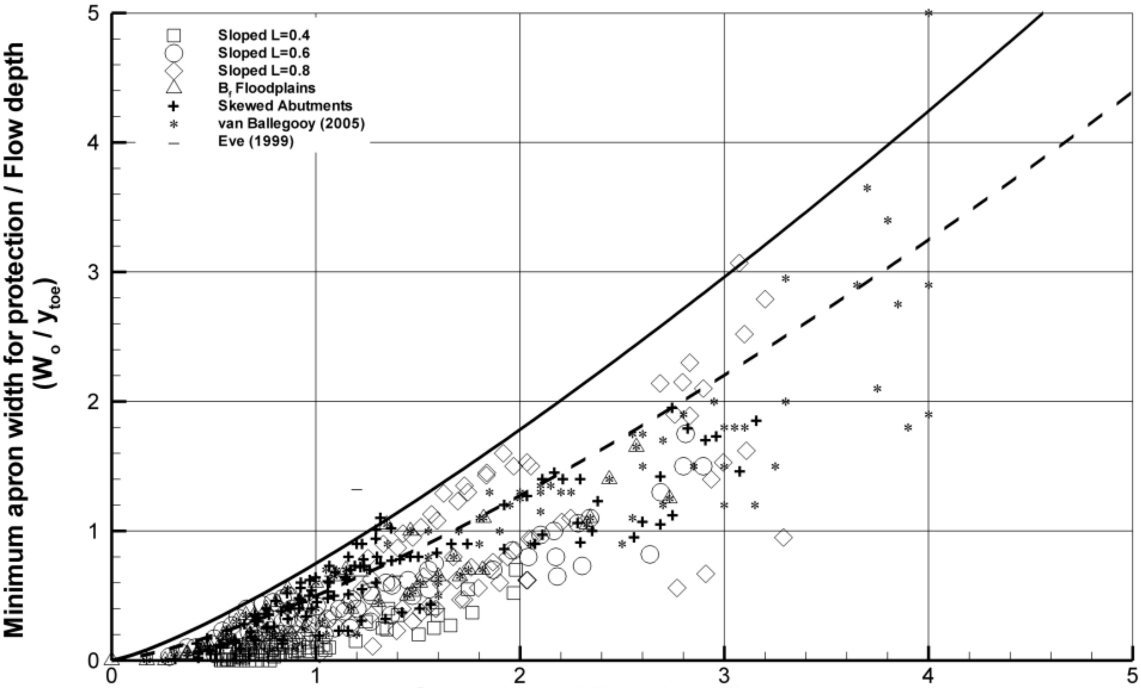


Figure 7. Minimum apron extent (W0) as a function of scour depth

modified geometry used in this study and the scour data from [4] yield significantly smaller W_{min} values for a given scour depth.

The assumption here is that erosion of the riprap apron is increased by the lateral slope of the floodplain towards the developing scour hole. The scour hole geometry is significantly different under laterally-sloping floodplain conditions. Due to the lateral slope of the floodplain, the angle at the edge of the scour hole is greater than for a level floodplain. This lateral slope encourages apron erosion closer to the abutment toe.

IV. CONCLUSIONS

Abutment length dictates the final equilibrium scour depth (2), and it can be concluded that the flow velocity is a significant factor in scour. Increased flow velocities at the toe of long abutments increase the scouring potential of the principal vortex and result in greater d_s values.

The geometry of the scour hole as defined by R is found to be dependent upon the riprap apron width. Larger apron widths deflect the scouring action away from the abutment toe. While abutment length influences the initial location of scour, equilibrium scour locations remain consistent regardless of abutment length.

Skewed abutments influence scour depth and follow the trend suggested in previous studies [13]. Scour depth is seen to increase slightly with skew angle. Significant elongation of the scour hole toward the skewed abutments (θ=60° and θ=120°) compared with the scour hole geometry for the perpendicular abutment was also evident.

Greater riprap apron width is required for protection of laterally sloping floodplains than for non-sloping channels; the lateral slope of the floodplain encourages apron erosion. A new relationship, given as (5), allows for calculation of the minimum protection apron width for sloping and non-sloping floodplains.

V. NOTATION

B_f = *width of floodplain*
C_2 = *coefficient in (5, 6)*
d_{16} = *material size where 16% is finer by weight*
D_{50} = *median diameter of riprap*
d_{50} = *median diameter of bed material*
d_{84} = *material size where 84% is finer by weight*
d_s = *equilibrium scour depth*
d_{sf} = *scour depth from floodplain level*
Fr = *Froude number based on mean velocity*
L = *projected abutment length*
R = *resultant distance to centre of scour hole*
S_s = *specific density of material*
t = *elapsed time*
t_e = *time taken to reach equilibrium scour depth*
V/V_c = *mean flow intensity*
W = *riprap apron width*
W_{min} = *minimum riprap apron width*
W_0 = *minimum riprap apron width to ensure failure does not occur*
y_f = *flow depth on the floodplain*
y_{toe} = *flow depth at the toe of the abutment*
α_x = *distance downstream from the toe of the abutment to the centre of the scour hole*
α_y = *distance across the flume from the toe of the abutment to the centre of the scour hole*
α_e = *distance from the toe of the abutment to the outer edge of the scour hole*
θ = *resulting angle from the toe of the abutment to the centre of the scour hole*
σ = *geometric standard deviation*

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