RIPRAP PROTECTION OF BRIDGE ABUTMENTS

Transfund New Zealand Research Report No. 181

RIPRAP PROTECTION OF BRIDGE ABUTMENTS

Auckland Uniservices Ltd, University of Auckland

Transfund New Zealand Research Report No. 181

ISBN 0-478-11588-1
ISSN 117-05-74

PO Box 2331, Lambton Quay, Wellington, New Zealand
Telephone (04) 473-0220; Facsimile (04) 499-0733

Eve N.J., and Melville B. W. 2000. Riprap Protection of Bridge Abutments. *Transfund New Zealand Research Report No 181.* 31 pp.

Keywords: bridge scour, riprap, protection, hydraulic modelling, abutment, live bed, mobile bed, riprap apron

AN IMPORTANT NOTE FOR THE READER

The research detailed in this report was commissioned by Transfund New Zealand.

Transfund is a Crown entity established under the Transit New Zealand Act 1989. Its principal objective is to allocate resources to achieve a safe and efficient roading system. Each year, Transfund invests a portion of its funds on research that contributes to this objective.

Contents

Executive Summary......**5**
Abstract......**5**

1. Riprap Protection Practice......**6**
- 1.1 Introduction......6
- 1.2 Riprap Failure Mechanisms......6
- 1.3 Guidance for the use of Riprap at Abutments......6
  - 1.3.1 Riprap Size......7
  - 1.3.2 Launching Apron Extent......8
  - 1.3.3 Riprap Layer Thickness, t_r......8
  - 1.3.4 Riprap Gradation......9
  - 1.3.5 Filter Design......9
- 1.4 Riprap Scour Protection Practice in New Zealand......9

2. Experimental Study......**11**
- 2.1 Introduction......11
- 2.2 Experimental Method......11
  - 2.2.1 Experimental Equipment......11
  - 2.2.2 Clear Water Experiments......13
  - 2.2.3 Mobile bed experiments......15

3. Experiments and Results......**18**
- 3.1 Clear Water Tests......18
  - 3.1.1 Clearwater Test Results......19
- 3.2 Mobile Bed Experiments $U/U_{cs} = 1.25$......21
  - 3.2.1 Failure Mechanisms......22
- 3.3 Results of Mobile Bed Experiments $U/U_{cs} = 1.5$......22
  - 3.3.1 Failure Mechanisms......23

4. ANALYSIS AND DISCUSSION......**24**
- 4.1 Clear Water Results......24
  - 4.1.1 Launching apron parameters W, θ and ϕ......24
  - 4.1.2 Maximum Scour Depth d_s and Position d_x, d_y......27
  - 4.1.3 Guidelines for launching aprons......27
- 4.2 Mobile Bed Experiments......27

5. Recommentations for Further Testing......**29**
- 5.1 Clear Water Tests......29
- 5.2 Mobile Bed Tests......29
  - 5.2.1 Filter fabric......29
  - 5.2.2 Velocity......29

6. References......**30**

Executive Summary

Criteria for selecting riprap to protect bridge abutments against scour were investigated. Experiments were conducted with a spill-through abutment under both clear-water and live bed conditions in a laboratory flume. The riprap size and apron size and extent were varied.

An abutment was constructed from the bed sediment and riprap was laid on top, to a thickness of $2D_{50}$ (where D_{50} is the median diameter of the riprap) and tested for 24 hours. At the end of the test period, the abutment was assessed for failure, either total, partial or not at all. An abutment was ajudged to have failed if the side slopes of the abutment (including the riprap blanket) had shifted in any way.

The clear-water tests were constructed with a riprap apron that followed the HEC-23 (Hydraulic Engineering Circular No 23) recommendation. This recommendation was found to be conservative in all cases, and was reduced by increments in subsequent tests until an abutment failure occurred. This process was carried out for two abutment lengths and three riprap sizes.

The data were compiled graphically, with dimensionless variables representing riprap size and apron extent on the axes. A useful relationship was found, with a clear zone of partial failure.

Experiments under live bed conditions were conducted at multiples of 1.25 and 1.5 of the critical velocity of the bed sediment. The experiments revealed that an abutment protected by a uniform riprap layer would fail very rapidly at flows above the threshold velocity, due to winnowing of the bed sediment from the riprap voids. A filter fabric was used between the riprap and the bed sediment, which resulted in no further failures of the abutment sediment at $1.25U_{cs}$, however the riprap layer failed with varying degrees of severity for all of these tests. Tests at the higher velocity of $1.5U_{cs}$ revealed that the abutments failed due to undermining of the abutment toe, leading to slumping of the sediment beneath the filter fabric. All tests failed at this velocity.

Further tests are recommended to find a failure zone under live bed conditions, varying the flow velocity, riprap size and grading, and type of filter fabric.

Abstract

Criteria for selecting riprap to protect bridge abutments against scour were investigated. Experiments were conducted with a spill-through abutment under both clear-water and live bed conditions in a laboratory flume. The riprap size and apron size and extent were varied. The data were compiled graphically, with dimensionless variables representing riprap size and apron extent on the axes. A useful relationship was found, with a clear zone of partial failure.

1. Riprap Protection Practice

1.1 Introduction

Damage to highway bridge crossings during floods endangers the lives of the travelling public and causes costly disruptions to traffic flow. The interruption to traffic flow can have devastating impacts on local economies that rely on the bridge crossing for efficient transport of goods and services. Bridge scour can also lead to environmental damage, such as bed scour, bank erosion and destruction of downstream fish spawning beds.

A launching apron of riprap is frequently placed at the toe of the abutment with the intention that the apron will settle into the scour hole as it develops. Whether this practice is successful is not known in many situations, particularly for that of mobile bed conditions. Also, the recommended practice assumes the nature of the scour is already defined, despite the protective apron itself being a factor in determining the scour.

1.2 Riprap Failure Mechanisms

Riprap is subject to certain failure mechanisms, dependent on where it is placed in respect to the abutment. Riprap placed on the apron is subject to similar failure conditions as riprap placed about a pier. Chiew (1995) conducted experiments into riprap failure mechanisms around a pier under clear water scour conditions. Three modes of riprap failure were identified, namely riprap shear failure, where the stones are not large or heavy enough to withstand the flow; winnowing failure, where the underlying finer bed materials are removed through the voids of the coarser riprap stones; and edge failure, where the instability of the edge riprap stones and the underlying finer material initiates the formation of a scour hole.

Blodgett and McConaughy (1985) identified four failure modes for riprap placed on sloping embankments. These were particle erosion failure, where the forces of the flowing water were able to dislodge individual riprap stones; translational slide failure, where a mass of riprap stones moves down the embankment slope, with a horizontal fault-line; modified slump layer, where mass movement of riprap material occurs along an internal slip surface within the riprap layer; and slump failure, where a movement of material occurs along a rupture surface that has a concave upward curve.

1.3 Guidance for the use of Riprap at Abutments

Guidance for the use of riprap at bridge abutments is given by Ministry of Works and Development (1979), Gregorius (1985), Richardson et al. (1988), Harris (1988), Central Board of Irrigation and Power (1989), Brown and Clyde (1989), Austroads (1994), Richardson et al (1995) and others. The recommendations cover some or all of the following riprap parameters: stone size, layout, layer thickness, gradation, and filter requirement.

1.3.1 Riprap Size

Melville and Coleman (1999) carried out an extensive review of available literature. Equations for estimating riprap sizes are summarised in this work. Melville and Coleman compared the equations graphically, for a specific gravity (S_s) value of 2.65. This is shown below in Figure 1.1. It can be seen that the various equations give a wide range of recommended riprap sizes. The equation given by Croad (1989) is conservative in comparison with the other equations and is likely to lead to conservative riprap size. The modified equation by Croad is:

$$\frac{D_{50}}{y} = \frac{0.67}{(S_s - 1)K_{sl}} Fr^2 \qquad (1)$$

where

$$Fr = \frac{V_r}{\sqrt{gy}} \qquad (2)$$

where D_{50} is the mean riprap stone diameter, y is the flow depth, S_s is the specific gravity of the material, Fr is the Froude number of the approach flow, V_r is the velocity at the abutment end = 1.5 V, and K_{sl} is the embankment slope factor. K_{sl} can be calculated using

$$K_{sl} = \left(1 - \frac{\sin^2 \alpha}{\sin^2 \theta}\right) \qquad (3)$$

where α = embankment slope and θ = angle of respose of riprap stones.

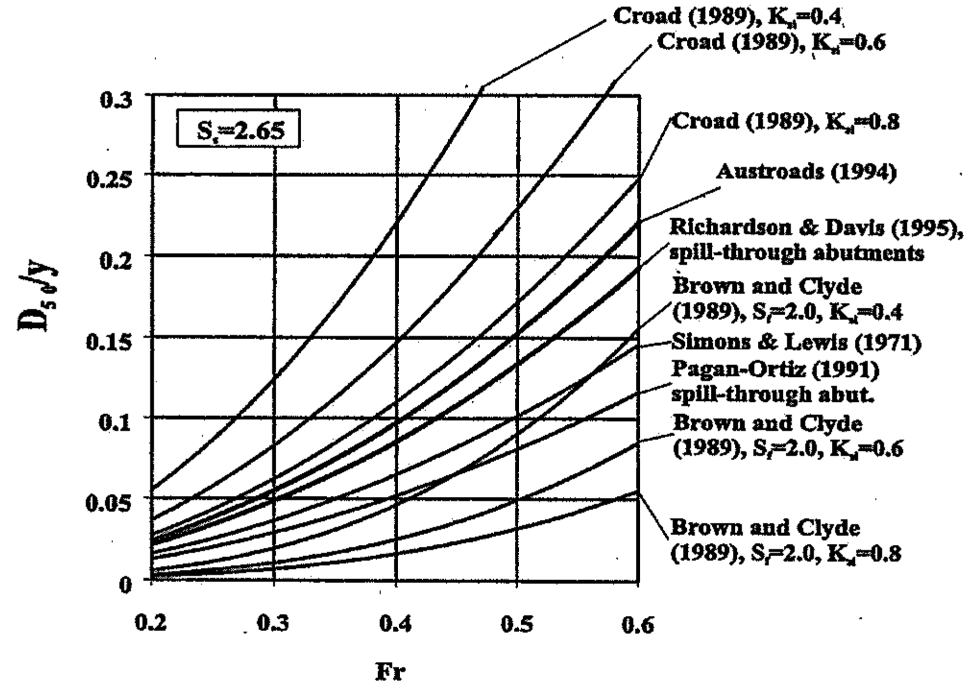

Figure 1.1 Comparison of equations for riprap sizing at bridge abutments (Melville and Coleman, 1999).

1.3.2 Launching Apron Extent

The recommended practice (eg Richardson et al, 1995; Austroads, 1994) is to extend the riprap right around the abutment and down to the expected scour depth. An alternative is to lay an equivalent blanket of riprap, known as a launching apron, on the existing bed. The launching apron protects the side of the scour hole as erosion occurs.

Richardson et al (1995) provide specific guidelines for riprap layout for a launching apron. The recommendations are based on the studies carried out by Pagan-Ortiz (1991) and Atayee (1993). The recommendations are repeated by Lagasse et al (1997) and accompanied by a plan view of the recommended apron extent as seen in Figure 1.2.

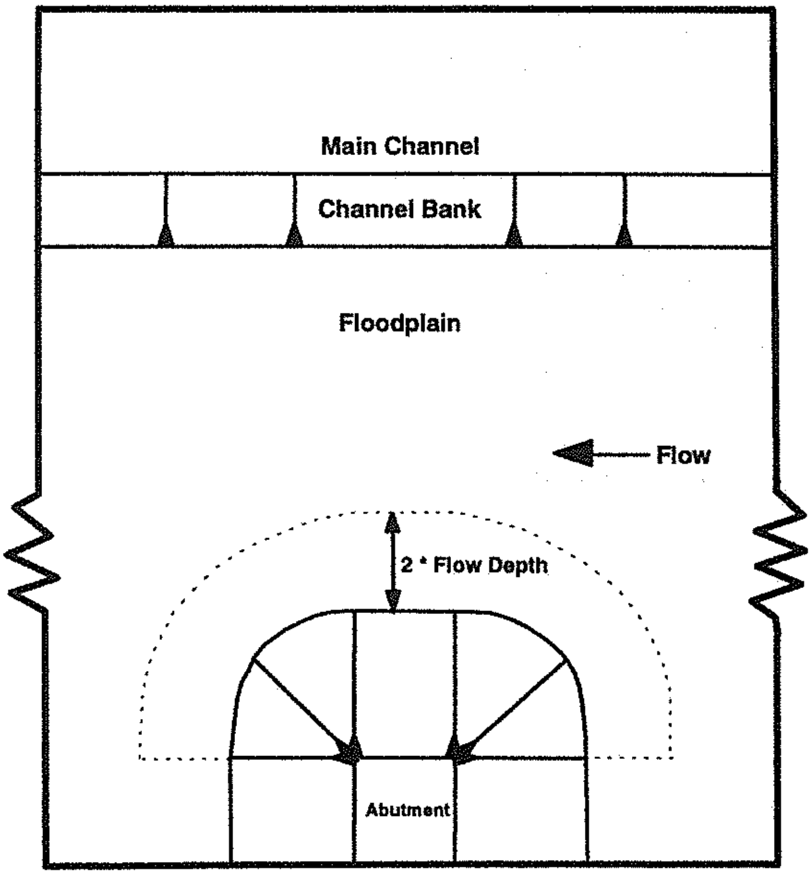

Figure 1.2 Plan view of the recommended extent of a rock riprap apron (Lagasse et al, 1997).

1.3.3 Riprap Layer Thickness, t_r

Ministry of Works and Development (1979) recommend a layer thickness of $2D_{50}$, as well as a suitably graded filter layer or filter cloth. Lagasse et al (1997) recommend that the rock riprap thickness should be at least the larger of 1.5 times D_{50} or D_{100} (largest riprap particle size) It is also recommended that the rock riprap thickness should be increased by 50% when it is placed under water, to allow for the uncertainties associated with placing riprap under water.

1.3.4 Riprap Gradation

Ministry of Works and Development (1979) recommend a filter if the riprap is not correctly graded. The Ministry of Works and Development recommended grading curve is shown in Figure 1.3. The variable *d* on the y axis is *D*, the riprap stone diameter.

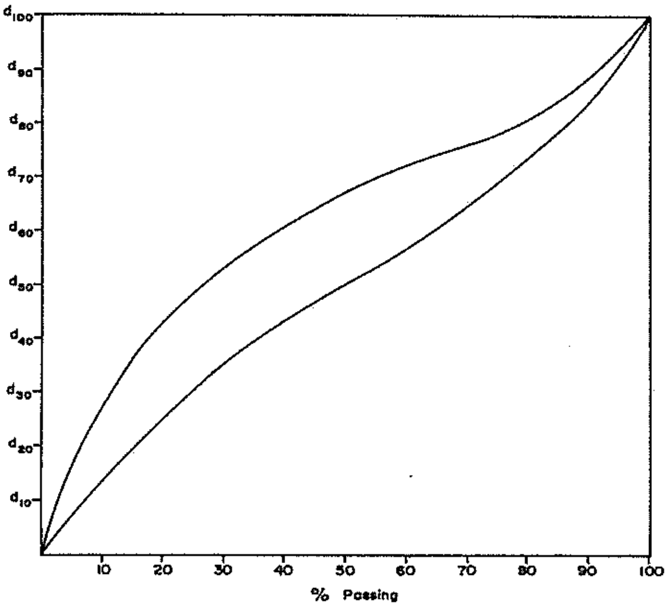

Figure 1.3 Optimum riprap grading curve (Ministry of Works and Development, 1979).

1.3.5 Filter Design

Filters can be used to combat winnowing effects on abutment slopes. Filters can be granular, making use of the filtering effect of graded sediments, or synthetic, commonly called geotextiles. Most authors recommend one of these options, but experimental data on the effectiveness of either method are lacking.

Recently, filter practice has tended towards the use of synthetic filters, because of the inherent difficulties in obtaining and placing granular filter material. Synthetic filters are flexible, in comparison with granular filters, in that they can deform and still remain intact. The important parameters in selecting a filter fabric are pore size, permeability, the long-term soil/fabric permeability and shear strength (Hudson and East, 1991).

1.4 Riprap Scour Protection Practice in New Zealand

Riprap scour protection in New Zealand is documented in Smart (1990), Ministry of Works and Development (1979) and Gregorius (1985). Smart (1990) reviewed riprap practices adopted by several Works Corporation (now Opus International Consultants Ltd) and New Zealand Railways (now Tranz Rail Ltd) offices. Interestingly, each local office of Works Corporation used a different method, often adjusted to suit local conditions and local availability of riprap. Smart concluded that, to a large extent, New Zealand riprap practice followed U.S.A. guidelines.

2. Experimental Study

2.1 Introduction

The experimental investigation was approached in two stages. Firstly a series of tests were performed under clear water conditions. Launching apron configurations were tested for effectiveness at protecting the abutment model from failure. The purpose of these tests was to assess the applicability of current guidelines, particularly the recommendation of launching apron width.

Secondly, another series of tests were performed under live bed conditions. The purpose of this series of tests was to examine the performance of launching aprons under live bed conditions, as no other experimental data were available. Similar apron configurations to those for clear water conditions were tested.

2.2 Experimental Method

The experiments were conducted in the Fluid Mechanics Laboratory of the School of Engineering, University of Auckland.

2.2.1 Experimental Equipment

2.2.1.1 2.4 m wide flume

The clear water experiments were conducted in a 2.4 m wide, 0.30 m deep and 16.5 m long wooden-sided recirculating flume. The sediment recess section was located 7.2 m from the upstream end of the flume. Water was supplied to the flume from the laboratory constant head tank.

2.2.1.2 1.52 m wide flume

The mobile bed experiments were conducted in a 1.52 m wide, 1.22 m deep, 45 m long, glass-sided recirculating flume. A false floor of height 400 mm was constructed over the entire length of the flume, except for a sediment recess of length 3.1 m which was situated 26.6 m down the flume. The discharge through the flume is controlled by two pumps of 60 hp and 27 hp. Sediment was recirculated as a sediment water slurry through a sediment pump of capacity 60 litres/sec.

2.2.1.3 Abutment mould

The test abutments were constructed from bed sediment using a mould. Three abutment shapes were tested in this study. All abutments had the same frontal shape and dimensions, but varied in length. Two abutments of length 863 mm and 1063 mm (where length L is measured to the mid-water depth) were used in the clear water tests, and a shorter abutment of length 513 mm was used in the 1.52 m wide flume. The abutment mould was 250 mm high, with side slopes of 1:1.5 (H:V). The mould was constructed of sheet aluminium and split into sections to allow the various lengths to be constructed.

2.2.1.4 Bed and riprap materials

Bed sediment S1 was used in the 2.4 m wide flume, and bed sediment S2 was used in the 1.52 m wide flume. The characteristics of these bed materials are listed in Table 2.1. Four uniform riprap materials were used in the experiments. Their properties are also listed in Table 2.1. Riprap materials R1, R2 and R3 were used in both the 2.4 m wide flume and the 1.52 m wide flume, while the large R4 size was used only in the 1.52 m wide flume.

Table 2.1 Sediment and riprap characteristics.

Description	d_{16} or D_{16} (mm)	d_{84} or D_{84} (mm)	d_{50} or D_{50} (mm)	σ_g	S_s or S_r	u_{*cs} (m/s)	U_{cs} (m/s)	Source
S1	0.51	1.01	0.85	1.41	2.65	0.022	0.364	River sand
S2	0.61	1.02	0.95	1.29	2.65	0.023	0.391	River sand
R1	14.4	18.1	16.3	1.12	3	0.134	1.31	Aggregate
R2	19.8	23.2	21.5	1.08	3	0.154	1.40	Aggregate
R3	25.2	30.3	27.8	1.10	3	0.175	1.48	Volcanic rock
R4	32.9	38.6	35.8	1.08	3	0.198	1.56	Aggregate

Note: D denotes riprap diameter, d denotes sediment diameter. D_{16} is the mean riprap stone diameter (for which 16% by weight is finer than the stated size). U_{cs} is the critical mean velocity for material entrainment and u_{*cs} is the critical shear velocity for the material.

Figure 2.1 An abutment model ready for testing.

2.2.1.5 Filter fabric

The filter fabric was a non-woven geotextile called 4545, obtained from the Amoco Fabrics and Fibres Company. The characteristic properties of the filter fabric are a puncture strength of 240 kN, an elongation strength of 50%, a trapezoid tear strength of 175 kN and an apparent opening size of 0.212 mm.

2.2.2 Clear Water Experiments

The first series of experiments were conducted under clear water conditions in the 2.4 m wide flume. Clear water conditions exist when the shear velocity of the flow is less than the critical shear velocity of the bed sediment, and when general mass movement of the bed material is not occurring.

An abutment was constructed in the sediment recess section, by levelling the bed and then filling the mould with bed sediment. The mould was removed and riprap placed in the desired configuration. An abutment ready for testing is shown in Figure 2.1.

All tests in the 2.4 m wide flume were run at the same flow depth (y = 150 mm) and discharge (Q = 49 L/s). The experiments were run for a maximum of 24 hours, if the abutment did not fail before this. Behaviour of the riprap layer was observed at intervals over the 24 hour test period. At the conclusion of each test, the scour hole was profiled with string, photographs were taken to record the profile of the scour hole, and the abutment was assessed for failure. An abutment was adjudged to have failed if the side slopes of the abutment had shifted in any way. This led to three areas of observed results:

- **Total failure**, where large-scale movement of abutment material and riprap had occurred on the abutment slopes. The slope of the abutment embankment had slumped to a gentler slope, and large areas of sediment were exposed with no riprap protection.

- **Partial failure**, where riprap and sediment movement had initiated in one part of the embankment, but not resulted in a change of the embankment slope as a whole. Typically, partial failure was observed at the water level, with a small number 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 positions.

(a) Total failure.

(b) Partial failure.

(c) No failure.

Figure 2.2 Types of observed results under clear water conditions.

The three types of result, total, partial or no failure, are illustrated in the following figures, Figure 2.2 (a) to (c). If there was any doubt as to what type of failure had occurred, the more conservative option was taken.

2.2.3 Mobile bed experiments

The second series of experiments were conducted under mobile bed conditions in the 1.52 m wide flume. The mean flow velocity was set at two values, 1.25 U_{cs} and 1.5 U_{cs}. The shear velocity of the flow was higher than the shear velocity of the bed sediment, causing dunes to form and progress along the sediment bed.

An abutment was constructed in the sediment recess section. Most tests were carried out with a synthetic filter layer beneath the riprap, because early tests failed rapidly due to winnowing of the bed sediment from between the riprap stones.

Tests were run at a flow depth of 150 mm, for a duration of 24 hours if the abutment did not fail before this. At the completion of each experiment, a profile of the bed depths was recorded using an ultrasound probe. The flume was then drained, and photographs were taken of the abutment. The mode of failure was assessed by examining the riprap layer, then removing the riprap and examining the filter layer, then removing the filter layer and examining the sediment foundation.

Three types of failure were seen:

- **Catastrophic rapid failure** (no filter fabric), where the abutment sediment was rapidly winnowed from between the riprap stones. The abutment was rapidly flattened, with no structural integrity remaining.

- **Slumping failure**, where the abutment failed due to the exposure of filter fabric at the toe of the abutment, allowing slumping of the sediment beneath the fabric. If exposure of the filter fabric at the toe occurred before a stable slope had been achieved on the side slopes of the scour hole, the sediment beneath the fabric would be rapidly eroded by the flow. This led to slumping of the sediment, reducing the height of the abutment. In a severe case, this led to overtopping of the abutment.

- **Riprap failure,** where the sediment foundation was still intact at the end of the test but the riprap blanket on the embankment slopes had failed. This failure type can vary in severity, depending on the amount of filter fabric exposed.

The three types of failure are illustrated in Figure 2.3 (a) to (c). The failure illustrated in Figure 2.3 (b) is considered less catastrophic than the failure illustrated in Figure 2.3 (a), due to the differing time scales. Failure of the abutment with no filter fabric occurred very quickly, whereas failure of the abutment due to exposure of the filter fabric footing was more gradual, and, in a real situation, would give more time for warning the public.

(a) Catastrophic rapid failure (no filter fabric).

(b) Failure due to exposure of the filter fabric at the abutment toe, allowing slumping of the sand embankment.

(c) Riprap failure

Figure 2.3 Types of failure for an abutment under mobile bed conditions.

3. Experiments and Results

3.1 Clear Water Tests

Tests were carried out under clear water conditions in the 2.4 m wide flume for two different abutment lengths. For each riprap size, initial tests were carried out with a launching apron width of 300 mm, equal to $2y$, as recommended by guidelines. The guidelines inherently assume apron reduction, measured by θ and ϕ, of zero. The launching apron width, W, was then reduced from 300 mm until a failure was observed. For the minimum apron size for which a failure did not occur, the launching apron coverage, in terms of θ and ϕ, was reduced until a partial or full failure was observed.

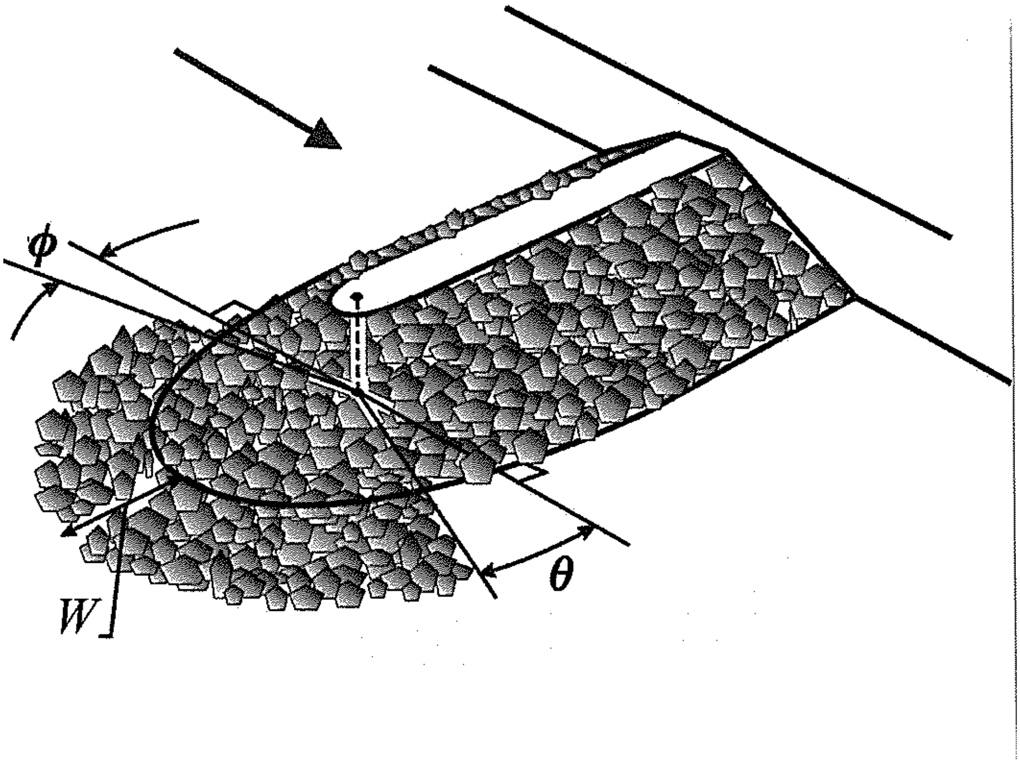

Figure 3.1 Abutment and riprap configuration variables.

All other aspects of experimentation were kept as constant as possible. These aspects included the uniformity of the bed sediments and riprap materials, the method of construction of the abutment and riprap, and the degree of compaction of the sediment. The riprap layer was applied to a thickness, t_r, of $2D_{50}$, and the flow depth, y, was maintained at 150 mm.

At the conclusion of each test, data were recorded as outlined in Table 3.1.

Table 3.1 Data parameters recorded at conclusion of each test

Parameter	Measurement method
Failure	Criterion as outlined in Section 2.2.2.
Scour depth, d_s	Measured from original sediment bed level
Position of maximum scour	Distances d_x and d_y, measured from original position of abutment toe (see Figure 3.2).
Contours of scour hole	Profiled with string and photographed.
Method of failure	Recorded from observations

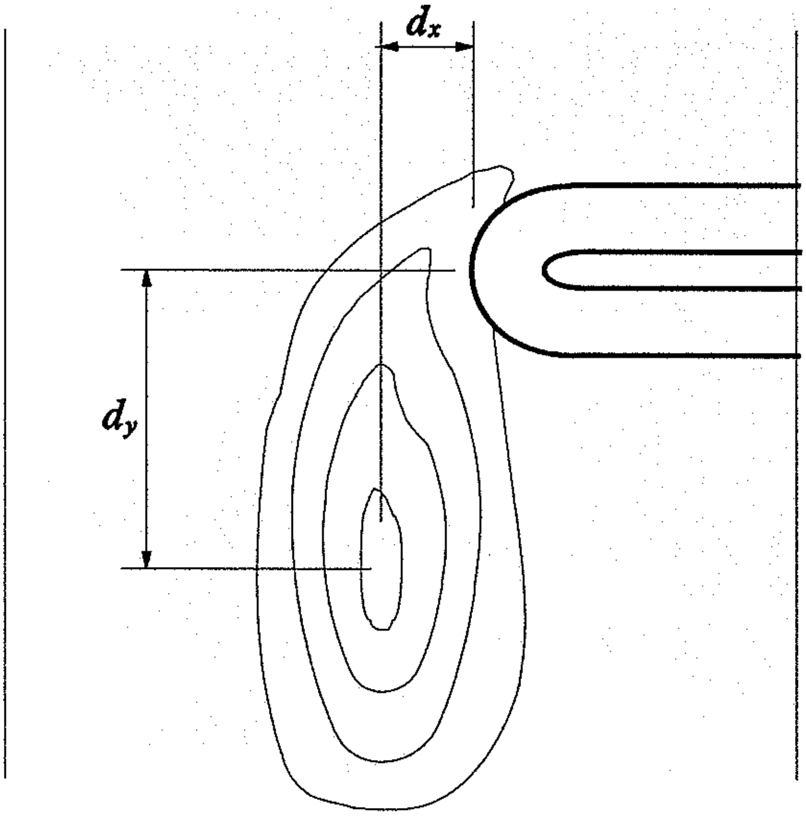

Figure 3.2 Distances *dx* and *dy* were measured relative to abutment toe for each test.

3.1.1 Clearwater Test Results

The experimental setup and recorded data from each test are summarised in Table 3.2. The tests have not been listed in sequence, but have been sorted, first by abutment length, then riprap stone size, then launching apron size to allow comparison.

3.1.1.1 Failure mechanisms

All abutments that failed exhibited translational slide failure where a mass of riprap stones moved down the embankment slope due to undermining of the abutment toe. This resulted in a gentler slope, which eventually became stable. When considering the stability of a foundation placed in the abutment, any movement of the abutment slopes is detrimental to the support of the foundation, thus any movement of the sediment was considered a failure.

Tests conducted using the smaller riprap materials R1 and R2 also exhibited particle erosion failure, where the hydrodynamic force of the flow was sufficient to pluck single stones from the riprap blanket. This failure only occurred upon the onset of translational slide failure, as individual stones rolled down the embankment slope and created a vulnerable area in the riprap layer. Once the riprap layer was breached, winnowing of the sediment beneath occurred, and both sediment and riprap stones were removed by the flow.

Table 3.2 Experimental setup and recorded data for clear water tests (U/Ucs = 0.9), y = 150 mm

Test	Setup Parameters					Recorded Data			
	L (mm)	D_{50} (mm)	W (m)	θ (°)	ϕ (°)	Failed Y/P/N	d_s (m)	D_x (m)	d_y (m)
16	863	16	0	0	0	Y	0.220	0.12	0.52
19	863	16	100	0	0	P	0.185	0.23	0.54
24	863	16	200	90	45	Y	0.180	0.22	0.53
22	863	16	200	90	0	N	0.170	0.22	0.55
23	863	16	200	45	45	N	0.160	0.23	0.59
21	863	16	200	60	0	N	0.210	0.23	0.59
20	863	16	200	45	0	N	0.205	0.24	0.62
18	863	16	200	0	0	N	0.205	0.24	0.62
17	863	16	300	0	0	N	0.205	0.26	0.69
10	863	22	0	0	0	Y	0.220	0.15	0.53
26	863	22	100	45	45	Y	0.210	0.22	0.70
25	863	22	100	45	0	P	0.160	0.22	0.69
14	863	22	100	0	0	N	0.180	0.24	0.71
15	863	22	200	0	0	N	0.160	0.29	0.73
13	863	22	300	0	0	N	0.180	0.32	0.72
1	863	28	0	0	0	Y	0.170	0.16	0.57
34	863	28	100	45	45	P	0.160	0.29	0.66
33	863	28	100	0	0	N	0.165	0.27	0.76
8	863	28	300	0	0	N	0.130	0.39	0.79
30	1063	16	100	45	0	Y	0.170	0.22	0.52
29	1063	16	100	0	0	P	0.175	0.24	0.53
28	1063	22	100	45	0	P	0.180	0.23	0.69
27	1063	22	100	0	0	N	0.180	0.24	0.72
32	1063	28	100	45	0	N	0.160	0.28	0.74
31	1063	28	100	0	0	N	0.160	0.15	0.74

Failed: Y = yes, P = partial, N = no.

3.1.1.2 Riprap stone behaviour in the scour hole

Riprap stones, both those in the launching apron and those that were displaced from the embankment slopes, acted to protect the side of the scour hole as the scour hole developed. The high turbulence created by the strong primary vortex in the scour hole would temporarily entrain the riprap stones and move them small distances downstream. In this manner riprap stones were displaced to positions nearer to the position of maximum scour depth. This in turn reduced the rate of scour.

3.2 Mobile Bed Experiments $U/U_{cs} = 1.25$

Tests were carried out under mobile bed conditions in the 1.52 m wide flume. The riprap coverage was varied in two aspects, riprap size D_{50} and launching apron width W. The launching apron extended right back around the abutment to the side walls of the flume, in comparison to the clear water tests where the apron was placed only around the nose of the abutment (see Figure 3.1).

Initial tests failed very quickly, and a filter fabric was introduced to prevent winnowing of the bed sediment from between the riprap stones. The filter fabric coverage was not varied in any way throughout testing, apart from a partial coverage used in test C. Tests were carried out with three riprap sizes, R1, R2 and R3 for a range of launching apron widths. The test parameters are summarised in Table 3.3.

Table 3.3 Test parameters for mobile bed conditions, $U/Ucs = 1.25$

Test	Filter Fabric Y/P/N	D_{50} (mm)	W (m)	Notes
A	N	28	0.3	Failed
B	N	28	0.3	Repeat of A, failed
C	P	28	0.3	Riprap failure
E	Y	28	0.2	Upstream scour reaching bed section, riprap failure
F	Y	28	0.2	Toe exposed downstream, riprap failure
G	Y	28	0.1	Toe exposed downstream, riprap failure
H	Y	22	0.3	Toe exposed downstream, riprap failure
I	Y	22	0.2	Toe exposed downstream, riprap failure
J	Y	22	0.1	Filter fabric exposed on slopes, riprap failure
K	Y	16	0.3	Filter fabric exposed at toe, riprap failure
L	Y	16	0.1	Filter fabric exposed on slopes, riprap failure

Filter Fabric: Y = yes, P = partial, N = no

Test A was conducted without a valve on the sand pipeline, and it was suspected that the initial surge when the sand pump was started may have damaged the abutment. A valve was fitted to the line which enabled flow to be slowly increased. This valve was used in Test B, and all subsequent tests.

3.2.1 Failure Mechanisms

In tests A and B, the abutments failed approximately thirty minutes after the start of the test. Initially the riprap stones were dislodged at the water surface, on the upstream face of the abutment. The failure mechanism was particle erosion failure, where the hydrodynamic forces were sufficient to dislodge individual riprap stones. Once this exposed the bed sediment beneath, failure was swift.

For tests C to L, assessment of the abutments showed that once the filter fabric was introduced, only riprap failure occurred, and the sediment foundation was found to be still intact at the completion of a test. However, this was mainly due to the presence of the filter fabric protecting the sediment even after the removal of riprap stones. The filter fabric used in these tests was capable of protecting the sediment if held in place on either side by riprap stones.

The riprap that had been removed from the filter fabric was typically removed in the first two hours of the test duration. Once the scour hole had formed to the maximum depth, the flow around the abutment was less turbulent and the riprap became stable.

3.3 Results of Mobile Bed Experiments $U/U_{cs} = 1.5$

Tests were carried out under mobile bed conditions in the 1.52 m wide flume at a higher velocity to attempt to find the point where the abutment fill material would fail. The tests were run in the same way as the tests described in Section 3.2, with the only difference being the increased velocity. Tests showed that the R3 riprap stones were not large enough to prevent slumping failure and a larger riprap, R4, was introduced.

While each test was in progress, regular observations were made. At the conclusion of each test, when the abutment had visibly failed or 24 hours had elapsed, the abutment and bed were profiled using a depth sounder. The flume was drained, the abutment visually inspected, and photographs were taken of the abutment.

Tests were carried out with four riprap sizes, and launching apron widths were varied from 100 mm to 300 mm. The test parameters are summarised in Table 3.4.

Table 3.4 Test parameters for mobile bed conditions, $U/Ucs = 1.5$ with R4 riprap.

Test	Filter Fabric Y/P/N	D_{50} (mm)	W (m)	Notes
M	Y	16	100	Visible failure, slumping of abutment
N	Y	16	200	Visible failure, slumping of abutment
O	Y	28	300	Slumping failure evident upon removal of filter fabric
P	Y	36	300	Slumping failure evident upon removal of filter fabric

3.3.1 Failure Mechanisms

All tests failed in the same manner, however this was more obvious in Tests M and N. The high turbulence and hydrodynamic forces at the constriction removed large quantities of riprap, both from the embankment slope and the launching apron, and deposited the riprap further downstream.

The exposed abutment toe was not sufficiently protected by riprap rolling down the embankment slope, and sediment was removed at the toe. Sediment from beneath the filter fabric would slump as the toe was undermined. As sediment was removed, the abutment slope became more gentle and the top of the abutment was lowered. This allowed flow to overtop the filter fabric layer, which caused the complete failures in tests M and N.

In comparison, tests O and P also experienced slumping of the abutment slope. This was not sufficient however, to expose the top of the filter fabric in 24 hours. It was necessary to examine the abutment once the flume had been drained to confirm that slumping had occurred.

4. ANALYSIS AND DISCUSSION

4.1 Clear Water Results

4.1.1 Launching apron parameters W, θ and ϕ

For a launching apron width $W = 0.3$ m, no abutments failed. This would indicate that a launching apron width of $2y$ is always sufficient for abutment protection, within the limits of these tests. However, this is a conservative solution. The launching apron width can be reduced, and the extent of the apron (in terms of θ and ϕ) can be reduced also.

4.1.1.1 Change in launching apron width, for θ and $\phi = 0$

Table 4.1 shows the failure results for the six groups of tests for θ and ϕ values of zero. As expected, failure occurred for smaller apron widths. The limits of failure shown in Table 4.1 are used in the following section to investigate the variation of θ and ϕ for a given W.

Table 4.1 Results of tests for θ and $\phi = 0$.

Test		W, launching apron width (m)			
D_{50} (mm)	L (mm)	0	0.1	0.2	0.3
16	863	Y	P	N	N
22	863	Y	N	N	N
28	863	Y	N	---	N
16	1063	---	P	---	---
22	1063	---	N	---	---
28	1063	---	N	---	---

Failure: Y = yes, P = partial, N = no.

4.1.1.2 Change in θ and ϕ for a constant value of W

Table 4.2 Percentage of total possible riprap area, defining point of failure.

		Failure			Partial failure			No failure		
D_{50} (mm)	L (mm)	U	D	T	U	D	T	U	D	T
16	863	25 %	0%	25 %	---	---	---	25 %	25 %	50 %
								50 %	0 %	50 %
22	863	25 %	25 %	50 %	50 %	25 %	75 %	50 %	50 %	100 %
28	863	---	---	---	25 %	25 %	50 %	50 %	50 %	100 %
16	1063	50 %	25 %	75 %	50 %	50 %	100 %	---	---	---
22	1063	---	---	---	50 %	25 %	75 %	50 %	50 %	100 %
28	1063	---	---	---	50 %	25 %	75 %	50 %	50 %	100 %

U = upstream riprap area coverage, D = downstream riprap area coverage, T = total riprap area coverage
Note: U and D have a maximum of 50%.

With the launching apron width set at the limit of failure established in the previous section, θ and ϕ are increased to the point of failure for each group of tests. These results are shown in Table 4.2. The percentage figures given in this table are the area of riprap used in the particular test as a percentage of the total area of riprap when θ and ϕ are equal to zero.

It is interesting to note that for a riprap size of 16 mm and an abutment length of 863 mm, there are two limiting cases. Both have the same area of riprap but have different θ and ϕ configurations. Unfortunately few conclusions can be made from these results. Clearly a reduction in the total area of the launching apron leads to a failure of the abutment, but from these results it is difficult to determine the influence of the upstream or downstream component.

4.1.1.3 Change in launching apron area, A_u and A_d

The results of the previous section suggest that there is a relationship between the total area of launching apron and degree of protection. The suggested form of this relationship, shown in Figure 4.1, allows a designer to calculate the riprap size required to protect an abutment, given a certain apron size. Conversely, the designer can calculate the required apron size, given a certain riprap size. Figure 4.1 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.

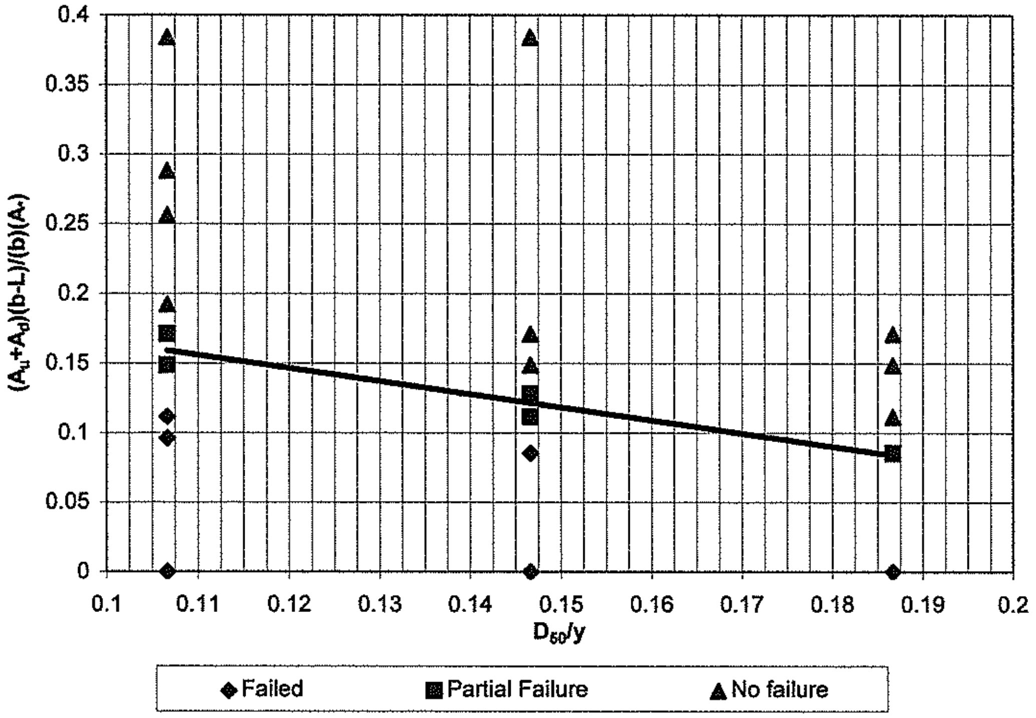

Figure 4.1 Relationship between launching apron extent and riprap size.

The variable on the y axis 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 launching apron on the upstream side of the abutment, and A_d is the similar area on the downstream side. A_* is the area of riprap protection as recommended by current guidelines ($W = 2y_o$), with θ and ϕ equal to zero. These areas exclude the riprap area on the embankment slope. An example is shown in Figure 4.2, for an abutment where $\theta = 45°$ and $\phi = 0°$.

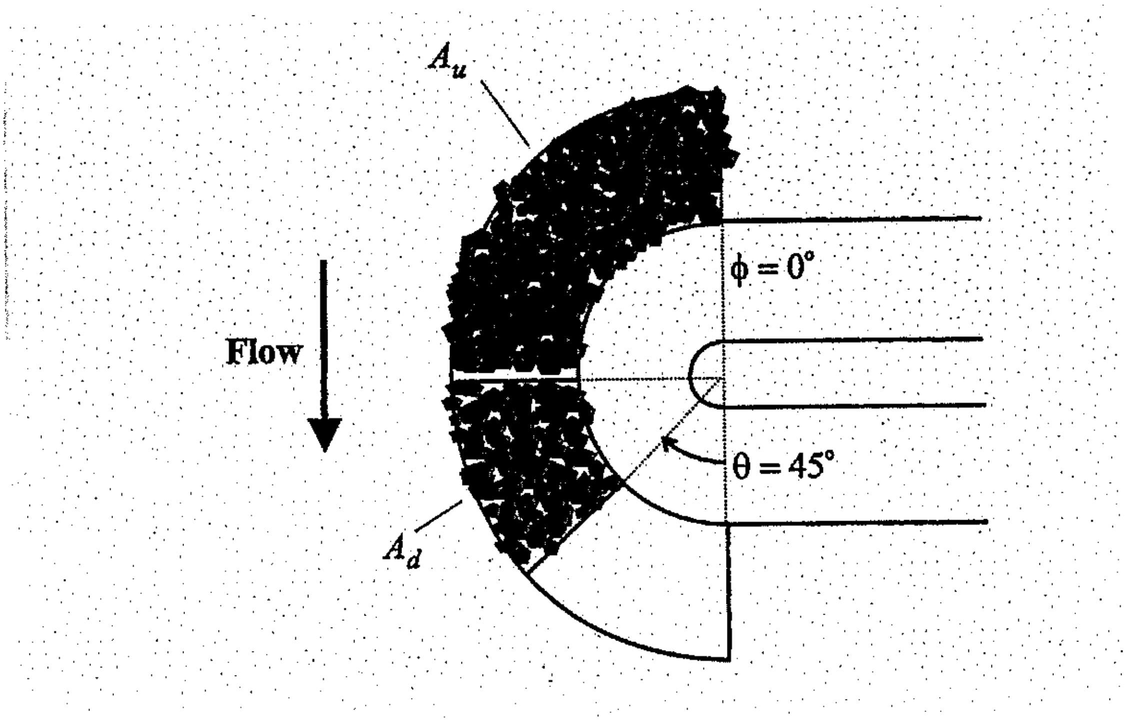

Figure 4.2 ***Au*** **and** ***Ad*** **for a launching apron.**

The summation $A_u + A_d$ can be represented as a proportion of A_*, such that

$$\left(A_u + A_d\right) = \frac{W}{2y}\left[\frac{180-(\theta+\phi)}{180}\right]A_*. \tag{4.1}$$

The term $\left(\frac{b-L}{b}\right)$ is the contraction ratio for the channel, where b is the channel width and L is the abutment length, measured at mid-depth.

The line shown in Figure 4.1 is a line of best fit for the partial failure data points, and follows the linear relationship

$$\frac{D_{50}}{y} = 0.28 - 1.1\left(\frac{A_u + A_d}{A_*}\right)\left(\frac{b-L}{b}\right), \qquad \text{for } 0.1 < \frac{D_{50}}{y} < 0.2. \tag{4.2}$$

The application of this relationship is limited to the test conditions under which it was formulated, hence the limiting condition for $\frac{D_{50}}{y}$.

If Equation 4.1 is substituted into Equation 4.2, the expression becomes

$$\frac{D_{50}}{y} = 0.28 - 1.1\frac{W}{2y_0}\left[\frac{180-(\theta+\phi)}{180}\right]\left[\frac{b-L}{b}\right], \qquad \text{for } 0.1 < \frac{D_{50}}{y} < 0.2. \tag{4.3}$$

For an abutment with no apron, where W = 0, Equation 4.3 reduces to

$$\frac{D_{50}}{y} = 0.28. \tag{4.4}$$

Equation 4.4 should however be treated with caution as this result has been extrapolated beyond the experimental data.

Simplified equation, θ and $\phi = 0$

If the designer only wishes to vary the launching apron width *W*, and does not wish to vary the launching apron extent, then θ and ϕ can be set to zero. Equation 3.3 can thus be simplified to

$$\frac{D_{50}}{y_0} = 0.28 - 1.1\left(\frac{W}{2y_0}\right)\left(\frac{b-L}{b}\right), \qquad \text{for } 0.1 < \frac{D_{50}}{y} < 0.2. \tag{4.5}$$

4.1.2 Maximum Scour Depth d_s and Position d_x, d_y

Reductions in d_s of 37% to 60% were achieved by protecting the abutment with riprap, compared to the expected scour depth at an unprotected abutment. The scour depth decreased with increasing launching apron width and increasing riprap size. The greater the width of the launching apron, the greater the decrease in scour depth for an increase in riprap size.

The distance d_x increased with launching apron size and riprap size. As the launching apron width increases to 0.3 m, the percentage increase in d_x, compared to an abutment with no apron, appears to become independent of riprap size. The distance d_y also increased with launching apron size and riprap size. Compared to an abutment with no apron, d_y was increased by an average of 36% due to the presence of a launching apron.

4.1.3 Guidelines for launching aprons

Based on the results from this study, the recommended apron size of twice the flow depth seems conservative for clear-water conditions. A guideline should be developed that takes into account both the riprap stone size and the launching apron width. This would allow more flexibility with recommendations. Local availability of riprap could then be taken into consideration when selecting a launching apron width.

4.2 Mobile Bed Experiments

These studies have shown that launching aprons under mobile bed conditions, in comparison to clear water conditions, are subject to different failure mechanisms and the riprap behaves in a much more unpredictable manner. The presence of a filter fabric is vital to prevent winnowing of sediment from between the riprap stones.

Once a filter fabric was in place, no abutment failures were observed at test velocities of $U/U_{cs} = 1.25$. However, riprap failures were observed in all tests, where the filter fabric was exposed by removal of some of the riprap stones. In some tests, the filter fabric was exposed at the toe during the tests, however by this time a stable slope had been achieved on the side of the scour hole and no subsidence occurred. Launching apron widths of 0.1 m provided sufficient riprap for an amouring layer to form in the scour hole. Any increase in apron width over this amount resulted in a thicker amouring layer and excess riprap being displaced downstream.

All abutments tested at 1.5 U/U_{cs} failed by undermining of the abutment toe leading to slumping of the sediment beneath the filter fabric. Increasing riprap size showed an increase in protection, with less severe slumping occurring.

5. Recommentations for Further Testing

5.1 Clear Water Tests

Expansion of the data set to further refine Equation 4.3 would be desirable. This could be achieved by varying the riprap layer thickness, the flow depth, riprap size, particularly smaller riprap sizes than those tested, and abutment length.

5.2 Mobile Bed Tests

Two test parameters, in particular, have been identified as being worthy of further investigation. These are filter fabric flexibility and flow velocity.

5.2.1 Filter fabric

It has been questioned as to whether the filter fabric should be able to stay in place once exposed at the abutment toe. Anecdotal evidence suggests that filter fabrics normally lift and roll up when exposed in this way. The reason why the filter fabrics used in this test did not do this is unknown. The flexibility of the fabric could be investigated by testing with alternative fabrics. The coverage of the filter fabric could be varied also. It seems from observations that the downstream side of the abutment nearest the side of the flume does not require the extra protection the filter fabric provides. Significant cost savings could be achieved by reducing the amount of filter fabric required.

5.2.2 Velocity

For the tests undertaken in this study, all abutments experienced riprap failure but the sediment abutment did not fail. The velocity ratio U/U_{cs} should be investigated to find a value where some abutments fail and some do not. The influence of the degree of contraction, $\left(\frac{b-L}{b}\right)$ may be important.

6. References

Atayee, A.T. 1993. Study of riprap as scour protection for spill-through abutment, *Transportation Research Board Record 1420*, Washington DC.

Austroads 1994. *Waterway design - A guide to the hydraulic design of bridges, culverts and floodways,* Austroads, Sydney, Australia.

Blodgett J.C. and McConaughy C.E. 1985. *Evaluation of rock riprap design practices for protection of channels near highway structures - Phase I,* Preliminary Report subject to revision, prepared by the U.S. Geological Survey in cooperation with Federal Highway Administration.

Brown, S.A. and Clyde, E.S. 1989. Design of riprap revetment, Federal Highway Admin., U.S. Department of Transportation, Washington, D.C., *Report FHWA-IP-89-016, HEC-11.*

Central Board of Irrigation and Power, 1989. River behaviour management and training, Editors, C.V.J Sharma, K.R. Saxema and M.K.Rao, *Publication No 204, Volume 1,* Central Board of Irrigation and Power, New Delhi.

Chiew, Y.M. 1995. Mechanics of Riprap Failure at Bridge Piers. *Journal of Hydraulic Engineering, ASCE, 121 (9)*: 635-643.

Croad, R.N. 1989. Investigation of the pre-excavation of the abutment scour hole at bridge abutments, *Report 89-A9303*, Central Laboratories, Ministry of Works and Development, Lower Hutt, N.Z.

Gregorius, B.H. 1985. *Waterway design procedures - Guidelines,* Civil Division Publication, Ministry of Works and Development, Hamilton, New Zealand.

Harris, J.D. 1988. Hydraulic Design of Bridges *Chapter I, MTC Drainage Manual,* Drainage and Hydrology Section, Ontario Ministry of Transportation, Downview, Ontario.

Hudson, K., East, G.R.W. 1991. Geotextiles *Transit New Zealand Research Report No XX,* Wellington, New Zealand.

Lagasse, P.F., Byars, M.S., Zevenbergen, L.W. and Clopper, P.E. 1997. Bridge scour and stream instability countermeasures, *Hydraulic Engineering Circular No. 20* (HEC-20), Federal Highway Admin, U.S. Dept of Transportation, Report FHWA-IP-90-014, Washington, D.C., U.S.A.

Melville, B.W. and Coleman, S.E. 1999. *Bridge Scour,* Water Resources Publications, Colorado.

Ministry of Works and Development, 1979. Code of practice for the design of bridge waterways, *Civil Division Publication CDP 705/C*, Ministry of Works and Development, Wellington, New Zealand.

Pagan-Ortiz, J.E. 1991. Stability of rock riprap for protection of the toe of abutments located at the flood plain, Federal Highway Administration, *FHWA-RD-91-057*,

Richardson, E.V., Harrison, L.J., Richardson, J.R. and Davis, S.R. 1995. Evaluating Scour at Bridges, Federal Highway Adminstration, U.S. Dept of Transportation, *HEC 18.*

Richardson, E.V., Simons, D.B., Julien, P.Y. 1988. *Highways in the river environment.* Federal Highway Administration, U.S. Dept of Transportation.

Smart, G.M. 1990. *Rip-rap scour protection: Practices for New Zealand roads,* DSIR, Hydrology Centre, Christchurch.

Table 3.1 Data parameters recorded at conclusion of each test

Parameter	Measurement method
Failure	Criterion as outlined in Section 2.2.2.
Scour depth, d_s	Measured from original sediment bed level
Position of maximum scour	Distances d_x and d_y, measured from original position of abutment toe (see Figure 3.2).
Contours of scour hole	Profiled with string and photographed.
Method of failure	Recorded from observations

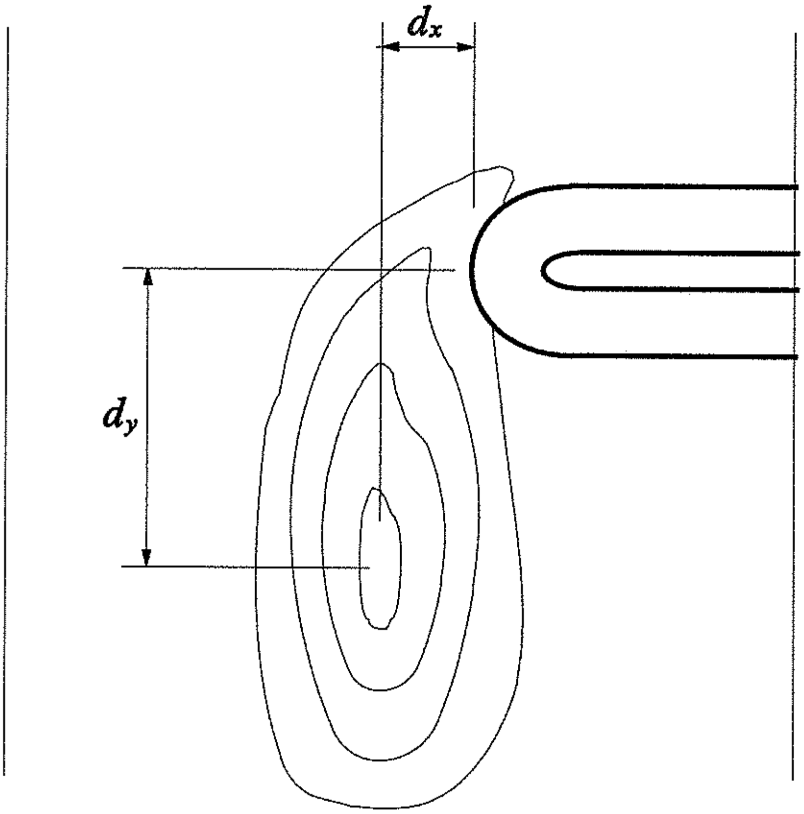

Figure 3.2 Distances *dx* and *dy* were measured relative to abutment toe for each test.

3.1.1 Clearwater Test Results

The experimental setup and recorded data from each test are summarised in Table 3.2. The tests have not been listed in sequence, but have been sorted, first by abutment length, then riprap stone size, then launching apron size to allow comparison.

3.1.1.1 Failure mechanisms

All abutments that failed exhibited translational slide failure where a mass of riprap stones moved down the embankment slope due to undermining of the abutment toe. This resulted in a gentler slope, which eventually became stable. When considering the stability of a foundation placed in the abutment, any movement of the abutment slopes is detrimental to the support of the foundation, thus any movement of the sediment was considered a failure.

by current guidelines ($W = 2y_o$), with θ and ϕ equal to zero. These areas exclude the riprap area on the embankment slope. An example is shown in Figure 4.2, for an abutment where $\theta = 45°$ and $\phi = 0°$.

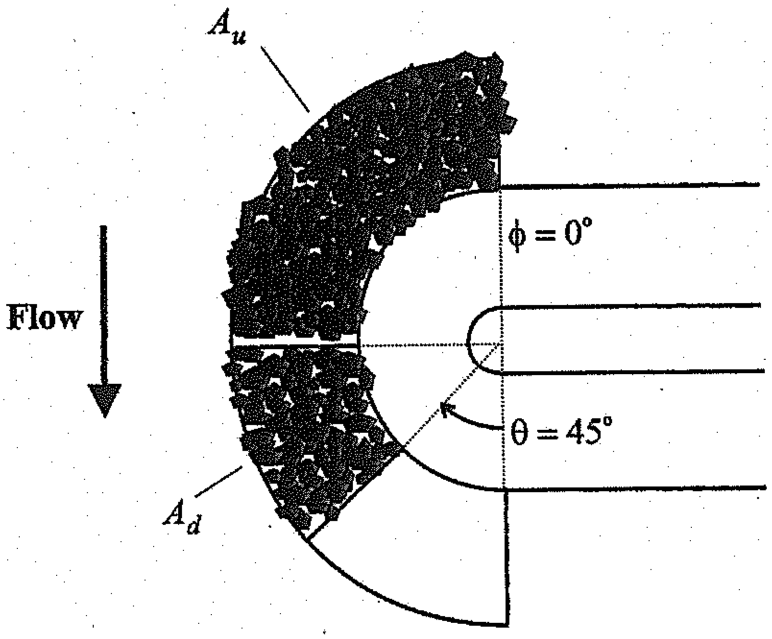

Figure 4.2 *Au* and *Ad* for a launching apron.

The summation $A_u + A_d$ can be represented as a proportion of A_*, such that

$$\left(A_u + A_d\right) = \frac{W}{2y}\left[\frac{180-\left(\theta+\phi\right)}{180}\right]A_*. \tag{4.1}$$

The term $\left(\frac{b-L}{b}\right)$ is the contraction ratio for the channel, where b is the channel width and L is the abutment length, measured at mid-depth.

The line shown in Figure 4.1 is a line of best fit for the partial failure data points, and follows the linear relationship

$$\frac{D_{50}}{y} = 0.28 - 1.1\left(\frac{A_u + A_d}{A_*}\right)\left(\frac{b-L}{b}\right), \qquad \text{for } 0.1 < \frac{D_{50}}{y} < 0.2. \tag{4.2}$$

The application of this relationship is limited to the test conditions under which it was formulated, hence the limiting condition for $\frac{D_{50}}{y}$.