http://researchspace.auckland.ac.nz

ResearchSpace@Auckland

Copyright Statement

The digital copy of this thesis is protected by the Copyright Act 1994 (New Zealand).

This thesis may be consulted by you, provided you comply with the provisions of the Act and the following conditions of use:

- Any use you make of these documents or images must be for research or private study purposes only, and you may not make them available to any other person.
- Authors control the copyright of their thesis. You will recognise the author’s right to be identified as the author of this thesis, and due acknowledgement will be made to the author where appropriate.
- You will obtain the author's permission before publishing any material from their thesis.

To request permissions please use the Feedback form on our webpage. http://researchspace.auckland.ac.nz/feedback

General copyright and disclaimer

In addition to the above conditions, authors give their consent for the digital copy of their work to be used subject to the conditions specified on the Library Thesis Consent Form.
BRIDGE ABUTMENT SCOUR COUNTERMEASURES

by

Sjoerd van Ballegooy

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Engineering, The University of Auckland, 2005

Supervised by

Prof. Bruce W. Melville
Dr. Stephen E. Coleman

Department of Civil and Environmental Engineering
The University of Auckland
Private Bag 92019
Auckland
New Zealand
ABSTRACT

The use of riprap and cable-tied blocks as scour countermeasures at bridge abutments is investigated. Riprap is the most common armouring scour protection method used at bridge abutments and approach embankments. Despite the widespread use of riprap protection, the guidelines for its use at bridge abutments are based on limited research.

The aim of the experimental study was to determine the requirements of riprap and cable-tied block apron countermeasures to protect bridge abutments from scour damage, and to produce design guidelines for their use.

The two types of bridge abutments used in the experimental study were a spill-through abutment situated on the floodplain of a compound channel, and a wing-wall abutment sited at the edge of the main channel. The spill-through abutment experiments were run under clear-water conditions, and the variations in the scour hole geometry were measured for different abutment and compound channel geometries, apron widths and apron types. The wing-wall abutment experiments were run under live-bed conditions, and the settled apron geometries were measured for different flow depths, flow velocities, apron widths, apron types and apron placement levels. The flow fields around the abutments were also measured for both abutment types.

The clear-water spill-through abutment results show that the protection aprons do not significantly reduce the scour depth at abutments, but instead deflect the scour hole further away from the abutment, protecting it from scour failure. The experiments also show that cable-tied block aprons allow the scour hole to form much closer to the abutment compared to equivalent riprap aprons. Equations were developed to predict the scour hole position and size, and the minimum apron extent required to prevent the scour hole from undermining the abutment. For the live-bed wing-wall abutment experiments, the troughs of the propagating bed-forms undermined the outer edges of the aprons, causing them to settle. Equations were developed to predict the settled apron geometry at the equilibrium scour conditions.

The predicted scour hole depth and position for clear-water scour conditions, or the predicted apron settlement geometry for live-bed scour conditions can be used in a
Abstract

geotechnical stability analysis of the abutment. The geotechnical stability analysis forms the basis of the abutment scour countermeasure design procedure, which was developed from the experimental study. Further experimental work is required to increase the robustness of the bridge abutment scour countermeasure design procedure and make it applicable to a wider range of situations.
ACKNOWLEDGEMENTS

This study was supervised by Prof. B. W. Melville and Dr. S. E. Coleman, to whom I am grateful for the advice, guidance, support and general help given throughout the course of study.

The study was undertaken with the financial support from the National Cooperative Highway Research Program, Transportation Research Board, NCHRP 24-18. Also, the financial support provided by the Tertiary Education Commission in the form of a Top Achiever Doctoral Scholarship is gratefully acknowledged.

Throughout the study many people have assisted in the research work. In particular I would like to thank the following people:

- My wife, Priscilla van Ballegooy, for supporting and encouraging me during the course of the studies, being willing to spend many late nights and weekends in the laboratory helping to set-up, checking up on and contouring experiments;
- My brother, Rick van Ballegooy, for his friendship and for spending countless hours in the laboratory helping me set-up experiments;
- The Department of Civil Engineering from the University of Canterbury, for the use of their PTV software to analyse the flow field measurements around the abutments;
- The laboratory technicians, Ray Hoffman, Jim Luo and Geoff Kirby. A special thanks to Ray for his interest, help and encouragement in the research work; and
- My fellow post-graduate students, Stuart Cameron, Dougal Clunie and Heide Friedrich. A special thanks to Stuart for his assistance with computer related problems encountered throughout the study.

Finally, I would like to thank my family for their support and encouragement, and most importantly I would like to thank God for giving me the opportunity to do this study.
# TABLE OF CONTENTS

Abstract i  
Acknowledgments iii  
Table of Contents iv  
Nomenclature ix

## SECTION 1. INTRODUCTION

## SECTION 2. BACKGROUND THEORY

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Introduction</td>
<td>4</td>
</tr>
<tr>
<td>2.2</td>
<td>Sediment Transport Theory</td>
<td>4</td>
</tr>
<tr>
<td>2.2.1</td>
<td>Sediment entrainment</td>
<td>4</td>
</tr>
<tr>
<td>2.2.2</td>
<td>Bed-forms</td>
<td>6</td>
</tr>
<tr>
<td>2.3</td>
<td>Mechanics of Scour</td>
<td>7</td>
</tr>
<tr>
<td>2.3.1</td>
<td>Types of scour at bridge crossings</td>
<td>7</td>
</tr>
<tr>
<td>2.3.2</td>
<td>Scour development at abutments</td>
<td>8</td>
</tr>
<tr>
<td>2.3.3</td>
<td>Scour mechanisms at abutments</td>
<td>10</td>
</tr>
<tr>
<td>2.4</td>
<td>Prediction of Local Scour Depth at Bridge Abutments</td>
<td>13</td>
</tr>
<tr>
<td>2.4.1</td>
<td>Parameters affecting scour depth</td>
<td>13</td>
</tr>
<tr>
<td>2.4.2</td>
<td>Methodology for predicting scour depth</td>
<td>15</td>
</tr>
</tbody>
</table>

## SECTION 3. LITERATURE REVIEW

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Introduction</td>
<td>21</td>
</tr>
<tr>
<td>3.2</td>
<td>Riprap as a Scour Countermeasure</td>
<td>22</td>
</tr>
<tr>
<td>3.2.1</td>
<td>Riprap failure mechanisms</td>
<td>22</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Riprap stability</td>
<td>25</td>
</tr>
<tr>
<td>3.3</td>
<td>Cable-tied Blocks as a Scour Countermeasure</td>
<td>28</td>
</tr>
<tr>
<td>3.3.1</td>
<td>Cable-tied block failure mechanisms</td>
<td>29</td>
</tr>
<tr>
<td>3.3.2</td>
<td>Cable-tied block stability</td>
<td>31</td>
</tr>
<tr>
<td>3.4</td>
<td>Guidance for the Use of Riprap at Abutments</td>
<td>33</td>
</tr>
<tr>
<td>3.4.1</td>
<td>Riprap size</td>
<td>33</td>
</tr>
<tr>
<td>3.4.2</td>
<td>Aerial extent of riprap protection</td>
<td>35</td>
</tr>
</tbody>
</table>
3.4.3 Riprap layer thickness  38
3.4.4 Riprap gradation  38
3.4.5 Filter requirements  39
3.4.6 Riprap placement  41

3.5 Guidance for the Use of Cable-tied Blocks at Abutments  43
3.5.1 Cable-tied block size and shape  43
3.5.2 Aerial extent of cable-tied block protection  46
3.5.3 Anchoring  46
3.5.4 Cabling  47
3.5.5 Concrete quality  47
3.5.6 Filter requirements  48

3.6 Previous Experimental Studies of Scour Countermeasures at Abutments  49
3.6.1 Macky (1986)  49
3.6.2 Croad (1989)  51
3.6.3 Pagan-Ortiz (1991)  54
3.6.4 Atayee (1993)  57
3.6.5 Eve (1999)  59
3.6.6 Hoe (2001)  63
3.6.7 Cheung (2002)  65
3.6.8 Martinez (2003) and Korkut (2004)  68

3.7 Summary  71

SECTION 4. EXPERIMENTAL METHODOLOGY  73
4.1 Introduction  73

4.2 Experimental Equipment  75
4.2.1 Cable-tied block stability experimental equipment set-up  75
4.2.2 Spill-through abutment experimental set-up  78
4.2.3 Wing-wall abutment experimental set-up  84
4.2.4 Materials used in the experimental studies  91
4.2.5 Instrumentation used in the experimental studies  96

4.3 Cable-tied Block Mat Stability Study  100
4.3.1 Introduction  100
4.3.2 Experimental procedure  100
### 4.3.3 Critical flow measurements

#### 4.4 Bridge Abutment Flow Fields

- 4.4.1 Introduction
- 4.4.2 Establishing upstream flow conditions
- 4.4.3 PTV technique

#### 4.5 Spill-through Abutment Clear-water Study

- 4.5.1 Introduction
- 4.5.2 Preliminary experiments
- 4.5.3 Experimental procedure
- 4.5.4 Measurements

#### 4.6 Wing-wall Abutment Live-bed Study

- 4.6.1 Introduction
- 4.6.2 Preliminary experiments
- 4.6.3 Experimental procedure
- 4.6.4 Measurements

---

#### SECTION 5. CABLE-TIED BLOCK MAT STABILITY STUDY

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1 Introduction</td>
<td>135</td>
</tr>
<tr>
<td>5.2 Experimental Results</td>
<td>135</td>
</tr>
<tr>
<td>5.3 Experimental Observations</td>
<td>135</td>
</tr>
<tr>
<td>5.3.1 Failure mechanisms</td>
<td>135</td>
</tr>
<tr>
<td>5.3.2 Block mat flow conditions</td>
<td>138</td>
</tr>
<tr>
<td>5.4 Discussion</td>
<td>139</td>
</tr>
<tr>
<td>5.4.1 Individual block and cable-tied block mat comparisons</td>
<td>139</td>
</tr>
<tr>
<td>5.4.2 Data analysis</td>
<td>140</td>
</tr>
<tr>
<td>5.4.3 Comparison of the experimental results with previous work</td>
<td>143</td>
</tr>
</tbody>
</table>

---

#### SECTION 6. BRIDGE ABUTMENT FLOW FIELDS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1 Introduction</td>
<td>145</td>
</tr>
<tr>
<td>6.2 Data Analysis</td>
<td>145</td>
</tr>
<tr>
<td>6.3 Results</td>
<td>150</td>
</tr>
<tr>
<td>6.4 Spill-through Abutment Flow Field Observations</td>
<td>150</td>
</tr>
<tr>
<td>6.5 Discussion</td>
<td>157</td>
</tr>
<tr>
<td>6.5.1 Comparison of the experimental results with previous work</td>
<td>157</td>
</tr>
</tbody>
</table>
6.5.2 Bed shear stress estimation
6.5.3 General trends for the spill-through abutments

SECTION 7. SPILL-THROUGH ABUTMENT CLEAR-WATER STUDY 162

7.1 Introduction
7.2 Experimental Results
  7.2.1 Summary of results
  7.2.2 General trends
7.3 Experimental Observations
  7.3.1 Riprap and CTB apron behaviour
  7.3.2 Flow field observations
7.4 Discussion
  7.4.1 Comparison of the experimental data with previous work
  7.4.2 Data analysis
  7.4.3 Comparison of the scour depth prediction method with other experimental data
  7.4.4 Flow field correlations with scour hole depths

SECTION 8. WING-WALL ABUTMENT LIVE-BED STUDY 204

8.1 Introduction
8.2 Experimental Results
  8.2.1 Summary of results
  8.2.2 General trends
8.3 Experimental Observations
  8.3.1 Riprap and CTB apron behaviour
  8.3.2 Comparison of riprap observations with Lauchlan (1999)
8.4 Discussion
  8.4.1 Comparison of the experimental results with the clear-water spill-through abutment study
  8.4.2 Bed-forms
  8.4.3 Riprap and CTB stability
  8.4.4 Data analysis
### SECTION 9. APPLICATION

- 9.1 Abutment Failure Mechanisms 233
- 9.2 Countermeasure Design Procedures 238
- 9.3 Design Procedure Advantages 243
- 9.4 Scour Countermeasure Design Example 245

### SECTION 10. CONCLUSIONS AND RECOMMENDATIONS

- 10.1 Conclusions 247
  - 10.1.1 Cable-tied block mat stability 247
  - 10.1.2 Abutment flow fields 248
  - 10.1.3 Scour countermeasures for spill-through abutments under clear-water conditions 248
  - 10.1.4 Scour countermeasures for wing-wall abutments under live-bed conditions 249
- 10.2 Recommendations for Further Experimental Work 251

### SECTION 11. REFERENCES

### APPENDICES

- Appendix 1. Flume Settings 263
- Appendix 2. Bed Profiles 266
- Appendix 3. Cable-tied Block Velocity Profiles 275
- Appendix 4. Abutment Flow Field Plots (contained in the CD) 300
- Appendix 5. Spill-through Abutment Clear-water Scour Photographs 302
- Appendix 6. Wing-wall Abutment Live-bed Scour Photographs 305
- CD Containing Material from Appendices 4, 5 and 6 308
NOMENCLATURE

The following symbols are used in this thesis:

- $a_{cb}$ = coefficient in Eq. (3.9);
- $a_r$ = parameter used in Eq. (6.2);
- $A_l$ = parameter describing the abutment alignment;
- $A_2$ = cross-sectional flow area in the contracted bridge section (Fig. 3.6);
- $A_{2f}$ = cross-sectional flow area on the floodplain in the contracted bridge section (Fig. 3.6);
- $B$ = flume width;
- $B_f$ = floodplain width (Figs. 4.7 and 4.12);
- $B_L$ = distance between the abutment toe and the main channel (Fig. 3.6);
- $C_1$ = coefficient in Eq. (7.3);
- $C_2$ = coefficient in Eq. (7.4);
- $C_3$ = coefficient in Eq. (7.10);
- $C_4$ = coefficient in Eq. (8.2);
- $C_5$ = coefficient in Eqs. (8.5 and 8.6);
- $C_6$ = coefficient in Eq. (8.6);
- $d$ = sediment diameter;
- $d_b$ = placement level of the apron, measured from average bed level (Fig. 4.47);
- $d_s$ = local scour depth;
- $d_{se}$ = equilibrium local scour depth;
- $d_{se-max}$ = maximum equilibrium scour depth;
Nomenclature

\(d_{sf}\) = local scour depth measured relative to the floodplain bed level (Fig. 4.43);

\(d_{sl}\) = depth of settlement of the apron at the abutment face (Fig. 4.48);

\(d_{s2}\) = depth of settlement of the outer edge of the apron (Fig. 4.48);

\(d_{15}\) = sediment diameter for which 15\% of the sediment is finer by weight;

\(d_{16}\) = sediment diameter for which 16\% of the sediment is finer by weight;

\(d_{50}\) = median size of bed sediment (size for which 50\% of the sediment is finer by weight);

\(d_{84}\) = sediment diameter for which 84\% of the sediment is finer by weight;

\(d_{85}\) = sediment diameter for which 85\% of the sediment is finer by weight;

\(d_{90}\) = sediment diameter for which 90\% of the sediment is finer by weight;

\(D_r\) = riprap diameter;

\(D_{15}\) = riprap size for which 15\% of the stones are smaller by weight;

\(D_{16}\) = riprap size for which 16\% of the stones are smaller by weight;

\(D_{30}\) = riprap size for which 30\% of the stones are smaller by weight;

\(D_{50}\) = median size of riprap (size for which 50\% of the stones are smaller by weight);

\(D_{84}\) = riprap size for which 84\% of the stones are smaller by weight;

\(D_{100}\) = riprap size for which 100\% of the stones are smaller by weight;

\(E\) = coefficient in Eq. (3.1);

\(F\) = function given in Eq. (7.7);

\(F_D\) = drag force;

\(F_L\) = lift force;

\(Fr\) = flow Froude number;

\(Fr_f\) = flow Froude number on the floodplain;
\( Fr_{fc} \) = critical flow Froude number on the floodplain;
\( Fr_2 \) = flow Froude number in the contracted bridge section;
\( g \) = acceleration of gravity (=9.81m/s\(^2\));
\( G \) = parameter describing the channel geometry;
\( h \) = parameter used for Eq. (2.7);
\( \bar{h}_d \) = parameter used for Eq. (2.7);
\( H \) = cable-tied block height;
\( k_s \) = bed roughness (=2d\(_{50}\));
\( K_d \) = sediment size factor;
\( K_G \) = channel geometry factor;
\( K_i \) = flow intensity factor;
\( K_s \) = abutment shape factor;
\( K_{sf} \) = embankment slope factor;
\( K_s^* \) = adjusted abutment shape factor;
\( K_t \) = time factor;
\( K_{yl} \) = flow depth-abutment length factor;
\( K_h \) = abutment alignment factor;
\( K_h^* \) = adjusted abutment alignment factor;
\( l_1, l_2 \) = moment arms of the weight of the block (Fig. 3.5);
\( l_3, l_4 \) = moment arms of the drag and lift forces on the block (Fig. 3.5);
\( L \) = length of abutment, including the approach embankment;
\( L_b \) = length of the base of the cable-tied blocks;
\( L_s \) = slope length of settled riprap layer (Fig. 8.17);
\( L_t \) = length of the top of the cable-tied blocks;
\( m \) = parameter used for Eqs. (2.6 and 2.7);
\( M \) = channel hydraulic radius;  
\( n \) = exponent in Eq. (3.6);  
\( n_f \) = Mannings roughness of the floodplain bed;  
\( n_m \) = Mannings roughness of the main channel bed;  
\( N_{sc} \) = dimensionless stability factor;  
\( O_{50} \) = median geotextile filter pore size;  
\( p \) = volume fraction pore space in a cable-tied block mattress;  
\( P \) = cable-tied block protrusion above the flume bed;  
\( q \) = parameter used for Eqs. (2.6 and 2.7);  
\( Q \) = flow rate;  
\( Q_r \) = total flow rate;  
\( Q_0 \) = portion of the approach flow in the bridge opening;  
\( Q_{150-1} \) = flow discharge in the silver-coloured 150-mm diameter pipe;  
\( Q_{150-2} \) = flow discharge in the yellow-coloured 150-mm diameter pipe;  
\( Q_{2f} \) = flow discharge on the floodplain in the contracted bridge section (Fig 3.6);  
\( Q_{200} \) = flow discharge in the silver-coloured 200-mm diameter pipe;  
\( r \) = radius of the spill-through abutment toe;  
\( R \) = distance from the end of the abutment to the deepest point of the scour hole (Fig. 4.43);  
\( Re^* \) = grain Reynolds number;  
\( Sh \) = parameter describing the abutment shape;
Nomenclature

\[ S_s = \text{specific gravity of sediment or riprap material;} \]
\[ SF = \text{factor of safety;} \]
\[ t = \text{time of flood duration;} \]
\[ t_e = \text{time required for equilibrium scour to develop;} \]
\[ T = \text{sediment transport parameter;} \]
\[ U, V = \text{mean velocity of flow;} \]
\[ U_c, V_c = \text{critical flow velocity at the threshold of sediment motion;} \]
\[ U_{tip}, V_{tip} = \text{velocity at the end of the abutment;} \]
\[ U_2, V_2 = \text{mean flow velocity in the contracted bridge section;} \]
\[ U_s = \text{shear velocity;} \]
\[ U_{sc} = \text{critical shear velocity;} \]
\[ U_{ecr} = \text{critical shear velocity for riprap movement;} \]
\[ U_s' = \text{parameter used in Eq. (2.5);} \]
\[ V_a = \text{mean velocity at the armour peak (=} V_c \text{ for uniform sediments);} \]
\[ V_f = \text{flow velocity on the floodplain;} \]
\[ V_{fc} = \text{critical flow velocity on the floodplain;} \]
\[ V_x = \text{flow velocity in downstream (x) direction;} \]
\[ V_y = \text{flow velocity in transverse (y) direction;} \]
\[ V_z = \text{flow velocity in vertical (z) direction;} \]
\[ V_{2-ave} = \text{surface flow velocity in the contracted bridge section;} \]
\[ V_{2-surf} = \text{depth-averaged flow velocity in the contracted bridge section;} \]
\[ W = \text{extent of apron protection (Figs. 4.39 and 4.47);} \]
\[ W_A = \text{weight force;} \]
\[ W_{min} = \text{minimum width of apron protection after scour development} \]
\text{(Figs. 4.43 ad 4.48);}
**Nomenclature**

\[ W_0 \] = value of \( W \) when \( W_{min} = 0 \);

\( y \) = flow depth;

\( y_f \) = flow depth on the floodplain (Figs. 4.7 and 4.12);

\( y_m \) = flow depth in the main channel (Figs. 4.7 and 4.12);

\( y_2 \) = flow depth in the contracted bridge section;

\( y_{2f} \) = flow depth on the floodplain in the contracted bridge section (Fig. 3.6);

\( z \) = elevation above the flume bed;

\( \alpha \) = flow direction, measured relative to the longitudinal direction of the flume (Fig. 4.7);

\( \alpha_e \) = position of the outer edge of the scour hole (Fig. 4.43);

\( \alpha_s \) = longitudinal distance from the end of the abutment to the deepest point of the scour hole (Fig. 4.43);

\( \alpha_p \) = lateral distance from the end of the abutment to the deepest point of the scour hole (Fig. 4.43);

\( \alpha_2 \) = lateral extent of the apron after settlement (Fig. 4.48);

\( \beta \) = angle between the vertical plane and the direction of particle movement (Fig. 3.5);

\( \delta \) = angle between the direction of the drag force and the direction of particle movement (Fig. 3.5);

\( \Delta h \) = head of mercury (Hg) in the manometer;

\( \Delta x \) = grid spacing in the \( x \) direction;

\( \Delta y \) = grid spacing in the \( y \) direction;
Nomenclature

\( \phi \) = exponent in Eq. (7.3);
\( \phi_1 \) = upstream apron extent (Fig. 3.26);
\( \phi_2 \) = downstream apron extent (Fig. 3.26);
\( \phi' \) = angle of repose;
\( \Phi_d \) = parameter used in Eqs. (2.6 and 2.7);
\( \varphi \) = exponent in Eq. (7.4);
\( \lambda \) = channel slope (Fig. 3.5);
\( \lambda \) = exponent in Eq. (7.10);
\( \lambda_D \) = bed-form trough depth (measured from the average bed level);
\( \lambda_{D-ave} \) = average bed-form trough depth;
\( \lambda_{D-max} \) = maximum bed-form trough depth;
\( \lambda_H \) = bed-form height (measured from crest to trough);
\( \lambda_{H-ave} \) = average bed-form height;
\( \lambda_{H-max} \) = maximum bed-form height;
\( \lambda_L \) = bed-form length (measured from crest to crest);
\( \lambda_{L-ave} \) = average bed-form length;
\( \lambda_{L-max} \) = maximum bed-form length;
\( \theta \) = abutment alignment angle (Fig. 2.8);
\( \theta \) = angle defining the position of the deepest point of scour (Fig. 4.43);
\( \theta_0 \) = bank slope angle (Fig. 3.5);
\( \theta_c \) = dimensionless shear stress;
\( \theta_c \) = critical dimensionless shear stress;
\( \rho \) = fluid density;
\( \rho_{cb} \) = block density;
\[ \rho_s = \text{sediment density}; \]
\[ \sigma_g = \text{sediment geometric standard deviation}; \]
\[ \tau = \text{shear stress}; \]
\[ \tau_c = \text{critical shear stress}; \]
\[ \tau_{wc} = \text{critical bed shear stress, adjusted for localised bed slope}; \]
\[ \nu = \text{fluid kinematic viscosity}; \]
\[ \omega = \text{vorticity}; \]
\[ \omega_{\text{max}} = \text{maximum vorticity}; \]
\[ \zeta = \text{weight per unit area of the cable-tied block mattress}; \]
\[ \bar{\zeta} = \text{parameter used in Eq. (2.7)}. \]