Appendix 16  
Review of the Impact of Blasting on Rock Mass Permeability
Bickham Coal Company

Impact of Blasting on Rock Mass Permeability

Prepared by
Andrew Scott
12th January, 2009
Bickham Coal Company

Review of the Impact of Blasting on Rock Mass Permeability

Prepared by

Andrew Scott

12th January, 2009
Executive Summary

The Bickham Coal Company Pty Ltd (Bickham) are preparing a proposal to develop an open pit coal mine approximately 13 km south of Murrurundi in the northern Hunter Valley of New South Wales. The Pages River flows around the northern and eastern boundaries of the proposed mining area at the base of a steep ridge. The Department of Natural Resources – Hunter Region have designated the Pages River as a Schedule 3 Stream requiring approval if mining operations are to be undertaken within a prescribed distance from the river.

This report reviews mining industry experience with respect to the effect of blasting on the permeability of adjacent strata and assesses the potential for this to occur as a result of the proposed Bickham blasting operations. Disruption of stream flows from the effects of blasting in adjacent mining operations is not a feature that has been observed in Hunter Valley mining operations. An extensive literature search has failed to find any cases described in the Australian or international mining or groundwater literature.

Because there are no documented case studies to work from, a fundamental approach has been taken to assess the likely impact of mine blasting on the permeability of strata between the Pages River and the mine. The mechanisms of blast damage and the impact of this damage on rock mass permeability are discussed from both theoretical and practical points of view. The likely impact of the mining operations at Bickham on the permeability of the rock mass between the mine and the Pages River is estimated and recommendations are made for the design and conduct of blasting operations to manage the extent of such damage.

The pit boundaries have been planned so that the workings are a minimum of 300 m from the river at or below the level of the river at normal flow.

To the north of the proposed mining operations the river bed lies down dip of the coal seams to be mined. This means that any leakage path between the river and the pit would have to flow across the strata bedding planes, which is not consistent with the usual flow behaviour in bedded strata. On the eastern side of the pit the river is up-dip of the pit and potential leakage paths could lie along these bedding planes.

There are four mechanisms by which the mining operations could affect the permeability of these strata. These are:

- stress relaxation caused by the excavation leading to the opening of rock mass structures
- block instability leading to movement on some of the persistent structures.
seepage occurring along coal seams or strata bedding on the north-eastern side of the pit

- blast damage creating new leakage paths through the overburden.

The first two of these mechanisms can be subjected to conventional geotechnical analysis to determine their possible effect on the potential leakage paths from the Pages River into the Bickham pit and the third can be evaluated by ground water modeling. This report discusses the fourth of these mechanisms – the potential impact of mine blasting on the permeability of adjacent strata.

The author inspected the proposed mining area in January 2005. There do not appear to be any unique circumstances associated with the proposed Bickham mining operation that would make the routine design and management of the blasting operations difficult or especially challenging. Blasting operations in the Bulk Sample Pit are reported to have been effective in preparing muckpiles for excavation and have caused minimal visible damage to pit walls.

The report summarises the basic mechanisms involved in blast fragmentation and the basis of the design of blasts to maximise excavation efficiency while minimising damage and environmental disturbance. Basic blast designs are recommended in the report for blasting in the northern part of the mine near the river. These designs need to form part of a blasting system that should include:

- A pre-split blast on all critical walls fired well before production blasts are fired in the area
- Production blasts designed to ensure good fragmentation and loose digging while leaving clean trim benches 10m to 15 m from the walls
- Excavation of the production patterns to leave a clean free face and even burdens for the trim blasts
- Trim blasts designed with adequate powder factor, three rows and large spacing to burden ratios
- Focussed clean-up of final walls.

A fundamental discussion is provided on the flow of water through structured rock and the potential blast damage mechanisms that could lead to an increase in permeability. Theoretical approaches to estimate the extent of damage in a rock mass for a given blast design are discussed. The wide range of circumstances under which research into these matters has been conducted means that there are still some divergent views about these basic mechanisms and the methods that should be used to predict damage. However, there is also abundant practical experience in the blasting of rock similar to that at Bickham and so the overall requirements for blasting operations to limit the extent of damage to the pit walls can be identified with considerable confidence.

The rock mass properties expected in the northern part of the proposed Bickham mine have been reviewed. The rock mass exposed in the Bulk Sample Pit substantially
confirms the interpretations previously made from exploration borehole logs and geophysics. There are no unusual challenges to be overcome in designing blasts to meet the production, environmental and damage requirements for the proposed Bickham operation.

A useful case study involving the measurement of damage behind a production blast in Hunter Valley sandstone is discussed and used to demonstrate the application of a simple but useful damage model. The role of basic blast geometry and design parameters in the management of blast damage is discussed and the resulting trends are used to propose initial designs for both production and wall control blasts in the critical areas of the Bickham mine.

The damage expected from the blasting operations at Bickham has been modeled using the approaches described in the report. Provided the operations are designed using the approaches recommended and implemented to a reasonable standard then there should be negligible impact on the permeability of the pit walls more than 15 m from the blast. Damage beyond two trim blast burdens (about 8 m) is likely to be very minor and difficult to discern.

These distances are very small compared with the 300 m off-set provided by the mine design. It is therefore concluded that any direct damage caused by the blasting operations proposed for the Bickham Mine will be limited to the immediate vicinity of the blast and will not affect the permeability of the strata between the mine and Pages River.
Table of Contents

Executive Summary ................................................................. i

1. Introduction ........................................................................... 1

2. Mining Near Bodies of Water
   2.1 Basic Issues and Industrial Experience ............................... 3
   2.2 Bickham Situation .......................................................... 4

3. Blasting Mechanisms and Principles of Blast Design
   3.1 Objectives of Blasting ...................................................... 7
   3.2 Blast Design Principles .................................................... 7
   3.3 Basic Blasting Mechanisms .............................................. 10
   3.4 Bickham Mine and Blast Designs ..................................... 15

4. Permeability and Rock Mass Damage
   4.1 Permeability .................................................................... 17
       4.1.1 Flow though Structured Rock
       4.1.2 Measurement of Permeability
   4.2 Rock Mass Damage ......................................................... 19
       4.2.1 Definition
       4.2.2 Basic Mechanisms
   4.3 Prediction of Damage ....................................................... 21
       4.3.1 Vibration
       4.3.2 Gas
   4.4 Measurement of Blast Damage ......................................... 29
   4.5 Management of Blast Damage .......................................... 29
# Table of Contents

<table>
<thead>
<tr>
<th>5. Potential Effect of Blast Damage on Rock Mass Permeability at the Bickham Mine</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1 Rock Mass Properties</td>
<td>31</td>
</tr>
<tr>
<td>5.2 Potential Damage from Bickham Blast Designs</td>
<td>34</td>
</tr>
<tr>
<td>5.3 Recommended Blast Designs for the Bickham Operation</td>
<td>36</td>
</tr>
<tr>
<td>5.3.1 Blasting System</td>
<td></td>
</tr>
<tr>
<td>5.3.2 Pre-Split</td>
<td></td>
</tr>
<tr>
<td>5.3.3 Production Blasts</td>
<td></td>
</tr>
<tr>
<td>5.3.4 Trim Blasts</td>
<td></td>
</tr>
<tr>
<td>6. Conclusions</td>
<td>39</td>
</tr>
</tbody>
</table>

Bibliography
List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>Proposed mining area at Bickham</td>
<td>1</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Location of Sections</td>
<td>4</td>
</tr>
<tr>
<td>Figure 3</td>
<td>Cross Section N-S 2</td>
<td>5</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Cross Section N-S 3</td>
<td>5</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Cross Section E-W 3</td>
<td>5</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Cross Section E-W 2</td>
<td>5</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Basic terminology used in blast design</td>
<td>8</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Simple bench layout with two free faces</td>
<td>8</td>
</tr>
<tr>
<td>Figure 9</td>
<td>Typical pre-split charges using bulk explosives</td>
<td>9</td>
</tr>
<tr>
<td>Figure 10</td>
<td>Pre-split results in F seam interburden</td>
<td>10</td>
</tr>
<tr>
<td>Figure 11</td>
<td>Combination of stress and gas effects</td>
<td>12</td>
</tr>
<tr>
<td>Figure 12</td>
<td>Fracture pattern in hydrostone model</td>
<td>13</td>
</tr>
<tr>
<td>Figure 13</td>
<td>Influence of blast geometry and relief on breakage and damage</td>
<td>14</td>
</tr>
<tr>
<td>Figure 14</td>
<td>Control of fragmentation and damage in coal overburden</td>
<td>15</td>
</tr>
<tr>
<td>Figure 15</td>
<td>Basic pit and blast geometry proposed for the Bickham mine</td>
<td>16</td>
</tr>
<tr>
<td>Figure 16</td>
<td>Parameters for the Holmberg-Persson Equation</td>
<td>22</td>
</tr>
<tr>
<td>Figure 17</td>
<td>PPV verses distance from a Bickham blast hole</td>
<td>23</td>
</tr>
<tr>
<td>Figure 18</td>
<td>Vibrations at different burdens</td>
<td>25</td>
</tr>
<tr>
<td>Figure 19</td>
<td>Gas pressures measured at different distances behind blasts</td>
<td>26</td>
</tr>
</tbody>
</table>
# List of Figures (Contd)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 20</td>
<td>Typical gas pressure measurement trace</td>
<td>27</td>
</tr>
<tr>
<td>Figure 21</td>
<td>Correlation of negative pressures and visible fractures</td>
<td>28</td>
</tr>
<tr>
<td>Figure 22</td>
<td>F Seam interburden in the base of the bulk sample pit</td>
<td>32</td>
</tr>
<tr>
<td>Figure 23</td>
<td>E Seam overburden in the northern wall of the bulk sample pit</td>
<td>33</td>
</tr>
<tr>
<td>Figure 24</td>
<td>Modelled vibration attenuation for different blast designs</td>
<td>34</td>
</tr>
<tr>
<td>Figure 25</td>
<td>Expected vibration behind the recommended Bickham trim blast and pre-split designs</td>
<td>35</td>
</tr>
<tr>
<td>Figure 26</td>
<td>Pre-split, production and trim blast geometry</td>
<td>36</td>
</tr>
<tr>
<td>Figure 27</td>
<td>Section through production and trim blast</td>
<td>38</td>
</tr>
</tbody>
</table>
# List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1</td>
<td>Representative interburden and material properties</td>
<td>33</td>
</tr>
<tr>
<td>Table 2</td>
<td>Nominal production blast designs</td>
<td>37</td>
</tr>
<tr>
<td>Table 3</td>
<td>Nominal trim blast designs</td>
<td>38</td>
</tr>
</tbody>
</table>
1. Introduction

The Bickham Coal Company Pty Ltd (Bickham) hold exploration licenses EL5306 and EL5888 approximately 13 km south of Murrurundi in the northern Hunter Valley of New South Wales. Open cut resources of 50 million tonnes of in-situ coal have been identified as being suitable for mining by open pit methods. A sample of 25,000 tonnes of coal has been recovered from a bulk sample pit in the northern end of the resource to confirm the marketability of the coal.

Bickham are preparing a proposal for the development of a mine to recover up to 36 million tonnes of coal from a mining area of approximately 3.95 km by 1.0 km as shown on Figure 1. The Pages River flows around the northern and eastern boundaries of the proposed mining area at the base of a steep ridge.

![Figure 1 Proposed mining area at Bickham](image)

The Department of Natural Resources – Hunter Region have designated the Pages River as a Schedule 3 Stream. If mining is intended within a prescribed distance from the river then an assessment is required of the potential impact that this may have on river flows. The pit boundaries have been planned so that they are a minimum of 300 m from the river at or below the level of the river at normal flow.
Leakage from the river to the pit would be possible if:

- stress relaxation caused by the excavation leads to the opening of rock mass structures
- the creation of the excavation caused block instability leading to movement on persistent rock mass structures
- seepage occurred along coal seams or strata bedding on the north-eastern side of the pit
- blasting caused damage that creates new leakage paths through the coal or overburden.

This report assesses the potential for rock mass damage from mine blasting to increase the permeability of the strata between the mine and the Pages River via the fourth of these mechanisms.

Disruption of stream flows from the effects of blasting in adjacent mining operations is not a feature that has been observed in Hunter Valley mining operations. An extensive search of the Australian and international mining and groundwater literature has failed to find any case of this occurring in a situation similar to the proposed Bickham development.

Because there are no documented case studies to work from, this assessment has taken a fundamental approach. The mechanisms of blast damage and the impact of this damage on rock mass permeability are discussed from both a theoretical and practical point of view. The likely impact of the proposed blasting operations at Bickham on the permeability of the rock mass between the mine and the Pages River is estimated and recommendations are made for the design and conduct of blasting operations to ensure that these estimates are not exceeded.
2. Mining near Bodies of Water

2.1. Basic Issues and Industrial Experience

Open pit mining below the water table creates a void in the rock mass and will attract the flow of groundwater under the influence of gravity. Some interaction between the mine and the groundwater table is therefore inevitable. The extent of this interaction and the inflows involved depend on the height of the ground water table, the nature of its source, the natural permeability of the rock mass around the mine, and the effect of the mining operation on the permeability of this rock mass.

There are a number of examples of mining being successfully undertaken adjacent to large or sensitive bodies of water. In the Hunter Valley, Rio Tinto Coal Australia are mining in the river sediments close to the Hunter River, mining operations were successfully undertaken on Koolan Island close to the Indian Ocean and Island Copper have mined successfully adjacent to the northern Pacific Ocean on Vancouver Island in Canada.

An extensive search of Australian and international mining and groundwater literature was conducted by the University of Queensland for this review. The review failed to identify any examples where mine blasting has been identified as the primary cause of leakage from an external water source into an open pit mine.

Potential mechanisms affecting changes in permeability may relate to the stability of the strata between the water source and the mine (Juranka et al 1991). Examples are quoted in the literature where blasting is thought to have influenced permeability. In these cases the interaction between the mining operation and the water source has been evaluated, understood and managed (Oriard and Sheeran 1998).

The management of groundwater near mines is usually concerned with controlling the extent of inflow and the effect of any inflow on the mining operations. However, there are also instances where inflows need to be managed to protect the quality or quantity of the water source. Examples include the effect of mining on the salt/fresh water balance in the Great Artesian Basin, the health of streams (Conrick and Choy, 2003), preservation of groundwater resources as domestic supplies (Gallagher and Hair, 2003), industrial supplies (Dippel, 2003), or community resources (Salmon, 2003).

A substantial search of the industrial and academic literature failed to identify any case studies where blasting had substantially affected leakage from a body of water adjacent to a mining operation. It is,
however, appropriate that the impact of a mining operation on near-by water resources is fully understood and subject to a management plan prior to mining being approved (Milligan et al 2003, Welsh 2003).

2.2. **Bickham Situation**

An open cut mine is planned at Bickham to extract coal from a series of seams that dip from under the course of the Pages River to the south west. Figure 2 shows a general plan of the northern part of the proposed mine in relation to the river. The mine plan is based on a separation distance of at least 150 m between the river and the mine workings at or below the level of the river at normal flow. An obvious concern is that the development of the mine might lead to a reduction in the flow in the Pages River caused by leakage into the mining void. Figures 3 to 6 show cross sections that illustrate the relationship between the mine and the Pages River in the northern and north eastern areas where the river runs closest to the proposed mining area. Sections NS3 and EW3 lie at the eastern and northern extremities of the proposed pit.

![Figure 2](image_url)  
*Figure 2*  
*Plan showing the northern part of the mine, Pages River and the location of the sections shown in Figures 3 to 6*
Figure 3  Cross Section N-S 2 looking east

Figure 4  Cross Section N-S 3 looking east

Figure 5  Cross Section E-W 3 looking south

Figure 6  Cross Section E-W 2 looking south
Any flow between the river and the Bickham mine will be controlled by the permeability of the strata along potential leakage paths. Leakage into the pit from the north requires the flow to cross the bedding of the strata as seen on Figures 3 and 4. The permeability of the strata to this cross-bedding flow will be considerably less than that for flow along bedding and should also be less vulnerable to the effects of mining.

There are potential leakage paths along bedding from the north-east. However, Figure 6 shows that the path the water would have to follow would be considerably longer than the horizontal off-set between the mine and the river.

Bickham have commissioned groundwater studies to determine the permeability of the strata in this area and to model potential ground water flows. This work is reported to indicate that the surrounding strata are of low permeability and that the groundwater table in the vicinity of the proposed mine is essentially independent of the Pages River. This means that any change in the groundwater table that may accompany mining should have little or no impact on the flows in the Pages River (Dundon, 2005). Mining would therefore have to alter the permeability of the strata between the mine and the river if the mining operation were to affect flows in the Pages River.

There are four mechanisms by which the mining operations could affect the permeability of these strata. These are:

- stress relaxation caused by the excavation, leading to the opening of rock mass structures
- block instability causing movement on existing persistent structures
- seepage occurring along coal seams or strata bedding on the north-eastern side of the pit
- blast damage creating new leakage paths through the coal or overburden.

The first two of these mechanisms can be subjected to conventional geotechnical analysis and the third can be evaluated by ground water modeling. This report addresses the fourth of these mechanisms – the potential impact of mine blasting on the permeability of adjacent strata.
3. Blasting Mechanisms and Principles of Blast Design

3.1 Objectives of Blasting

Excavation machinery used by the mining industry is capable of digging soft, weathered material in its natural state. However, once the strength of the material to be excavated increases above modest levels, the productivity of excavation machinery reduces significantly. Specialist rock cutting and tunneling machines have been developed to cut through quite strong rock but the productivity of these machines is still too slow for them to compete economically with blasting followed by excavation using conventional mining equipment.

Blasting is used to “pre-condition” the rock mass when it is too strong to be excavated efficiently in its in-situ condition. The objective of blasting is to convert the in-situ rock mass (which has properties pre-determined by nature) into a muckpile with an appropriate fragment size distribution and a suitable shape and looseness to suit the available excavation equipment. This needs to be achieved without causing excessive damage to the surrounding rock or creating a nuisance through noise, vibration or fly-rock.

Blast designs need to suit the rock mass conditions and the operation’s excavation, environmental and damage targets. Blast design is based on a number of well understood principles and a subtle combination of quantitative and qualitative guidelines. The general mechanisms of blast fragmentation and damage are well understood, but the complexity of the rock as an engineering material, and the complex and violent nature of blasting as an event, make a fully quantitative description of the process impractical.

The author inspected the site of the proposed Bickham mining operation in January 2005. There do not appear to be any unique circumstances associated with the Bickham mining operation that would make the routine design and management of the blasting operations difficult or especially challenging. The following sections describe the mechanisms of blast fragmentation and basic elements of blast design and how these would apply to the operations at Bickham.

3.2 Blast Design Principles

Figure 7 shows a sketch of a blast hole in a typical mine bench and explains the terms used to describe the physical parameters involved in a blast design. The rock targeted to be blasted is the burden in front of the blast hole. The blast hole is drilled a short distance (sub-drill) below
the new mine bench to ensure adequate breakage to this level between blast holes. When a blast extends to the roof of a coal seam the sub-drill will be negative to separate the explosive from the coal. The explosive is confined within the blast hole by broken rock placed above the charge (stemming) like a cork in a bottle.

![Diagram of blast design terminology](image)

**Figure 7** Basic terminology used in blast design

Figure 8 shows a plan view of a typical blast pattern showing how the burden and spacing are defined. The basic objective of a blast design is to provide enough explosive in each blast hole to adequately fragment the volume of rock defined by the bench height, burden and spacing associated with that hole. Design rules based on “good practice” guide decisions such as the bench height, hole diameter, type and amount of explosive placed in each hole, burden, spacing and the configuration of the blast hole pattern.

![Diagram of simple bench blast layout](image)

**Figure 8** Simple bench blast layout with two free faces
It is important that the blast design ensures adequate fragmentation and movement of the blast burden. If this is not the case, some of the explosive’s energy might cause damage to parts of the rock mass not intended to be broken. The extent of blast damage can be managed by controlling the physical distribution of the explosive (drilling pattern and charge designs) and the initiation sequence with which the blast is detonated.

Pit walls can be further protected from blast damage by pre-splitting the walls prior to the main blast. The purpose of a pre-split blast is to create a line of fractures in the plane of the final pit wall. The fractures in this plane attenuate the stress waves and provide a path to vent the explosion gases generated by the main production blasts. Experience throughout the coal industry demonstrates that pre-splitting can effectively define and protect pit walls in all but soft or intensely fractured ground.

A pre-split is created by firing a line of closely spaced blast holes that have been charged with a decoupled or distributed light explosive charge. Continuous “sausages” of explosive are manufactured for this purpose and can be placed in a blasthole of larger diameter than the sausage to produce this decoupling of the charge from the blasthole. For larger diameter blastholes the use of very large diameter “sausages” is not practical and individual decks of bulk explosive are used as shown on Figure 9.

![Figure 9](image_url)  
*Figure 9  **Typical pre-split charging using bulk explosive**

In pre-split blasting the objective is to drive a crack between the blastholes without damaging the rock outside this plane. The detonations generate a stress field around the blastholes. If the stress that is generated is too weak to cause compressive breakage of the rock
then little damage will be done. The neighbouring holes distort the stress field and induce a tensile stress normal to the line between the holes. If this tensile stress is strong enough then the rock will fracture in tension and the split will be formed (Dunn and Cocker, 1995).

A number of simple rules are available for the design of pre-split blasts based on rock mass and explosive properties and blasthole geometry. In massive, brittle materials, pre-splits can protect a pit wall from further damage and leave a very clean undamaged surface like that shown on Figure 10. The frequency and orientation of structures in the rock mass will affect pre-split performance, with some soft or very blocky rock masses not appreciably benefiting from pre-splitting at all. The rock mass exposures in the wall of the bulk sample pit at Bickham indicate that pre-splitting can play a constructive role in blasting in the Bickham mine.

![Pre-split results in F seam interburden in the Bickham Bulk Sample Pit](image)

**Figure 10** Pre-split results in F seam interburden in the Bickham Bulk Sample Pit

### 3.3 Basic Blasting Mechanisms

The actual processes that take place during the blasting of rock are incredibly complex and it may never be possible to describe them explicitly. Bulk mining explosives are chemical mixtures of oxidizer salts and fuels which, when initiated by shock from a separate initiating explosive, react very rapidly to generate high pressure, high temperature gasses.
The detonation reaction takes place in a reaction zone that progresses along the explosive column at the Velocity of Detonation. For most commercial explosives in coal overburden strata, the detonation reaction occurs faster than the surrounding rock can transmit the energy away – i.e. it is a shock phenomenon and the resulting shock wave crushes and breaks the rock in the immediate vicinity of the blast hole.

In bulk commercial explosives a significant component of the explosion reaction takes place behind the detonation front in the sub-sonic region of the reaction zone (Essen, 2005). This means that the last of the explosive’s energy is released more slowly, resulting in the pressurisation and expansion of the blast hole over a longer period of time than experienced during the initial shock loading phenomenon. This pressurisation leads to a second phase of dynamic loading of the rock surrounding the blast hole.

A dynamic stress field is generated by the pressure in the blast hole and this will include a tangential component capable of forming and extending cracks that radiate from the blast hole (Lee and Farmer, 1993). The extent of this cracking is influenced by the strength of the rock, the characteristics of pre-existing discontinuities and the in-situ state of stress.

Very complex interactions take place between the dynamic stress field and the rock mass internal structures and boundaries. Stress waves will be attenuated as they do work on the rock, they will be refracted and reflected by discontinuities in the rock mass and diminish in intensity as they propagate away from the blast hole. They will also interact with stress waves generated from neighbouring blast holes in the blast pattern. These processes will take a few milliseconds.

Over the next 10 to 100 milliseconds (a long time in terms of the discussion so far), the high pressure gases trapped in the blast hole expand into the now fractured rock mass. The rock mass in front of the blast hole will be more intensely fractured than the rock in the solid ground behind it because it will have suffered some damage from the earlier firing blast holes and has been subjected to the effects of the initial shock wave and tensile reflections from the free surfaces. The explosion gases will therefore flow preferentially into the burden rock and contribute to the formation and displacement of individual rock fragments.

The presence of any discontinuities such as joints or bedding planes provides preferred paths for the explosion gases and encourages the formation of fragments defined in part by the surface of those discontinuities. This can lead to the preservation and liberation of larger
fragments than would have resulted from the blasting of an unstructured or massive rock mass. These larger fragments are more likely to be found in the stemming zone or mid-pattern between blast holes because of the greater distance from these areas to the explosive charges. Figure 11 shows a glimpse of these mechanisms in action.

The explosion gases generated within the blast hole will find the path of least resistance to reach the atmosphere. In doing so, significant force is applied to the rock fragments generated by the mechanisms discussed previously. These forces displace the rock fragments from their initial positions within the blast volume and lead to the creation of the pile of broken rocks known as the muckpile. The extent and distribution of this displacement depends on the forces applied (which are related to the amount, distribution and confinement of the explosive charge) and the resistance to movement provided by the surrounding intact and broken rock.

The relative roles of the shock (more truthfully both the shock and dynamic loading phases of the detonation) and gas in the fragmentation and damage processes are still under active debate within the blasting scientific community (Olsson et al 2001). The lack of clarity about the detailed breakage mechanisms arises from the difficulties involved in measuring these very rapid, violent processes and the wide range of rock mass and explosive properties with which one has to deal. However, there is general consensus that dynamic loading is primarily responsible for the development of new cracks and the extension of the fracture network. The explosion gases then work within these fractures to define and displace the rock fragments to form a muckpile.
The role of “relief” is fundamental to rock blasting. The creation of a loose, well fragmented muckpile (basic requirements for excavation) requires that the rock has the opportunity to move – that is it has some relief. If an explosive is detonated in a fully confined environment (placed many times its charge length from any free surface) then it will simply crush and fragment the rock in the immediate vicinity of the blast hole and generate a system of radial cracks. The result would look like the model result shown on Figure 12 and would generate a poorly fragmented, tight muckpile quite unsuitable for excavation.

![Fracture pattern in hydrostone model (Hudson 1993)](image)

**Figure 12 Fracture pattern in hydrostone model (Hudson 1993)**

Such confined blasts are sometimes used to increase the permeability of a rock mass. For instance, this may be undertaken to increase the yield of wells or improve the drainage of gas. Experience with these operations indicates that significant increases in permeability are limited to the immediate vicinity of the blast and do not extend over long distances. Other attempts to increase permeability close to the surface to assist drainage are reported to require very high powder factors compared with the levels required for routine fragmentation (Smerekanicz et al 1999).

If a charge is over-burdened then the only free face available to generate relief is the ground surface. Under these circumstances the blast will form a symmetrical crater around each blast hole, with equal breakage and damage in all horizontal dimensions, but unequal breakage vertically. Some mining operations seek to limit the movement of the blasted muck to avoid contamination of ore with waste and so deliberately employ crater blasting.
Bench blasts (such as those required for the Bickham mine) are quite different and might have geometry similar to that shown on Figure 13. Figure 13 shows the blast hole closest to the back of the blast near the pit wall. The blast holes in front of this hole have already detonated and broken the ground within the blast volume depicted in the diagram by the dashed lines. Given the presence of the two (or perhaps even three) free faces that would exist at the time when this blasthole detonates, the blasthole’s burden has access to a lot of relief. The burden rock will also have suffered some damage from the earlier firing holes, increasing the intensity of fractures. This relieved, damaged rock is vulnerable to further damage from the dynamic loads imposed by the blasthole when it detonates, making it easy for the explosion gases to enter the fractures and displace the resulting rock fragments.

The situation for the wall rock is quite different. The rock immediately behind the blasthole will suffer some damage and a proportion of this (generally about half a burden width) is expected to fragment and is regarded as being part of the volume of rock to be blasted. Further away from the blast hole, the rock mass is less disturbed and less vulnerable to the influence of dynamic loading from the detonation. The absence of free faces makes it much more difficult for the rock to be displaced in response to the dynamic loading, and higher stresses are required to cause breakage than in the more vulnerable burden rock (Persson 1990).

These differences in breakage are readily observed in practice and are utilised to manage both fragmentation and damage. Figure 14 shows an example of the degree of control that can be imposed over the complete
destruction of the in-situ rock mass structure (fragmentation) on the left of the photo and the preservation of intact rock mass material on the right. The rock remaining between the blast and the pre-split line collapsed and broke easily with the encouragement of an excavator bucket leaving a clean, undamaged rock wall. This control is achieved by managing the explosive distribution and the relief available to individual charges during a blast.

![Pre-split line](image)

**Figure 14 Control of fragmentation and damage in coal overburden**

### 3.4 Bickham Mine and Blast Designs

Detailed mine planning and optimisation studies are still being undertaken for the Bickham operations. Geotechnical recommendations for the pit walls call for individual slope faces to be no steeper than 75° and to be no higher than 50 m between benches. Recommendations also call for bench faces to be pre-split prior to production blasting. The accuracy with which these pre-split patterns are drilled will control the actual profile of the resulting slope. Control over pre-split drilling may therefore limit the maximum individual bench height that can be created.

Excavation will be undertaken by 500 tonne hydraulic excavators which will work efficiently in 5 m to 7 m benches. Allowing for swell in the blasted muckpile, three such excavation benches could be blasted at a time based on 15 m deep blasts. Two blast horizons could therefore be combined to form a 30 m face in the pit wall. Figure 15 shows this geometry which has been adopted for the purposes of this review.
Bench and blast geometry will have to be modified to follow and expose the coal seams as they are encountered by the operation.

Pre-split blasts can be effectively undertaken over the full 30 m bench height. It is likely that 165 mm diameter blast holes would be used and charged with up to three decks of bulk explosive. Pre-split holes should not be stemmed to avoid crest damage from cratering in the stemming zone. However, usual New South Wales practice is to stem pre-split holes to limit air-blast effects. Pre-split blasts must be fired in advance of the development of the adjacent bench.

![Diagram of basic pit and blast geometry proposed for the Bickham Mine](image)

**Figure 15  Basic pit and blast geometry proposed for the Bickham Mine**

Based on the use of 200 mm diameter blast holes, the main bench blasts would involve patterns using approximately 6.5 m burdens and 7.5 m spacing. In dry conditions ANFO would be the preferred explosive, but wet conditions or atypical blast geometries may require the use of emulsion (water resistant) explosives or Heavy ANFO explosives. Patterns may be expanded slightly where these higher density explosives are used.

Blasting for the Bulk Sample Pit at Bickham involved similar blast geometries to those described above. Exceptions involved the use of smaller diameter blast holes in steep areas where access for the larger drill would have been difficult and the use of higher powder factors in areas of hard cap-rock.
4. Permeability and Rock Mass Damage

4.1 Permeability

4.1.1 Flow through Structured Rock

A rock mass consists of the rock substance itself and a network of discontinuities. Fluid flow through a rock mass is controlled by the properties of both the rock substance and its discontinuities or structures. For the overburden materials at Bickham the permeability of the intact sandstones, mudstones and shales will be very low and any fluid flow of concern to the project will be dominated by flow through a network of natural or induced structures. These structures might be bedding planes, cleavages, cracks, joints or faults in the rock mass.

Dundon (2003) reports that while all measurements taken to date indicate low permeability, there is some local variation. This will be a reflection of the detailed nature of the structure network and the direction of flow relative to this network in these locations.

Flow through a structured rock mass can be modelled, but either:

- the rock mass must be regarded as being an equivalent continuum where “effective average” properties are applied to the whole rock mass volume, or
- a discrete network of flow paths must be explicitly modelled.

The former approach is most often adopted because of the ease with which field tests can be undertaken to measure the effective hydraulic properties of the rock mass. Explicitly modeling individual flow paths requires an accurate representation of the rock mass and the hydraulic properties of its various structures, both of which are unobtainable in a practical mining situation.

Individual structures will vary widely in terms of their size and their hydraulic characteristics. While the number of such discontinuities and their apertures (or open area) are obvious indicators of likely permeability, the extent to which they are interconnected also has an important influence on the permeability of the overall discontinuity network.

Changes to the rock mass structure will affect rock mass permeability. These changes might be caused by:

- changes in the distribution of in-situ stress caused by the removal of adjacent material during mining
• instability leading to the relative movement of different sections of the rock mass near the mine
• blasting.

The resulting structural changes might involve:

• an increase in the number of structures
• extension of existing structures
• opening or dilation of structures

all of which would lead to an increase in the permeability of the rock mass.

Lee and Farmer (1993) report that the spacing between discontinuities generally increase with depth and fracture apertures generally reduce. Significant changes in both properties can be observed in rock masses over the depth range contemplated by the Bickham operation. These observations are consistent with widespread measurements of reduced permeability with depth.

Similarly, Lee and Farmer (1993) report that confining pressure (from depth of burial or residual in-situ stresses) has a marked effect on rock mass strength and the extent of dilation (and hence permeability) generated by a disturbance. If damage is defined in terms of significant increases in rock mass permeability then new fractures may not be required and the dilation of existing fractures may be sufficient to cause damage.

4.1.2 Measurement of Permeability

Permeability is a measure of the ability of a medium to transmit fluid through its connected pore space. The rate of fluid flow in response to a given hydraulic gradient is described by Darcy’s Law (Farmer 1968):

\[
\frac{Q}{A} = K \frac{h}{L} \quad \text{Equation 1}
\]

where

- Q is the volume flow rate
- A is the area of the rock through which flow takes place
- L is the length of the flow path
- h is excess hydrostatic head acting across L
- K is the coefficient of hydraulic conductivity.
Lee and Farmer (1993) report that permeabilities measured in the field are usually obtained by testing intervals of vertical boreholes and so the results represent an average for that interval of the borehole. The most common methods for measuring permeability in the field involve:

- a packer or injection test in which the flow from a section of borehole is measured as a function of the applied pressure
- a slug or pulse test in which pressure recovery or decline is observed as a function of time following disruption of the pre-test equilibrium.

It is possible to equip a borehole with appropriate screens and measuring equipment to perform these tests on a regular basis. Bauer et al (1995) report that permeability measurements can be used to identify disturbance zones around excavations. Some success is reported by workers attempting to estimate the permeability of a rock mass based on observation of its structure. However, Suzuki (1988) notes that the results depend on “hydraulic aperture” rather than observable aperture. The hydraulic aperture can only be determined by back analysis from hydraulic tests rather than physical measurements in the field. Relating simple observations of rock mass structure to the permeability of an extensive rock mass remains problematic with field tests like those described above remaining as the only practical approach.

### 4.2 Rock Mass Damage

#### 4.2.1 Definition

Damage is any change in rock mass properties resulting from the mining operation that impedes mining performance to an unacceptable extent. This is in contrast to “failure” which occurs when the rock is no longer able to sustain the loads applied to it, leading to its collapse (Chitombo and Scott, 1990). In the case of the Bickham mine, the surrounding rock mass would be damaged if:

- the angle of the pit walls had to be reduced or the width of the berms had to be increased to ensure stability
- the walls were not safe to work under for the period required by the mining operation
- the permeability of the rock mass between the mine and the Pages River was increased to a level that caused unacceptable leakage from the river.
Geotechnical studies have been commissioned to determine the safe pit slope angles and designs. The routine blasting operations will be designed to minimise damage that would affect the stability of the walls or the safety of operations underneath them. The following discussion relates to the potential of blasting operations at Bickham to increase the permeability of the rock mass between the mine and the river.

4.2.2 Basic Mechanisms

Damage to the walls of open pit mines has been the subject of extensive research. The wide range of circumstances under which this research has been conducted means that there are still some divergent views about the basic mechanisms. However, industry 'best practice' provides clear guidelines for the best approaches to the management of damage. There is abundant practical experience available to guide the successful blasting of the rock mass at Bickham and so the overall requirements can be clearly defined.

Damage is an unacceptable change in the rock mass properties (in this case permeability) as a result of blasting. Permeability will be increased if new open discontinuities are formed in the rock mass or if existing discontinuities are extended or dilated and these link to provide new flow paths from a water source to the pit. In the particular situation at Bickham, increases in the permeability of the pit walls will only cause a problem for the Pages River if the permeability is increased over the full distance between the mining operations and the river. Three different mechanisms could cause this:

- The creation of the excavation will cause a re-distribution of the in-situ stresses causing the strata near the pit walls to relax and the rock mass structure to dilate. It is the author's opinion that the probability of this occurring is very low but a geotechnical analysis is recommended to determine the extent expected for this phenomenon.

- The creation of the excavation may lead to block scale instability that allows displacement on persistent pre-existing structures and results in the opening of these structures. This process may be exacerbated by blast vibrations and the action of explosion gases. Geotechnical analysis is required to determine whether such structures are present in the Bickham rock mass and their likely stability during mining.

- Disturbance of the rock mass structure during blasting may lead to the extension or dilation of existing structures in the wall rock.
The third mechanism falls into the category of conventional blast damage which can be assessed and managed using established blast engineering practices.

### 4.3 Prediction of Damage

Damage to open pit walls is caused by dynamic loading and the infiltration of explosion gases. The extent of damage is influenced by the properties of the rock mass, the type and distribution of explosive and the confinement provided by the blast design.

#### 4.3.1 Vibration

The impact of stresses generated by a blast can be analysed using the approach developed by Holmberg and Persson (1978) and further elaborated by Persson (1990) and McKenzie et al (1995). This approach is summarised below.

To estimate the Peak Particle Velocity (PPV) at any distance, $x$, from a charge of weight $W$, charge weight scaling relationships similar to:

$$PPV = K W^\alpha x^{-\beta} \quad \text{Equation 2}$$

are commonly used where $K$, $\alpha$ and $\beta$ are site specific constants. The equation in this form depends on the explosive being represented as a point source of explosive energy. For locations close to a blast hole (i.e. within the damage zone of interest) the explosive charge cannot be taken as a point source and the geometry shown on Figure 16 must be taken into account.

Under these conditions Holmberg and Persson proposed the following equation:

$$PPV = K I^\alpha \left[ \frac{dx}{\sqrt{R_0^2 + (R_0 \tan \phi - x)^2}^{\alpha/2}} \right] \quad \text{Equation 3}$$

where:

- $I$ is the linear charge density in kilograms per metre
- $K$, $\alpha$ and $\beta$ are site specific constants, and
- $R_0$, $\phi$, $x$ and $H$ are as shown on Figure 16.
For the case of square root scaling (i.e. $\alpha = \frac{1}{2} \beta$) the equation has an analytical solution as follows:

$$PPV = K \left[ \frac{I}{R_0} \right]^{\beta/2} \left[ \phi - \arctan \left( \frac{R_0 \tan \phi - H}{R_0} \right) \right]^{\beta/2} \quad \text{Equation 4}$$

The 'K' term reflects the source energy and the coupling efficiency of the explosive to the blast hole wall. Higher values of K indicate high energy, well coupled explosives. The "$\beta$" term represents the loss of vibrational energy with distance. A low value represents a competent rock mass with little structure which transmits the vibrational energy with little attenuation. Higher values of $\beta$ represent less competent rock which attenuates vibrational energy more quickly.

McKenzie et al (1995) recommend the following values for strong sedimentary strata:

$$K = 400$$
$$\alpha = 0.78$$
$$\beta = 1.56$$

The peak particle velocity values shown on Figure 17 result from the application of the Holmberg-Persson analysis using these values for the rock mass attenuation characteristics and a range of blast hole diameters charged with ANFO.

Figure 17 shows that the blasthole diameter has a significant effect on the vibrations imposed within about 15 m of the blasthole with rapidly decreasing difference beyond that distance. It is the linear charge density (the number of kilograms of explosive per metre of blasthole that is driving these differences. Also shown on Figure 17 is an estimate of
the vibration level above which genuine fragmentation can be expected. In this analysis, this level has been set to be 1850 mm/s. Based on this value, it can be seen that fragmentation is expected over a burden distance of about 4.5 m for the 165 mm holes, 6 m for the 200 mm holes and 8 m for the 270 mm holes. These would, in practice, be reasonable burdens for such holes when blasting in coal overburden.

As outlined by McKenzie et al (1995), the vibration level above which some damage may be expected can be estimated from basic mechanics as summarised by Equation 5.

\[ PPV_{\text{max}} = 1.2 \frac{\sigma_T}{V_p \rho_{\text{rock}}} \]  

\textbf{Equation 5}

Where  

- \( PPV_{\text{max}} \) is the vibration level above which minor damage may be observed  
- \( \sigma_T \) is the tensile strength of the rock (which may be approximated to be UCS/12)  
- \( V_p \) is the p-wave or sonic velocity of the rock  
- \( \rho_{\text{rock}} \) is the density of the rock.

Applying the properties for the Bickham rock mass (Section 5.1) results in a critical vibration level of about 465 mm/s. This is about one quarter of the vibration level expected at the designed burden distance from a blast hole.

The Holmberg - Persson analyses described above are widely used by blasting consultants and researchers. The approach depends on a
number of simplifying assumptions and has been criticised in the blasting literature for being too simplistic. Blair and Minchington (1996, 2006) identify discrepancies between the results of the Holmberg-Persson approach and analyses using dynamic finite element models and advanced analytical solutions, either of which satisfies the authors as providing a detailed and accurate description of damage from a single blast hole.

These theoretical or analytical analyses are inevitably limited by the difficulty in defining the rock mass properties and their variation in a practical field situation. This is why simpler approaches are relied upon by the industry for the design and management of blast performance and damage. For the issues under consideration at Bickham the shortcomings identified by Blair and Minchington are not relevant. The Holmberg – Persson analysis provides a useful description of the effect of different blast designs on the extent of blast damage that can be expected. The approach can be used with confidence if complemented by reliable field data and appropriate engineering judgement.

Consistent with this engineering approach it is appropriate to consider the factors that will affect the extent of blast damage in the field operations at Bickham. These factors are discussed below and considered further in Section 5 where predictions are made for the potential impact of blast vibration on the walls of the Bickham mine.

**Influence of Free Face**

A free face has the effect of increasing the influence of vibrations on the burden side of the blast hole. Persson (1995) recommended doubling the ‘K’ term in Equation 3 to account for the influence of the free face. Blair and Minchington (1996) acknowledge that the influence exists but argue that a simple doubling is not accurate. The fact is that more breakage is going to occur in the burden rock than behind it providing some relief is available to the burden. This means that a lower value of K should be used in Equation 3 for the rock in the wall than for the rock in the burden.

**Influence of Burden**

The burden distance influences vibration levels experienced behind the blast. McKenzie et al (1992) provide data from controlled field measurements that quantify the variation in vibration behind blastholes for different burdens as shown of Figure 18.

This approach acknowledges that there are at least two components to the vibrations experienced behind a blasthole:
• the initial shock pulse and its sub-sonic derivatives
• response to the dynamic loading of the blast hole and reaction to the work done by the explosive in breaking and moving the rock.

Data published by McKenzie (1992) is shown on Figure 18. Practical experience supports this trend, especially when burdens are significantly less than their nominal values.

![Figure 18 Vibrations at different burdens (McKenzie et al 1992)](image)

**Figure 18  Vibrations at different burdens (McKenzie et al 1992)**

*Pre-split*

One of the prime objectives of providing a pre-split is to provide a fracture on the plane of the pit wall to act as a barrier to the propagation of vibrations. The effectiveness of a pre-split will be dependent on its design and the rock mass properties, particularly structure. Field data is required to quantify this effect, but experience in the coal measure strata in the Hunter Valley is that pre-splitting is generally an effective wall control technique and therefore will have a significant effect on the transmission of blast vibrations back into the wall.

**4.3.2 Gas**

Explosion gases may be trapped in the rock mass for a relatively long time during blasting. If the blast holes closest to the new pit wall are heavily confined and well stemmed then the burden rock may take up to 100 ms before appreciable movement occurs (Scott et al 1996) and the gases are able to escape to the atmosphere. During this time the gases move into the fracture network generated by the dynamic loading, extending the fractures to define individual rock fragments and displacing them towards the source of relief. If the burden movement time is
sufficiently long then the gases may also have the opportunity to enter fractures in the wall itself.

McKenzie (1999) provides a thorough summary of gas monitoring experience up to that point in time. Figure 19 is reproduced from McKenzie (1999) to show that only very low gas pressures have been reported beyond about 15 m (say two burdens) from a blast hole.

![Image](image.png)

Figure 19 Gas pressures measured at different distances behind blasts (McKenzie 1999)

This is consistent with practical observation that significant back-break is seldom observed more than a burden or two behind a blast unless it has been assisted by persistent pre-existing discontinuities in the rock mass.

Examples have been reported (Sarma 1994) of significant gas movement through pre-existing rock mass structures. Gases have been observed to travel many tens of metres at velocities of several hundred metres per second through open structures. It is emphasised that these events have only been observed in rock with pre-existing open structures and the blast itself has not created these structures.

Most people measuring gas pressure behind blasts have reported negative pressures either alone, or after the passage of a positive stage. For example Sarma (1994) provides Figure 20 in his PhD thesis, indicating that the pressure in his test holes experienced positive pressure (in-flow of gas from the rock mass structure) followed by a net negative pressure (outflow of gas from the monitoring hole to the rock mass). Many measurements (e.g. Brent and Smith 1996) have seen predominantly or only negative pressures.
These negative pressures recorded behind blasts are clearly real and are interpreted to be the result of the dilation of the ground adjacent to the blast (McKenzie 1999, Brent & Smith 1996, Sarma 1994, Le Juge et al 1994, Ouchterlony et al 1996 and others). This means that the volume of the bench immediately adjacent to the blast has increased and this increase in volume has involved the creation of increased void space within the rock mass structure. This increase in void space has occurred before air from the atmosphere has been able to flow through the discontinuity network to balance the pressure with the atmosphere.

There is no doubt that there is some mechanical prising apart of the rock mass strata behind the blast caused by friction with the burden rock as it is lifted and displaced by the explosion gases. The rock mass structure is unlikely to recover from this physical disturbance, leaving a slightly swollen, but otherwise undisturbed bench behind the blast. This disturbance would undoubtedly contribute to the dilation observed in rock mass structures within a burden or two of the blast.

Le Juge et al (1994) report direct measurements of bench dilation using extensometers. They report dilation effects up to 20 metres behind 381 mm diameter blast holes fired in the Rossing Mine in Namibia. The extensometer data indicated that the remnant swell in the bench behind the blast occurred over the full height of the bench near the blast hole, and was found only in the upper part of the bench further from the blast hole. This is consistent with their interpreted driving mechanism which was mechanical disturbance of the rock mass structure like a beam lifted at one end by the blast hole and fixed at the other end by the bench behind the blast.

Brent & Smith (1996) argue that this development of fractures and their dilation results from blast vibrations. They describe experiments
undertaken in Hunter Valley strata where these effects have been measured behind blasts and the results have been correlated with the generation of cracks observed in test holes. These blasts comprised a 7 m x 8 m pattern of 200 mm diameter blast holes charged with ANFO and a toe charge of Heavy ANFO. A close correlation was found between the distance over which new fractures were found and the distance over which negative pressures were observed. This is shown in Figure 21 from their paper.

![Figure 21 Correlation of negative pressures and visible fractures (Brent and Smith 1996)](image)

The correlation shown on Figure 21 appears reasonable and is accepted for the purposes of this review, but it is difficult to interpret this outcome in terms of the impact that this dilation may have on permeability. While the distance over which some disturbance is observed approaches 30 metres, the maximum dimension of the cracks observed more than 15 metres (two burdens) from the blast holes was less than 50 mm and less than one crack per metre of observation hole was found 14 m from the blast. There is little prospect of cracks formed at this frequency and of this size forming an effective connected flow path that would significantly change the permeability of the ground.

As discussed in Chapter 5, Brent and Smith’s experiment represents a worst possible case for the blasts anticipated at Bickham. Their data is accepted for the purposes of this analysis even though vibration is considered unlikely to be the driving mechanism for the observed dilation. Adopting their analysis provides a conservative (that is, likely to over-estimate) benchmark of the potential for blasting to affect rock mass permeability at Bickham.
4.4 **Measurement of Blast Damage**

Many of the techniques available to measure the extent of blast damage have been discussed already. The following summary is provided for clarity and completeness. Useful techniques include:

- Observation of visible breakage, displacement, cracking or instability of the wall rock or surface
- Observation of any visible breakage or cracking in observation holes drilled behind a blast
- Data from extensometers measuring the magnitude and location of bulk strains (dilation) in a bench
- Extent and magnitude of negative pressures observed behind a blast to interpret the extent of dilation (not a proven technique, but appears promising and worthy of further evaluation)
- Changes in seismic velocity observed by cross hole transmission techniques or seismic refraction
- Direct measurement of changes in the permeability of strata behind the blast.

The measurement of blast vibrations behind the blast may assist in the calibration of damage models and interpretation of damage that is subsequently observed, but does not in itself constitute a measurement of damage. The measurement of permeability is clearly the most direct technique for Bickham’s situation. It is not a trivial process to undertake these measurements but it would be possible to design field experiments to do so.

4.5 **Management of Damage**

The preceding sections have discussed the influence of the rock mass and blast design factors known to affect blast damage. Armed with this understanding it is a simple matter to define a strategy to manage this damage for any given blasting situation. For bench blasting at Bickham this should involve:

- Observing any signs or symptoms of damage and reacting to them to tune the day to day blasting operations
- Pre-splitting the final pit walls so that a fracture is developed along the plane of the wall to attenuate the blast vibrations and provide an escape path for trapped explosion gases
• Utilising trim blasts adjacent to final walls so that the blasthole diameter and the burden can be reduced (both of which will reduce the vibration levels imposed on the walls)

• Ensuring that the trim blast faces are clean and that burdens are controlled to minimise the confinement of these blasts

• Ensuring that the initiation timing is such that each blast hole has adequate burden relief.

If these principles are followed then appropriate blast designs can be determined to suit the Bickham rock mass and blast geometries. First pass designs to achieve this are provided in Section 5.3.
5. Potential Effect of Blast Damage on Rock Mass Permeability at the Bickham Mine

5.1 Rock Mass Properties

Geological and geotechnical descriptions of the overburdens and interburdens in the Bickham deposit indicate that they are typical of competent coal overburden strata in the Hunter Valley. The sequence consists of sandstones, siltstones and mudstones with occasional siderite bands. The coal seams contain some claystone, siltstone and carbonaceous mudstone bands.

The location of the Pages River relative to the proposed mine suggests that the ‘G’, ‘F’ and ‘E’ seam overburdens are the most significant horizons with respect to the possible leakage paths between the river and the pit.

Borehole FMDWDDH49 lies at the deepest point of the bulk sample pit. Logs from that hole indicate that the interburdens above the G seam (the target seam for the bottom of the pit) consist of sequences of siltstone and sandstone with minor thin bands of siderite. Such a sequence is typical of coal measure overburdens and when fresh, this rock can be expected to be moderately strong and to form competent excavated pit walls.

DDH49 was drilled using a diamond core bit and was logged using a “down hole televiewer” over most of its length. An 18 metre length of the hole (from 30.64 m to 58.64 m) apparently provided very poor video which precluded any measurements being used from this section. Reference to the detailed geological description of strata for this zone indicates that it consists of sandstones, the ‘F’ coal seam and siltstones and does not appear to vary significantly in nature from the strata either above or beneath it. The sonic log for the same zone shows an average sonic velocity of about 3,300 m/s which is typical for a sandstone-siltstone sequence. However the trace does tend to be ‘spiky’ through this region possibly indicating softer strata within harder layers.

The televiewer is reported to have identified bedding and jointing in the strata. Bedding was reported to have an average dip of 12° with an average dip direction of 300° which is consistent with the reported dip of the coal seams in that area. The distance between observed bedding planes varies widely from a few centimetres to nearly 2 metres.

Few joints were observed in the interburdens and those that are noted are several metres apart. The logs refer to a fracture zone from 82.0 to 91.0 metres in depth. Most of this interval (82.57 to 88.72 m) consists of
the ‘G’ seam. The fractured zone is reported to extend to the first few metres of the seam floor.

English and geophysical logs are available for BCWM70A and these are consistent with the description derived from DDH49. BCWM70A was drilled to the north of the pit. The critical area where the pit batters will be closest to the Pages River lies between these two drill holes.

It is concluded from the above that the interburdens tend to be well bedded but moderately jointed. The coal seams are more intensely structured and there is some indication that the “G” seam floor is more intensely structured than the majority of the strata. In blasting terms, the sequence appears to be quite typical of coal bearing strata, being of moderate strength with bedding being the dominant structure.

![Image](image-url)

**Figure 22  F Seam Interburden in the base of the Bulk Sample Pit**

This description is reinforced by the exposures in the Bulk Sample Pit excavated in the northern end of the proposed mining area. The pit has created access to the E and F seams and so exposed their respective overburdens and interburdens. Figure 22 shows that the grey sandstone sequence of the F seam interburden is quite competent, but that the frequency of jointing varies over a wide range. Some medium to high strength shale bands are seen in the face at 1 to 4 m spacing. A persistent angled joint is seen in the left of the image. The result is a tight, blocky to massive wall exposure similar to many of the highwalls to be found in the Hunter Valley coal mines.
Figure 23 shows the E seam overburden which has been moderately weathered due to its proximity to the surface in this area. The rock mass itself is a blocky, high strength, coarse grained sandstone. The blocks are formed by the intersection of two conjugate high angle joint sets, one trending essentially north-south and the other trending north-east to south-west. Nothing unusual or unexpected is revealed by these exposures that would give rise to any concerns for their blasting and excavation.

The majority of the interburden strata display a sonic velocity in the order of 3,000 m/s to 3,500 m/s. As large bulldozers cannot economically rip material with a sonic velocity above about 2,500 m/s, it is clear that the seam interburdens require blasting. The sonic logs indicate that some zones are interbedded with softer material and some are consistently harder. A conglomerate band above the F seam has a sonic velocity above 4,000 m/s and is probably quite strong.

The basic material properties shown on Table 1 have been used to represent the interburden materials for the purposes of the analyses which follow.

<table>
<thead>
<tr>
<th>Property</th>
<th>Lower</th>
<th>Average</th>
<th>Upper</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>2.2</td>
<td>2.3</td>
<td>2.4</td>
<td>t/bcm</td>
</tr>
<tr>
<td>Sonic Velocity</td>
<td>2,500</td>
<td>3,250</td>
<td>4,000</td>
<td>m/s</td>
</tr>
<tr>
<td>Strength</td>
<td>25</td>
<td>35</td>
<td>45</td>
<td>MPa</td>
</tr>
<tr>
<td>Stiffness</td>
<td>20</td>
<td>30</td>
<td>40</td>
<td>GPa</td>
</tr>
<tr>
<td>I/S Block Size</td>
<td>0.5</td>
<td>1.5</td>
<td>3</td>
<td>m</td>
</tr>
</tbody>
</table>
Lower and upper bounds are provided as well as likely average values because there is an inevitable variability in the nature of the materials to be blasted. However, only modest changes to blast design are required to provide suitable muckpiles for this range in rock mass properties.

5.2 Potential Damage from Bickham Blast Designs

The experimental data reported by Brent and Smith (1996) provide the most concrete example of what may be expected in terms of damage to Bickham overburden from blasting. As discussed in Section 4.3.2, Brent and Smith found a reduction in the number of new factures away from a production blast in Hunter Valley sandstones. They correlated this reduction with the peak negative pressures (argued to be a result of the formation and dilation of these cracks) observed in instrumented boreholes over the same distance.

No vibration data is provided in Brent and Smith’s paper. Figure 24 shows the Peak Particle Velocity (PPV) modeled for this situation based on the attenuation properties for coal overburden sandstone published by McKenzie (1995).

![Figure 24 Modeled vibration attenuation for different blast designs](image)

The blue line on Figure 24 confirms that fragmentation should be expected over the 7 m burden that was the basis of the blast pattern. Under conventional damage criteria, damage could be expected up to about 16 m from a blast hole. Based on the gas pressure data, some dilation of structures may have persisted for 30 m indicating a threshold vibration level of about 165 mm/s for this type of damage. This is a very
low level of vibration in terms of damage thresholds reported by others (Persson 1996, McKenzie 1995, Scott et al 1996) but is accepted for this study as representing a conservative outer limit of damage.

Curves are also shown on Figure 24 for the expected vibration attenuation associated with trim blasts based on either 165 mm diameter blastholes or 127 mm diameter blast holes. Each of these designs would lead to a reduction in the damage distances as shown.

Blasting at Bickham should have less impact on the surrounding rock mass than indicated in Figure 24. If 165 mm diameter blastholes are used in the final trim blasts and these are drilled on a 4 m x 7 m pattern, then the burden that the blast holes are working against is reduced by 33%. This will reduce the levels of vibration imposed on the walls. If a pre-split is used on all critical walls then this will lead to a significant reduction in the vibrations experienced. To account for these factors, Figure 25 shows the expected vibration levels in the walls for the proposed trim blasts and wall protection measures based on halving the ‘K’ term in Equation 3 as recommended by Persson (1995).

Figure 25 indicates that any observable damage imposed by these designs (in the absence of any vulnerable geotechnical feature) should be limited to about 7 metres from the blast. Based on the extended criterion derived from Brent and Smith’s observations, the limit of 165 mm/s is found to occur about 15 m behind the blast. These analyses are based on quite conservative assumptions. Observations made during the blasting and excavation of the bulk sample pit suggest that the extent of observable damage will be significantly less than this.
5.3 **Recommended Blast Designs for the Bickham Operation**

5.3.1 **Blasting System**

A consistent blasting system is required if Bickham’s blasting operations are to meet the production requirements and ensure that damage to pit slopes is minimised. The components of the recommended system are:

- A pre-split blast on all critical walls fired well before production blasts are fired in the area
- Production blasts designed to ensure good fragmentation and loose digging while leaving clean trim benches 10 m to 15 m from the walls
- Excavation of the production patterns to leave a clean free face and even burdens available for the trim blasts
- Trim blasts designed with adequate powder factor, three rows and large spacing to burden ratios
- Focussed clean-up of final walls.

Figure 26 shows a plan view of how these blasts will work together to control damage on pit walls.

![Figure 26 Typical pre-split, production and trim blast geometry](image)

The use of electronic initiation systems and “novel” initiation timing has been used to limit blast damage to pit walls without the use of separate trim blasts (Brent, Smith and Lye 2002). However, these blast designs depend on the rock mass conditions being suitable and are the result of extensive performance monitoring and sophisticated modeling and design. It is unlikely that a small operation like that planned for the Bickham mine could justify the costs involved. The consistent application of conventional wall control techniques similar to those described in the following sections should provide satisfactory mining performance while minimising damage to pit walls.
5.3.2 Pre-Split

Pre-split blasts for the Bulk Sample pit involved the use of 102 mm and 127 mm diameter blast holes charged with Orica’s Powersplit continuous explosive sausage. The blast hole spacing varied between 1.4 m and 1.6 m and the hole traces left in the walls indicate that the pre-splits were quite successful.

For the full development of the mine, consideration should be given to the use of up to 165 mm diameter blast holes for the pre-split. While this will necessitate the use of bulk decks of explosive rather than continuous pre-strip product, the larger diameter holes will provide greater directional accuracy and permit spacings of 3.5 m to 4.0 m. Accuracy may become an important issue when pre-splitting benches more than 30 m high.

5.3.3 Production Blasts

Blast designs at Bickham will need to be based on the ground conditions and geometry in place for each blast. However, based on the information available from exploration drilling and excavation of the Bulk Sample Pit, the basic production blast design described by Table 2 should form a suitable basis for most operations.

<table>
<thead>
<tr>
<th>Table 2 Nominal Production Blast Designs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Bench Height</td>
</tr>
<tr>
<td>Hole Diameter</td>
</tr>
<tr>
<td>Stemming Length</td>
</tr>
<tr>
<td>Sub-Drill</td>
</tr>
<tr>
<td>Explosive</td>
</tr>
<tr>
<td>Charge Weight per hole</td>
</tr>
<tr>
<td>Burden</td>
</tr>
<tr>
<td>Spacing</td>
</tr>
<tr>
<td>Powder Factor</td>
</tr>
</tbody>
</table>

Adjustments to these patterns will be required when blasting to coal (negative sub-drill) or to another waste bench (positive sub-drill). Optimisation should be on-going based on production experience.

5.3.4 Trim Blasts

Figure 27 shows a section through a mine batter showing the transition between the production blast and the trim blast. The production blast must be fired and excavated to leave a clean, even face for the trim
 blast. The trim blast can then be fired and excavated. The final batter clean-up will be responsible for the quality of the final walls.

Table 3 shows typical trim blast designs suitable for use at Bickham.

![Figure 27 Section through production and trim blast](image)

**Table 3** Nominal trim blast designs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dry</th>
<th>Damp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bench Height</td>
<td>15 m</td>
<td>15 m</td>
</tr>
<tr>
<td>Hole Diameter</td>
<td>165 mm</td>
<td>165 mm</td>
</tr>
<tr>
<td>Stemming Length</td>
<td>3.7 m</td>
<td>3.7 m</td>
</tr>
<tr>
<td>Sub-Drill</td>
<td>0 m</td>
<td>0 m</td>
</tr>
<tr>
<td>Explosive</td>
<td>ANFO</td>
<td>ANFO/HA35</td>
</tr>
<tr>
<td>Charge Weight per hole</td>
<td>190 kg</td>
<td>220 kg</td>
</tr>
<tr>
<td>Burden</td>
<td>4 m</td>
<td>4 m</td>
</tr>
<tr>
<td>Spacing</td>
<td>7 m</td>
<td>7 m</td>
</tr>
<tr>
<td>Powder Factor</td>
<td>0.45 kg/bcm</td>
<td>0.52 kg/bcm</td>
</tr>
</tbody>
</table>
6. Conclusions

Disruption of stream flows from the effects of blasting in adjacent mines is not a feature that has been observed in the Hunter Valley. An extensive search has also failed to find any such cases described in the Australian or international mining or groundwater literature.

The permeability of pit walls could be affected by the relaxation of stress or the movement of potentially unstable blocks freed by the removal of confining strata. Geotechnical analyses are required to assess the potential of these mechanisms to affect the permeability of strata between the proposed Bickham Mine and Pages River.

In the north of the proposed mining area the river bed lies down-dip of the coal seams to be mined. This means that any leakage path between the river and the pit would have to flow across the bedding planes of the strata which is not consistent with usual flow behaviour in bedded strata. On the eastern side of the pit, the river bed lies up-dip of the pit and a potential leakage path could lie along bedding.

The rock mass exposed in the Bulk Sample Pit substantially confirms the interpretations previously made based on exploration borehole logs and geophysics. There do not appear to be any unusual or unexpected features in the rock mass that would challenge the design of blasts to meet production, environmental and damage requirements. Blasting operations in the Bulk Sample Pit are reported to have been effective in preparing muckpiles for excavation and to have caused minimal visible damage to pit walls.

There is no universally agreed approach to the modeling of blast performance. Detailed theoretical or analytical descriptions are inevitably limited by the difficulty in defining the specific rock mass properties and their variation in a practical field situation. For the issues under consideration at Bickham, the Holmberg – Persson analysis provides a practical and useful description of the trends expected and the relative influence of the relevant blast design parameters on the extent of blast damage that can be expected. The approach can be used with confidence to compare the potential impact of alternative blast designs if complemented by reliable field data and appropriate engineering judgement. There is also abundant practical experience for the successful design of blasts in rock similar to that at Bickham and so the overall requirements for the future blasting operations can be clearly defined.
It would be possible to undertake trial blasts at Bickham to demonstrate the impact that appropriately designed blasts would have on the permeability of the adjacent strata. Because there is no established approach to relate rock mass damage to changes in permeability, it is important that the design of any such trials addresses the impact of blasting on rock mass permeability by direct measurement rather than relying on parameters that may be more easily measured (such as vibration or gas pressures) but cannot be directly related to changes in permeability.

Provided the operations are designed using the approaches recommended in this report and they are implemented to a high standard, there should be negligible impact from the blasting operations on the permeability of the pit walls more than 15 m behind the blast. Damage beyond two trim blast burdens (about 8 m) is likely to be very minor and difficult to discern.

These distances are very small compared with the 300 m off-set provided by the mine design. It is therefore concluded that any direct damage caused by the blasting operations proposed for the Bickham Mine will be limited to the immediate vicinity of the blast and will not affect the permeability of the strata between the mine and Pages River.
References


Blair, D., and Minchington, A. 2006, *Near-field blast vibration models*. Fragblast 8 – Conf of the ISEE Fragblast Section, Santiago, Chile


Dundon, P., 2005, Personal communication.


McKenzie et al, 1995, *Application of computer assisted modeling to final wall blast design*, EXPLO 95 – a conference exploring the role of rock breakage in mining and quarrying, AusIMM, Sep 4-7, Brisbane, Australia.


