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G. Li
NSW Department of Primary Industries

I. Forster
Connell Wagner Pty Ltd

M. Fellowes
Austar Coal Mine Australia

A. Myers
Centennial Coal Australia

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A CASE STUDY ON LONGWALL MINING UNDER THE TIDAL WATERS OF LAKE MACQUARIE

Gang Li¹, Ian Forster², Matthew Fellowes³ and Andrew Myors⁴

ABSTRACT: This article presents a case study of longwall mining under the tidal waters of Lake Macquarie, south of Newcastle, NSW. The mining operation took place at the Wyee Colliery from 1998 to 2002, without any incidence of ingress of water from the lake. This paper describes i) the design strategy used for a viable and robust mine layout that minimises the risk of water ingress ii) observations made during the operational phase and iii) a practical tool for designing underground coal mines under surface water bodies.

INTRODUCTION

This article presents a case study of longwall mining under the tidal waters of Lake Macquarie, south of Newcastle, NSW. The mining operation took place at the Wyee Colliery from 1998 to 2002, without any incidence of ingress of water from the lake or any abnormal underground water makes.

The water in a tidal lake is controlled by the sea to which the lake is connected. Therefore, for mine design and operation purposes, the task was to manage the risk of potential hydraulic connection between the underground mine workings and an inexhaustible body of surface water.

At the design stage, the most significant challenges were:

• The limited thickness of solid overburden strata (151 m to 178 m) relative to the requirement of the Wardell Guidelines (1975). Therefore, there was a need to understand the nature, magnitude and distribution of mining-induced surface and sub-surface ground deformations/fractures, and

• Part of the planned mining was in geologically disturbed areas. It was recognised at the design stage that the most significant unknown was whether or not the geological structures would act as conduits under the influence of mining-induced stresses and strains.

This paper describes the design strategy used for a viable and robust mine layout in the context of managing water ingress risk. The strategy comprised primarily:

• Summary of past experience of mining under surface water bodies;
• Characterisation of site-specific conditions relevant to the subject;
• Establishment of site-specific geotechnical and hydrogeological models for mining-induced surface and sub-surface deformations;
• Assessment of the interactions between geological structures and mining-induced surface and sub-surface deformations, and
• Development of mine design measures to minimise any potential impacts of the identified uncertainties and potential variations in site conditions.

This article also comments on the implemented mine layout based on the observations made during the operational phase and presents a practical tool for designing underground coal mines under surface or overlying water bodies.

PAST EXPERIENCE OF MINING UNDER SURFACE OR OVERLYING WATER BODIES

¹ NSW Department of Primary Industries (Author’s contribution was due to work as Manager of Underground Coal Mining of Coffey Geosciences Pty Ltd)
² Connell Wagner Pty Ltd
³ Austar Coal Mine
⁴ Centennial Coal
The lessons from studies of over 30 previous inrush/inflow cases reported in the literature (e.g. Singh 1986) and unpublished reports are that such incidences occurred due primarily to:

- Ambitious layout or excessive resource recovery relative to the thickness and competency of strata between the underground workings and the overlying water bodies. Inadequate solid rock cover was primarily responsible for most of the reported inrush/inflow events;
- Geological structures in combination with incompetent/permeable overburden strata, which were responsible for some apparently “abnormal” inrush or inflow incidences;
- Lack of understanding of site conditions or the nature, magnitude and distribution of mining-induced ground deformations/fractures, and
- Variations in site conditions and uncertainties, which were not adequately addressed in the mine designs and management processes.

These lessons influenced the development of the mine design strategies used for the project.

**MINING DATA AND SITE CONDITIONS**

**Mining data**

Figure 1 shows the layout of Longwalls 17 to 23 in Wyee Colliery, all of which are sub-critical panels (Table 1) within the Fassifern Seam. As shown in Table 1, the cover depth (from the surface of lake bed sediment to the top of the Fassifern Seam) ranges from 161 m to 197 m, whereas the thickness of rock cover (i.e. overburden strata excluding lake bed sediment) varies from 151 m to 178 m.

There are no existing workings at the subject site, with the exception of a small area of first workings in the overlying Great Northern Seam.

<table>
<thead>
<tr>
<th>Panel Name</th>
<th>LWs 17 to 19</th>
<th>LW20</th>
<th>LW21</th>
<th>LWs 22 &amp; 23</th>
</tr>
</thead>
<tbody>
<tr>
<td>Void Width (m)</td>
<td>130</td>
<td>140</td>
<td>140</td>
<td>150</td>
</tr>
<tr>
<td>Mining Height (m)</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Chain Pillar Height (m)</td>
<td>3.2</td>
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<td>n/a</td>
<td>3.2</td>
</tr>
<tr>
<td>Chain Pillar Width (m)</td>
<td>45</td>
<td>n/a</td>
<td>n/a</td>
<td>45</td>
</tr>
<tr>
<td>Chain Pillar Length (m)</td>
<td>51-95</td>
<td>n/a</td>
<td>n/a</td>
<td>145</td>
</tr>
<tr>
<td>Cover Depth (m)</td>
<td>162-174</td>
<td>175-181</td>
<td>161-185</td>
<td>179-197</td>
</tr>
<tr>
<td>Rock Cover (m)</td>
<td>151-159</td>
<td>158-162</td>
<td>157-173</td>
<td>162-178</td>
</tr>
<tr>
<td>Lake Bed Sediment (m)</td>
<td>11-21</td>
<td>17-23</td>
<td>11-23</td>
<td>18-26</td>
</tr>
<tr>
<td>Recorded Smax* (m)</td>
<td>0.65</td>
<td>0.4</td>
<td>0.45</td>
<td></td>
</tr>
</tbody>
</table>

* Smax = Maximum subsidence

**The lake bed sediment**

As shown in Table 1, the thickness of the lake bed sediment ranges from 11m to 26m in the subject area. The unconsolidated sediment consists generally of clay or silty clay with lenticular bodies of silty sand, sand and gravel. The materials have the potential to seal fractures and other mining-induced voids.

**In-situ stress**

Unusually high horizontal stress (about 5 to 7 times of the vertical) was measured at the adjacent Kangy Angy road cutting (Chappell, et al, 1984) and from a number of mine workings at depths less than 200m in this region (DMR, 1997).
According to the documented in-situ stress regime in the Newcastle-Gosford Region (DMR, 1997, Enever et al., 1998, Enever & Clark, 1998, Zhang et al., 1996), it is assessed that the in-situ major horizontal (compressive) stress is oriented NNE at Wyee, which would be sub-perpendicular to the dominant geological structures and would therefore act against the opening of these structures. Consequently, the high horizontal stress field should generally be beneficial from the viewpoint of controlling water ingress risk.

**Stratigraphy and strata conditions**

The Fassifern Seam is stratigraphically located in the upper section of the Late Permian Newcastle Coal Measures overlain by the Triassic Narrabeen Group. Figure 2 shows the generalised stratigraphy of the subject area to facilitate the discussions to be presented in this paper.

As illustrated in Figure 2, the overburden strata in the subject area are characterised by the dominant occurrence of massive conglomerates, separated by coal seams and tuffaceous rock units (e.g. Mannering Park Tuff and Awaba Tuff). Fresh conglomerate strata in the region have both high UCS strength and fracture resistance (Moelle et al., 1996), whereas the tuffaceous rocks, where they are degraded or mechanically weak, often behave plastically with a potential to seal fractures and other mining-induced voids.

**Massive conglomerate units**

A massive unit is geotechnically defined as a stratum that is substantially free from horizontal defects so that it may behave mechanically as a beam. The horizontal defects, which are the key features used for the identification of the massive units, may include bedding partings, erosional surfaces, horizontal structural discontinuities and layers of fine-grained sediments, such as mudstone, siltstone or fine-grained sandstone, etc.

The assessment of massive conglomerate units was aimed at determining the following:

- The location, thickness and mechanical properties of the massive units, and
- The distance between the top of the Fassifern Seam and bottom of the identified massive units.

The assessment of massive units was made based on geological logs from 25 boreholes surrounding the subject area. The stratigraphic units studied included the Karingal, Teralba, Karignan and Munmorah Conglomerates. Their locations relative to the Fassifern Seam are illustrated in Figure 2.
For reasons of conservatism (Sheehan, et al, 1997), the identification of the thickness of the massive units requires the assessment towards the lowest possible limit. This was done by using identifiable horizontal geological defects and any fine-grained sedimentary rocks as dividers, irrespective of their thickness. Thin medium-grained sandstone layers may be included as part of the massive units, judged by the overall pattern of the massive unit development. In addition, the weathered section of the uppermost Munmorah Conglomerate was excluded. The results of the assessment are presented later. The values of UCS, Young’s Modulus and frictional angle of the massive units were 65 MPa, 18500 MPa, and 35°, respectively, based on test results.

**Geological structures**

The geological setting of the Newcastle-Gosford Region is determined by the geometry and depositional history of the northern fringe of the Sydney Basin. It has been affected by post-depositional ductile and brittle tectonic deformational events. These events included primarily the creation of several regional folds, and subsequent faulting and igneous dyke emplacements, observable at the subject site.

Based on the results of surface/underground mapping, geophysical surveying and bore logging of the subject site and its surroundings, the following observations can be made:

- The majority of the structures in the subject area consist of NW trending, near vertical normal faults and their associated dykes. These structures were generally dry and tight and significant disturbances to the surrounding strata were not observed;
- Based on the Early Tertiary age of the geological structures in the subject area, they have a potential to affect both the Permian Newcastle Coal Measures and the overlying Triassic Narrabeen Group, through the full overburden height. It follows that the structures’ potential to form conduits between the lake and the underground workings must be critically assessed and managed;
- Although the longwall panels were positioned at the design stage to avoid the known large structures using the best information available at the time, variations in structural conditions must be expected and managed, and
- The longwall were located in areas with different structural conditions and with different orientations in relation to the dominant NW trending structures. In particular, Longwalls 19 and 21 are located in a geologically disturbed area (Figure 3). Therefore, the mine design (and the risk management process) needed to be robust enough to deal with any significant variations and uncertainties.
GEOTECHNICAL AND HYDROGEOLOGICAL ASSESSMENT

The geotechnical and hydrogeological assessment was aimed at establishing site-specific models that provide:

- A guide for designing the subject longwalls against water ingress risk, and
- A basis for effective communication of risks among all involved in the management of the risks.

Surface and sub-surface deformations

The transmission of water through the overburden strata may take place via a number of mechanisms such as i) inter-granular porosity, ii) mining-induced voids, fractures and strata dilation/bed separations and iii) structural discontinuities/geological defects.

Forster (1995) presented a hydrogeological model for the Central Coast Region, which divides the overburden into four different zones with different ground deformation characteristics, as shown in Figure 4. To provide a practical tool for designing subaqueous mining, this model was calibrated against the hydrogeological data relevant to super-critical panels in the Central Coast Region including the Wyee Colliery (Forster, 1995). In contrast to the required rock cover of 60t (t = extraction thickness) by the Wardell Guidelines (1975), the Forster Model suggested a reduced rock cover of 45t plus 10 m subject to further site-specific verification (Forster, 1995).

This article presents an enhancement to the Forster Model used during the project. As compared with the original Model, as shown in Figure 4 (Forster, 1995), the modifications were made to:

- Combine the "Caved Zone” and “Fractured Zone” into a single zone termed the “Dewatered Zone” located immediately above the extracted coal, and
- Introduce the findings of a number of recent studies dealing with the nature and distribution of the “Dewatered Zone”.

Consequently, the enhanced Forster Model divides the overburden into three major zones, namely, the Surface Zone, Constrained Zone and Dewatered Zone, as discussed below.
The Dewatered Zone

The Dewatered Zone, by definition as discussed above, provides an effective conduit between the underground workings and any overlying water bodies, which are either directly intersected by or hydraulically connected to this Zone. It follows that the concept of the Dewatered Zone highlights the critical importance of the thickness and integrity of the overlying Constrained Zone that is to function as a barrier to inflows from any overlying water bodies.

Studies on sub-surface deformations by Whittaker and Reddish (1989) show that the Dewatered Zone (as defined here) is bounded by hydraulically connected tensile fractures over the ribs, capable of transmitting large amount of water to underground workings.

It is assessed that the Dewatered Zone above the extracted void is likely to develop a dome-shaped geometry as shown in Figure 5. This important assessment is based on a comprehensive investigation into sub-surface deformations involving goaf drilling, geophysical testing and several years’ of gateroad mapping in strata about 35 to 40 m above the old Liddell longwall workings at Cumnock Colliery (Li & Cairns, 2000). Further evidence can be found in documented investigations on sub-surface deformations (e.g. Colwell 1993, Kelly et al, 1998, Mills, 1998).

The height of the Dewatered Zone was assessed to be up to 33 times the mining height for the subject site. This was the estimated maximum height of the Dewatered Zone based on super-critical panels in the Central Coast Region (Forster 1995). Subsequent verification tests for the present project by Forster (1998) at Wyee Colliery produced data to further support this assessment.

The Surface Zone

For descriptions of this deformation zone, reference is made to Figure 4 and the original Forster Model (1995). The significance of the Surface Zone has been demonstrated by a case study reported by Singh (1986) at the North Derbyshire Colliery, where the recharge of the “bed separation zone” through the fractures/joints in the surface zone caused an inundation event.

To assess the potential impacts of the Surface Zone on water ingress, the depth of tensile cracks was assessed during the project based on the test results and principles of rock fracture mechanics (Li & Moelle, 1993). It was estimated that the depth of any surface tensile cracks for the present case would be unlikely to reach 10 m from the ground surface.

The Constrained Zone

Again, for descriptions of this zone, reference is made to Figure 4 and the original Forster Model (1995). From the results reported by Holla (1986 & 1990) and Luo and Peng (2000), it can be seen that shear dilation, bed separations and the resulting changes in horizontal permeability can affect large portion of the overburden, however, with reducing intensity away from the extracted horizon. It is important to note that although some mining-induced changes in permeability may still take place within the Constrained Zone, it may still be designed to function adequately as a barrier to prevent hydraulic connections between the overlying water bodies and the Dewatered Zone. According to the studies by Forster (1995, 1998), the thickness of the Constrained Zone, as such a barrier, should be equal to or greater than 12 times the mining height assuming no significant geological structures within the Zone.

As discussed above, the level of water ingress risk at the subject site is critically determined by the thickness and integrity of the Constrained Zone and is also related to the occurrence of faulting and other geological discontinuities.
Interactions between geological structures and mining-induced ground deformations

It was assessed that the near vertical faults/dykes would not significantly change the height of the Dewatered Zone above an isolated panel. It follows that for a single sub-critical panel, the use of a Dewatered Zone height of 33t (t = extraction height), which is based on super-critical conditions, will provide a degree of conservatism as part of the risk management strategies, when applied to the sub-critical panels beneath the lake in this case.

Although the shape of the Dewatered Zone may be altered due to the presence of geological structures, the extent of such alteration should be limited since the geological structures are near vertical. However, to minimise the potential for interactions between the Dewatered Zones above the individual panels, it was decided to adopt a specific design measure so that the Dewatered Zones above adjacent longwalls could be effectively separated. This was achieved by using appropriate chain pillar widths, as illustrated in Figure 5. Despite the above-mentioned design measures, hydraulic connection between the lake and the mine workings would still be possible if the near vertical faults/dykes were activated/connected by ground deformations within the Surface and Constrained Zones. The spanning capacity of the massive units within the overburden was utilised to manage this risk.

Spanning massive unit

In the context of managing water inflow risks, the designed functions of the spanning massive units were to minimise surface tensile strains, the development of mining-induced fractures and, importantly, the interactions between the geological structures and the ground deformations.

The assessment of the spanning capacity of the massive units was made based on the Voussoir Beam Theory (Brady & Brown, 1985).
Notes:

According to a case study at Cumnock Colliery by Li and Cairns (2000), the average value of $\alpha$ was approximately 15 degrees (actual observations vary between 0 and 22 degrees).

For conglomerate overburden, $\alpha$ angle is likely to be higher according to Whittaker et al (1989).

Sources of the above reference are listed in the paper.

- The spanning distance is assumed to be the full panel width for all massive units in the overburden despite their different locations in relation to the Fassifern Seam. For the massive units in the Karignan and Munmorah Conglomerates (Figure 2), the use of the full panel width as the spanning distance is conservative.
- The surcharge on the beam is assumed to be the dead weight of the full overburden above the massive unit, including the weight of the beam itself. Again, this is a conservative assumption.
- The design factor against compressive failure of the conglomerate beam was selected as 1.2. It is important to note that the value of the design factor was selected in conjunction with the above conservative assumptions and by referring to the results of previous unpublished and published case studies in a similar geotechnical environment (e.g. Frith & Creech, 1997).

Based on the above assumptions and the mechanical properties of the conglomerates as quoted earlier, the conglomerate beam thickness required for spanning across various void widths from 130m to 170m was determined and is presented in Figure 6.

A comparison of the required beam thickness (Figure 6) for the panel widths shown in Table 1 with the assessed massive unit thicknesses has resulted in a plot (Figure 7) showing the indicative distribution of the spanning strata over the subject area and its surroundings. The common occurrence of spanning massive units in the subject area, as indicated by Figure 7, was confirmed by reduced subsidence in the subject area after the completion of mining.
Potential variations and uncertainties

The geotechnical assessment identified a number of potential variations and uncertainties requiring consideration:

- Unexpected variations in thickness of solid overburden strata;
- Unexpected significant geological structures, outside the requirements of the Wardell Guidelines (1975);
- Variations in mechanical properties/integrity of the Constrained Zone (i.e. the barrier to potential water ingress);
- Variations in thickness/mechanical properties of the massive units;
- The capacity of massive units to span across multiple panels even though they are sub-critical panels separated by large chain pillars, and
- Effects of geological structures affecting the stability of chain pillars and spanning capacity of massive units.

MINE DESIGN STRATEGIES

Principal design strategy

Considering the severity of consequences of a potential inrush incidence, the principal design strategy used in the project aimed to ensure minimal residual risks. The implemented measures were:

- To maintain adequate thickness and mechanical integrity of the Constrained Zone to form an impermeable barrier between the lake and the Dewatered Zone. This was primarily achieved by ensuring the minimal required thickness of rock cover in accordance with the Forster Model (i.e. the
thickness of rock cover $\geq 45 + 10 \text{ m}$, with $t$ being the extraction height), rather than the Wardell Guidelines. By selecting a mining height of 3.2m, this requirement was principally met, and

- To develop a robust mine layout design, supported by a risk management system during the operational phase, to manage the risks of any re-activated geological structures, uncertainties or unexpected variations as discussed above, while maintaining a viable mining operation. This was achieved by building into the design a number of additional measures discussed below.

**Additional design measures**

The additional measures included:

- Appropriate panel width and stable chain pillars (Table 1) to ensure spanning of the massive strata across the longwall panels. The functions of the spanning strata have been discussed above;
- Separation of individual sub-critical panels by adequately sized chain pillars to limit panel interactions as well as the height/extent of Dewatered Zones, and
- A number of conservative assumptions used in the geotechnical models, as discussed above.

The potentially beneficial sealing effects of the lake-bottom deposits and tuffaceous strata and the effects of high in-situ stresses preventing opening of the geological structures were not considered when defining the layout parameters (Table 1), as an additional measure for an appropriate safety margin.

In summary, the key design issues were to use sub-critical panels, an appropriate mining height and suitable chain pillar sizes so that the dome-shaped Dewatered Zones above each of the extracted panels could be sufficiently separated from each other and be limited to a maximum height of 33 times the mining height with a degree of conservatism.

Figure 8 is an illustration of the major elements of the design process against water ingress risks, which contributed to the final mine layout shown in Figure 1 and Table 1.

![Fig. 8 - Design Process against Water Ingress Risk](image)

**OBSERVATIONS AND COMMENTS**

**Observations**

The main observations made during the extraction of the subject panels are summarised as follows:

- Irrespective of the differences in the degree of structural disturbance, orientation of panels in relation to the dominant NW trending geological structures and any other variations in strata conditions, ingress of water from the lake or abnormal water makes were never detected during the extraction of the subject panels;
- Surface subsidence over the subject panels was surveyed using the baythymetric method. Although the accuracy of this method is much lower than that of the conventional methods used for land surveys, the magnitude of the recorded subsidence (Table 1) provides a clear indication that there was reduced subsidence across all subject panels confirming the existence of spanning massive strata within the overburden;
• Longwalls 19 and 21 are located in a geologically disturbed area. Several normal faults are parallel and within the two panels with throws up to 1.2 m. These faults remained generally dry during the extraction and the test results of seepage from the faults showed that the water was not from the lake, and
• The development of the tailgate for Longwall 21 exposed an unexpected fault zone with a throw greater than 3m, probably up to 3.5 m. Subsequent exploration at other locations along the gateroad further confirmed the existence of this parallel fault in close proximity to Longwall 21. The structural conditions were outside the requirements of the Wardell Guidelines (1975), which recommend no extraction under tidal waters within 50 m of a fault with displacement greater than 3 m or a dyke of thickness greater than 6 m. The subsequent reviews conducted by the management team suggested that there would be minimal interactions between this fault and the dome-shaped Dewatered Zone, as illustrated in Figure 9. Longwall mining proceeded with the support of various actions documented in the risk management system developed and implemented by Wyee Colliery. Again, no ingress of lake water or abnormal water makes were observed during the extraction of this panel. Note that Longwall 21, like the adjacent Longwalls 17 to 19, was retreating down-dip meaning that any abnormal water makes would be easily detectable.

Fig. 9 - Dewatered Zone in Relation to the Unexpected Fault in TG21

Comments
The Wardell Guidelines (1975) are likely to be overly conservative at the subject site and possibly for other Central Coast areas with similar geotechnical and hydrogeological conditions.

The enhanced Forster Model discussed in this paper provided a practical tool for the design of the subject longwalls against water ingress risks. The design tool was developed based on the understanding of surface and sub-surface ground deformations at the subject site. Importantly, this understanding has facilitated the development of the mining system’s capability in dealing with unexpected geological disturbances as well as variations in site conditions, as discussed above.
It follows that the application of the Forster Model, being the original (Forster, 1995) or the enhanced version as presented in this paper, to other areas may be possible provided that there are adequate investigations and understanding of the site conditions and ground deformation characteristics. As demonstrated by this case study, such site-specific investigations and understanding as well as any necessary modifications to the Model are critical for the successful application of this design tool.

It may be argued that the implemented mine design is conservative and there could be room for better resource recovery for the present case. While it is worthwhile to further improve our understanding of the ground deformations caused by longwall mining in order to achieve optimal resource recovery, the required safety margin, which can be systematically developed through various measures as demonstrated by the present case (e.g. by limiting the panel widths to ensure spanning of the massive strata), needs to be critically considered for any particular mine sites.

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