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Dr W Timms

### Summary of the abstract

Groundwater in mining operations presents a number of challenges and opportunities

Analysis of high frequency pore pressures can reveal how systems work, and provides insitu specific storage values to improve numerical groundwater models.

Environmental tracer techniques are increasingly common to quantify groundwater connectivity and flows.

Several ongoing technical challenges with groundwater and mining are highlighted that require

- more strategic baseline monitoring
- a variety of conceptual models and
- adoption of leading practices that are commensurate with the risks of the project



### Abstract

Groundwater in mining operations presents a number of challenges and opportunities – this talk presents examples of leading practice and R&D in progress. Evaluating potential hydrological changes due to mining is challenging where there is competition for water from mining, farming and the environment and with more variable climate conditions. Opportunities for mine sites to share and store water are increasingly valuable, provided that water discharged is of suitable quality.

Analysis of high frequency pore pressures can reveal how systems work, and provides in-situ specific storage values to improve numerical groundwater models. Examples from the Gunnedah Basin show how pore pressure response to barometric and earth tide loading provides in situ specific storage values that can replace assumed values in models. A new technique for short-term monitoring of response to small stresses in low permeability formations is highlighted. And a unique example from the Sydney Basin shows where specific storage values can change in response to mining stresses and links with geomechanics and rock core testing.

Leading practice investigations now more commonly include environmental tracer techniques to quantify groundwater connectivity and flows, given a trend towards smaller volumes, less expensive and a greater range of tracer options. Radio-isotopes and geochemical tracers are increasingly applied in mine water studies to better evaluate the possibility of groundwater seepage. An advanced technique is highlighted that enables stable isotope analysis in moist sediments and rock core and comparison with rainwater and groundwater values. A high resolution vertical profile of stable isotopes through the Hawkesbury sandstone shows the critical role of thin layers of cemented sandstone barriers to flow.

Several ongoing technical challenges with groundwater and mining are highlighted that require more strategic baseline monitoring, a variety of conceptual models and adoption of leading practices that are commensurate with the risks of the project.



### **Research team & collaborators:**























### Research outputs highlighted in this talk

- Timms W;Holley C, 2016, 'Mine site water-reporting practices, groundwater take and governance frameworks in the Hunter Valley coalfield, Australia', *Water International*, vol. 41, pp. 351 370, <u>http://dx.doi.org/10.1080/02508060.2016.1173278</u>
- Acworth RI;Rau GC;Halloran LJ S;Timms WA, 2017, 'Vertical groundwater storage properties and changes in confinement determined using hydraulic head response to atmospheric tides', *Water Resources Research*, vol. 53, pp. 2983 -2997, http://dx.doi.org/10.1002/2016WR020311
- Cook SB;Timms WA;Kelly BF J;Barbour SL, 2017, 'Improved barometric and loading efficiency estimates using packers in monitoring wells', *Hydrogeology Journal*, vol. 25, pp. 1451 1463, <u>http://dx.doi.org/10.1007/s10040-017-1537-9</u>
- David K;Timms WA;Barbour SL;Mitra R, 2017, 'Tracking changes in the specific storage of overburden rock during longwall coal mining', *Journal of Hydrology*, vol. 553, pp. 304 320, <u>http://dx.doi.org/10.1016/j.jhydrol.2017.07.057</u>
- David K;Timms W;Baker A, 2015, 'Direct stable isotope porewater equilibration and identification of groundwater processes in heterogeneous sedimentary rock', *Science of the Total Environment*, vol. 538, pp. 1010 -

1023, http://dx.doi.org/10.1016/j.scitotenv.2015.08.075

Poster downloads etc available here: https://www.researchgate.net/profile/Wendy\_Timms



### The big picture for mining & water



Multiple water users/communities

\$\$ Costs

Not enough water Too much water TREATMENT Quality of water fit for use or discharge

More info on each aspect in MINE8910 mine water and waste management course



# 1 ring 5 grams gold





# 120 x 10 litres $H_20$



# 2 to 21 tonnes rock waste



### **10 litres diesel**

Ryan (2003) CSIRO Sustainability Network Update 24E



### Water use by mines in the Hunter Valley



### Analogous to a mine cost curve



Energy	Water use		
спегду	(L/ GJoule)		
Biomass <sup>1</sup>	71,000		
Crude oil <sup>1</sup>	1060		
Solar thermal <sup>1</sup>	300		
Biomass ethanol corn (USA) <sup>5</sup>	250		
CSG - Surat Basin <sup>6</sup>	192		
Coal <sup>1</sup>	160		
Uranium – nuclear energy <sup>1</sup>	90		
Gas - conventional (AUS) 6	67		
Coal – depressurization <sup>3</sup>	63 -126		
CSG - Bowen Basin <sup>6</sup>	50		
Gas – conventional <sup>1</sup>	40		
Uranium – open pit <sup>2,4</sup>	20		
Coal - Hunter Valley <sup>7</sup>	10 - 56		
Oil <sup>3</sup>	8.6 -13		
Gas – shale <sup>3</sup>	8.3		
Uranium – in situ recovery <sup>3</sup>	6.1		
Coal surface - rehab <sup>2</sup>	5		
Coal surface – no rehab <sup>2</sup>	2		
CSG - Sydney Basin <sup>6</sup>	1.1		
Wind energy <sup>1</sup>	0		

# How much water is used?

- Large range of water use which is site dependent
  - Biomass very high
  - CSG in Sydney Basin very low
- Water use is higher if including depressurization of aquifers, rehab, processing, and energy production.
- Limited recent data for some energy types, specific locations and full life-cycle of extraction & production.

### References

- 1. Gerbens-Leenes et al. 2008 UNESCO-IHE
- 2. Gleick 1994 in Nicot & Scanlon, 2013
- 3. Nicot et al in Nicot & Scanlon, 2013
- 4. DOE 2006 in Nicot & Scanlon, 2013
- 5. Wu et al. 2009
- 6. RPS 2011
- 7. Timms & Holley, 2016



### **Future options for final mine voids**

### 4<sup>th</sup> year students supervised by W Timms

The will be approximately 30 final mine voids in the Hunter Valley, with a combined footprint of 3,840 hectares (or 0.18% of the total region).

Typical mine void models (A to F) were designed in GOLDSIM-AWBM for a range of realistic site conditions to evaluate engineering design, backfill feasibility and water quality scenarios over 500 years.

Future use options can be evaluated for specific sites including: for **water storage**, aquaculture, **pumped hydro storage**, and the possibility of wetlands managed for carbon sequestration.

ACSCMP website project summary here.









# Adding value? Storing water





- This model case assumed constant groundwater inflow 4 ML/day
  - 2 voids overflowed at <100 years, 3 voids stable equilibrium levels, 1 void did not equilibrate, 5 voids ultimately brackish water & 1 was moderately saline
- For all model cases, water salinity at 500 years was estimated to be:
  - fresh (n=6), brackish water (n=9), moderately saline (n=2), and seawater salinity (n=1), and thus with a range of beneficial uses for the water.



# Squeezed by gravity: how tides affect the groundwater under our feet

Courtesy G Rau et al. 2017



https://theconversation.com/squeezed-by-gravity-how-tides-affect-the-groundwater-under-our-feet-74928

Evolution of new know-how in this area led by UNSW researchers:

Timms and Acworth (2005) Hydrogeology J.; Acworth et al. (2015) Hydrogeology J; Acworth et al. (2016) Water Resources Research, Cook et al (2017) Hydrogeology J.; David et al (2017) Journal of Hydrology, Acworth Rau Timms et al.(2017) Water Resources Research, Rau et al, in review.



### Leading practice – high frequency pore pressure analysis

### Monitoring requirements:

- groundwater monitoring piezometers
- auto loggers for pore pressure & barometric pressure
- high frequency (hourly or 4 hourly) data
- shut-in piezometers with packers for low K conditions

### Interpretation:

- de-trending, amplitude and phase changes; transformation from time to frequency domain
- correlation with stress changes: barometric changes & earth tide stresses, mining stresses

### Provides in-situ, aquifer specific parameters

- outcomes depend on the site conditions and monitoring setup
- moisture storage changes in soil, evaporative losses
- barometric and loading efficiency (BE, LE), confining changes
- matrix compressibility (B), storage parameters (S, S<sub>s</sub>)
- hydraulic conductivity  $(K_h, K_v)$

### $\rightarrow$ Improved numerical models for groundwater flow

TOM elevations: ~312.4 m 312-311-310-309-2011 **Multiple** depth piezos or VWP

SWL: Australian Elevation Height (m)



# Bulk modulus and compressibility

Bulk modulus (K) of strata is the reciprocal of strata compressibility  $(\beta)$ 

Bulk modulus is related to Youngs modulus (E) and Poisson's ratio (v)

$$K = \frac{E}{3(1-2\nu)} = \frac{1}{\beta}$$

Strata compressibility (β) can be determined in situ from pore pressure response to small stresses

eg barometric and earth tide analysis

# Specific storage and compressibility

The specific storage of the strata (Ss with dimensions  $m^{-1}$ ) depends on

density of water ( $\rho$ ) the porosity ( $\phi$ ) compressibility of water ( $\beta$ ) compressibility of the formation ( $\beta p$ )

$$S_{\rm s} = \rho g(\phi \beta + \beta_{\rm p})$$

Strata or formation compressibility  $\beta$  is also known as  $\alpha$ .

Assumes incompressible particles (ie. not clay)



### How to improve reliability of a groundwater model

All models are wrong, but some are useful

• A specific storage (Ss) value that is too high underestimates drawdown (or vice versa)

Analyze site specific, in situ Ss values for modelling
3 pore pressure methods vs. rock core tests

Track changes in Ss over time due to disturbancesExample: underground excavation and mining

Example from Theis drawdown analysis for a confined aquifer in the constrained zone.



Timms et al 2017 IAH 44<sup>th</sup> Congress David et al 2016 *Journal of Hydrology* 



### Mining example: a confined aquifer in the constrained zone



A confined aquifer can be maintained in the constrained zone above a longwall mine.

Saturation and confined groundwater (under pressure) in this zone depends on mining stresses, deformation and subsidence.

~ 2 meters of surface subsidence with extraction of a ~3 meter thick coal seam (depends on depth of cover, geology, panel width etc).

### Industry in-kind data provided



David K, W. Timms, L. Barbour and R. Mitra (2016) Changes in specific storage of overburden rock aquifers due to longwall coal mining. *Journal of Hydrology*, 553: 304 - 320

### How to measure LE compressibility: from small stresses in situ

 Barometric efficiency – LE estimated using both trial and error smoothing of pore pressure hydrographs AND least-squares regression between pore and barometric pressures over short LE<sub>s</sub> and long times LE<sub>L</sub> (Davis and Rasmussen 1993)



 Earth tide analysis – LE<sub>ET</sub> estimated from Fourier transform using TSOFT code to identify cyclic components, 2 cpd evident in pore pressure data, S2 earth and M2 moon amplitude. Band pass filter to isolate pore pressure responses to these (Acworth et al 2015)





Unit	Depth (mBG)	Porosity	LE <sub>et</sub>	S <sub>s</sub> (m <sup>-1</sup> )	LE	S <sub>s</sub> (m <sup>-1</sup> )
			earth tides		barometric pressure	
HBSS1	9.7	0.11	0.68	1.6E-06	0.67	2.12E-06
HBSS2	125	0.09	0.80	2.0E-06	0.64	1.57E-06
BGSS1	169	0.03	0.30	1.9E-07	0.40	2.81E-07
BGSS2	247	0.07	0.30	4.5E-07	0.35	5.90E-07
SBSS1	274	0.13	0.50	1.2E-06	0.32	1.03E-06

 In compressible formations the pore-water carries nearly the entire applied load (i.e. LE=1) while in stiff formations the load is shared by the water and soil skeleton (i.e. LE<1)</li>

• Stiff formations with increasing depth

• Porosity from wireline density logs



### Change in compressibility after mining: resulting from mechanical changes

A systematic change in  $S_s$  due to disturbance during mining within hydrostratigraphic units were up to two orders of magnitude. Consequently, the drawdown and inflow estimation could be overestimated if constant  $S_s$  is assumed.



 $S_s$  changes at ~250 m depth indicated this confined aquifer may have became unconfined, while other zones remained confined.



### Specific storage values: comparison of in situ and other methods

In situ Ss values from barometric and earth tide loading methods for the pre-mining period compare favourably with S<sub>s</sub> values derived from long term (35 days) pumping test data analysis within the southern part of the basin (PB, 2009 and RES, 2006). The aquifer test S<sub>s</sub> values ranged from 10<sup>-6</sup> to 8x10<sup>-7</sup> m<sup>-1</sup> for these sandstone strata.

**UCS or triaxial test of rock cores** to obtain Poisson ratio, Young modulus and compressibility. Rock core tests in the laboratory derived  $S_s$  was up to an order of magnitude higher than field obtained data (using LE), because of higher strains.

Geomechanical properties of rock assumed to be at unsaturated conditions. Eg. UCS is lower when saturated.

Masoumi H; Horne J; Timms W, 2017, **'Establishing Empirical Relationships for the Effects of Water Content on the Mechanical Behavior of Gosford Sandstone**', *Rock Mechanics and Rock Engineering*, vol. 50, pp. 2235 - 2242







### Improving Ss estimates for piezos in aquitards

out of phase

exaggerated

Drained compressibility ( $\alpha$ ) can be calculated from LE (or BE) in confined and semi-confined formations and used to calculate specific storage (Ss).

However, in aquitards or large diameter monitoring wells, time lags caused by well storage etc may be so long that BE cannot be properly assessed in open monitoring wells in confined or unconfined settings.

Packers to shut-in a piezo reduces time lags to enable reliable assessments over ~30 day period.

Cook SB; Timms WA; Kelly BF J; Barbour SL. 2017. 'Improved barometric and loading efficiency estimates using packers in monitoring wells', Hydrogeology Journal, vol. 25, pp. 1451 - 1463





### **Current research using high frequency pore pressures**

Researchers: Dr G Rau, Dr W Timms, K David, T McMillan, Prof I Acworth and others

Advanced pore pressure analysis in various sedimentary basin settings to determine:

- Combining methods to estimate multiple parameters eg. cross-hole seismic methods combined with earth tide analysis
- Compressibility and surface settlement related to groundwater extraction near CSG projects
- Monitoring changes in aquifer confinement with underground excavations

- Pore pressure responses in sandstone to shallow moisture and lake level loading (ie geological weighing lysimeters)
- Differential pore pressure responses near faults as indicator of dis-connectivity along strike, across strata

→ Leading to improved conceptual and numerical models, and evaluations of risk



### Why environmental tracers?

<u>Model independent data</u> is needed to improve useful and unique outcomes of groundwater flow models.

Eg. geophysical surveys, environmental tracers

Information required of proponents of coal mines and CSG projects now needs to include suitable environmental tracers.

http://www.iesc.environment.gov.au/

Timms W;Acworth RI;Jankowski J, 2001, 'Quantifying leakage and mixing in an alluvial aquifer system: a combined hydrochemical and hydrodynamic modelling approach constrained by isotopic evidence', in Seiler KP;Wohnlich S (eds.), *NEW APPROACHES CHARACTERIZING GROUNDWATER FLOW, VOLS 1 AND 2*, A A BALKEMA PUBLISHERS, MUNICH, GERMANY, pp. 419 - 423



Available online at www.sciencedirect.com

ScienceDirect

Procedia Environmental Sciences 32 (2016) 211 - 220

International Conference – Environment at a Crossroads: SMART approaches for a sustainable future

Using natural tracers to track the groundwater flow in a mining area

Alexandra Iulia Cozma, Calin Baciu\*, Mircea Moldovan, Ioan-Cristian Pop



Proce

Environmental Science

### What are environmental tracers?

Types of environmental tracers:

- Conservative (non-reactive) eg. chloride
- Reactive indicators of surface sources eg. nitrate, atrazine, caffeine
- Stable isotopes eg. oxygen-18
- Radio isotopes eg. tritium
- Noble and dissolved gases eg. argon-39, CFC's
- Organic tracers eg. fluorescence
- Bio-markers eg. DNA

Tracers can be:

- in aqueous phase, solid phase, or in pore water eg. VE isotopes
- naturally occurring, or introduced eg. dye tracer tests

Distinctive end-members essential to 'fingerprint' water sources and mixing

Trends towards smaller volumes, less expensive, greater range of tracers



### **Off –axis Integrated Cavity Output Spectroscopy (OA-ICOS)**

- Analysis of stable isotopes tracers <sup>18</sup>O and <sup>2</sup>H technology now for small water volumes, and moist soil/rock samples.
- Laser absorption spectroscopy a laser beam is directed through a sample and the mixing ratio of a gas is determined from the measured absorption using Beer's Law
- OA-ICOS offers superior performance, value and reliability compared to cavity ringdown spectroscopy (CRDS)
- Optical cavity traps the laser photon using highreflectivity mirrors
- The measured absorption spectra is recorded and combined with measured gas temperature and pressure in the cell and effective path length
- Ultrasensitive trace-gas measurements operate in the near infrared wavelength

Wassenaar et al. 2008 *Env. Sci Tech.* Hendry et al., 2015, *HESS* Timms et al. 2012 WRL report, Crane et al. 2013 AIG, David et al. 2015, *Science of the Tot. Env.* 







Immediate preservation (vacuum packing) of selected moist rock or sediment samples on site is ESSENTIAL





Multiple thin beds of sandstone control GW seepage. Similar <sup>18</sup>O and <sup>2</sup>H values throughout sequence.

David, K., Timms, W., Baker, A.(2015). Science of the Total Environment. 538, 1010-1023.

Hughes and Crawford. 2013. Journal of Hydrology for LMWL



### Hydrogeology of constrained zone

Multi-layered aquitards in the constrained zone under shallow waters. Aquitard (cemented sandstones, claystones) integrity varies pre/post mining.



Important:

- Thick overburden
- Multiple thin aquitards of cemented sandstone

### • our article in The Conversation

David, K., Timms, W., Baker, A.(2015). Direct stable isotope porewater equilibration and identification of groundwater processes in heterogeneous sedimentary rock. *Science of the Total Environment*. 538, 1010 – 1023.

### Industry in-kind data provided



### Swamp moisture – piloting new scientific approaches

•Where's the water sourced from and going?

- Rainfall fed, or groundwater discharge?
- Stable isotope tracers on water, peat and vegetation roots and rainfall
- Piloting other new tracers
- Moisture & carbon content depth profiles
- Correlation with time series water level & moisture data
- ? Comparison with UAV drone surveys of vegetation health & stress

•What is the critical base layer of the peat swamps?

• Clay base or sand mixes?

Timms, David, Baker (2017) IAH 44<sup>th</sup> congress







### Water dependent assets – supply reservoirs & swamps

~2000+ swamps in Sydney Basin, of which currently ~20 are impacted by mining

*Multiple stresses including:* forestry, urban runoff, erosion, climate change, wild fire, longwall mining & ground movement







East Wolgan Swamp was once dense with Gliechenia fern, Grevillea acanthifolia and Tea-tree (Photo: C. Jonkers, various dates).



Two metre deep collapse in East Wolgan Swamp. The dry swamp is now susceptible to bushfire and weed invasion (Photo: J. Favell , May 2010).



### **Challenges with longwall mining & water**

The *long term consequences* for shallow aquifers, creeks and peat swamps require further monitoring, research and adaptive management.

Monitoring basic to advanced, depending on risk level:

- High frequency pore pressure monitoring
- Moisture monitoring within thin peat swamps
- Water tracer studies
- Site investigation of fault zone geology and hydrogeology

### Ground movement in *near-field and far-field*:

- along strike of potential faults
- outside the angle of draw and
- >500 m from goaf



More to the story from: Galvin J, Longwall Mining Impacts on Groundwater and Surface Water: Aspects Significant to Gaining Mining Approval. MSTS Proceedings, Pokolbin, November 2017.

Major projects website for mine site extension – Independent Monitoring Panel advices <a href="http://majorprojects.planning.nsw.gov.au/index.pl?action=view\_job&job\_id=5594">http://majorprojects.planning.nsw.gov.au/index.pl?action=view\_job&job\_id=5594</a>



# Unconventional subsidence & faults

Corbett & Sheffield, 2015, AusIMM-UNSW Future mining conference

3D time-series analysis of high-intensity geotechnical and groundwater data

Fault zone hazards



Significant faults: *in-situ stresses* 



Significant faults: *mining induced stresses* 



Overlying swamps, subsidence, groundwater data





# Critical question: Height of drainage above goaf?

- Are the relevant processes adequately quantified?
- Are the data bases adequate for all locations, all site conditions?
- What multiple lines of independent evidence verifies empirical approaches?

# Tammetta, 2013, *Hydrogeology Journal Doesn't include geological factors*



 $u = wt^{1.4}d^{0.2}$ 

 $H = 1438 \ln(4.315 \times 10^{-5}u + 0.9818) + 26$ 

Ditton S. and Merrick N. (2014) A new subsurface fracture height prediction model for longwall mines in the NSW coalfields, Proceedings of Sydney Basin symposium, Newcastle.

### Ditton S. and Frith, R. (2003). ACARP Project 10023.

This model includes panel width, cover depth, mining height and local geology factors to estimate the fractured and constrained zones above a given longwall panel. This method appears *less conservative than that of Tammetta, although geological conditions should be considered.* 

2017 study by PSM, peer reviews by Galvin, Mackie http://planspolicies.planning.nsw.gov.au/index.pl?action=view\_job&job\_id=7441



# **Critical question:** Depth of connective fracturing and storage change?

# Includes flow and storage within fractures and bedding plane separation

Discrete fracture model below creek bed

Small scale, within 15 m of surface

Figure 9 Flow velocity for horizontal injection (1.0 MPa)

Morris D, Timms W, Xu C . Modelling of Groundwater Flow and Grout Injection To Remediate Near-Surface Fractures from Longwall Coal Mining, submitted for journal review.

### Depth below center of panel



Greater density post mining in surface zone to ~40 m depth.

Porosity changes depend on lithology.

David, K.,Timms, W., Mitra, R. (2017) IAH Green book, in press.

> Industry inkind data provided



4-3b

### Mine design & adaptive management

Mine seepage from overlying strata that is associated with subsidence & underground mining can be reduced by:

- 1. Avoiding sensitive features eg. splitting panels
- 2. Mining methods eg. mini-walls, Pine feather
- 3. Mining geometry panel width, mining height, cover depth eg. sub-critical design
- 4. Changing distribution & length of panels
- 5. Orientation of panels to principle stresses
- 6. Increasing distance of panels from dam wall
- 7. Barrier pillars coal left in place, reduced resource extraction ( $80\% \rightarrow 50\% \rightarrow 35\%$ )
- 8. Backfill emplacement of coal rejects into mine voids





### New research: Geology below Thirlmere Lakes



The mysterious hydrology of Thirlmere Lakes, NSW Government, 2016 http://www.environment.nsw.gov.au/publications/water/thirlmere-lakes-hydrology-160716.htm



### Thirlmere Lake levels 1982-2014



Banerjee B, Raval S, Timms W (2016) International Journal of Environmental Science and Technology



**162 Landsat images**, 1982 to 2014. Lake area calculation for a dry period (2010-2011) was validated with ~12 historical observations (courtesy of P Pells).

Running average of lake area, strong correlation with residual mass rainfall however lake specific data and independent verification methods needed.



### Leading R&D - Advanced water materials characterisation

### **Geotech centrifuge**



### **ITRAX core scanner**



### **CT** imaging



# **Pore water extraction** & analysis



**Isotope tracers** eg. VE <sup>18</sup>O, <sup>2</sup>H on soil/rock



### In situ sensors & analysis

- moisture, redox,
- high-freq pore pressure





### Summary

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Analysis of high frequency pore pressures can reveal how systems work, and provides insitu specific storage values to improve numerical groundwater models.

Environmental tracer techniques increasingly common to quantify groundwater connectivity and flows

Several ongoing technical challenges with groundwater and mining are highlighted that require

- more strategic baseline monitoring
- a variety of conceptual models and
- adoption of leading practices that are commensurate with the risks of the project



# Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC)



Established and supported by the Australian Government Statutory committee under the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act)

The IESC provides advice to governments on:

- the water-related impacts of coal seam gas and large coal mining development
- bioregional assessments
- research priorities and projects

### Website: www.iesc.environment.gov.au

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# Thanks, your comments, questions?









### School of Mining Engineering Groundwater Flow and Stress Modelling of Bolts in Underground Mines

Jack A. Smith

Dr. Wendy Timms, Dr. Hamed L. Ramandi, Dr. Chengguo Zhang

Results

#### Introduction

Bolts in underground mines are long anchor bolts that are used as permanent and temporary support systems for stabilising rock excavations. Bolts were introduced in the mining industry in the 1890's and has since played an imperative role in all underground mining operations worldwide. Testament to its importance in mining is the considerable amount of research and development being put into understanding the failure of bolts. One of the major failure modes of bolts underground is Stress Corrosion Cracking (SCC). SCC describes the service failure of bolts due to the combined influences of tensile stress and a corrosive environment (Vandermaat, Saydam, Hagan, & Crosky, 2016). SCC of the bolts is primarily driven by groundwater which is known to contain chemical and biological compounds that facilitate corrosion.

A field study conducted by UNSW found that SCC was likely to occur in mines with thick coal roofs and saturated roof strata (Crosky, Fabjanczyk, Gray, & Hebblewhite, 2002). SCC was also promiter in bolts which intersected clay or tuffaceines has.

The modelling of groundwater flow and stress in bolts, its grout, and the surrounding rock strata, will provide a better understanding on what conditions lead to bolt failure through SCC. This study would provide an insight into bolt failure conditions as well as assist in advances towards solutions in preventing SCC bolt failure.



Figure 1. A - Visible signs of corrosion of an installed bolt. B - A rock bolt affected by SCC. With initial cracking on the darker left edge, exposure to a corrosive environment and increased stress lead to eventual brittle fracturing.

#### Objective

The aim of this study is to develop a two-dimensional groundwater flow and stress model of a roadway/tunnel in underground mines to investigate what conditions promote groundwater flow and stress near installed bolts.

### Methodology

Groundwater flow rates and bolt failure due to SCC has been found to bear a strong correlation, i.e. the higher the groundwater discharge near the bolt, the increased likelihood for SCC to occur. The model setup involved a single 2m grouted steel bolt in the roof of a 5 m x 5 m roadway with coal, sandstone, claystone, clay and shale as the major rock types (Figure 2). Forty seven different rock strata configurations and 9 different grout conditions.

The modelling of groundwater flow and stress near the bolt was simulated using RS<sup>2</sup>, RS<sup>2</sup> (or Phase<sup>2</sup> 9.0) is a two-dimensional finite element software for soil and rock applications capable of performing steady-state finite element groundwater seepage analysis (Rocscience Inc.,2017).

Fundamental to the design of the model was defining the necessary model parameters. The parameters were based on data from a mine in NSW ,and included:

- Material properties strength, stiffness
- Hydraulic material properties hydraulic conductivity
   Joint properties
- Hydraulic boundary conditions hydraulic head
   Field stresses

The model provided groundwater discharge flow rates, pore pressure and flow lines schematics, and Sigma YY schematics illustrating normal stresses in the vertical direction. Discharge flow rates were measured at the interface between the grouted bolt and the roof of the roadway, i.e. groundwater leaving the grout and bolt.



Figure 2. Model setup of the 5m x 5m roadway with a single bolt installed. Orange lines



Figure 3. A – Fully Grouted, B – Left 20cm, C – Right 20cm, D – Bottom 20cm, E – Whole Left, F – Whole Right, G – Upper Half, H – Lower Half, I – No Grout

### Poster downloads etc available here:

https://www.researchgate. net/profile/Wendy\_Timms

#### The results showed that model scenarios with a coal roof observed the highest groundwater discharge flow, particularly at the non-grouted grout condition (Scenario 5 and 9 in Figure 4). Strata configurations with a clay band intersecting in the middle of the bolt had a higher discharge flow rate then the same strata configuration without it. The simulations demonstrated that changing grout conditions for the same strata configuration resulted in variations in groundwater discharge flow rates as Figure 4 suggests. Figures 5A & B demonstrates the change in groundwater flow patterns from a fully-grouted condition to non-grouted. The absence of grout around the bolt installation appears to directly contitude to increased groundwater discharge flow which could promote SCC.

Different grout conditions for the same strata configuration produced varied compression and tensile stresses to the bolt. The grout condition with the absence of grout in the upper half of the bolt (Figure 30) produced the highest tensile stress to the bolt as illustrated in Figure 5D. The lowest tensile stress was exhibited when no grout was present. This may suggest that improper grouting or grout ension contributes to the tensile stresses that cause SSC.



Figure 4. Groundwater disharge flow rates at the different grout conditions for 11 of the 47 scenarios. Scenario 1 represents a tratte configuration without a city band and Scenaria 2 is the same configuration with a city band. Scenario 3 and 9 segments are stratted a coal roof. The fully grouted condition for majority of scenarios fails to register due to the higher hydraulic conductivity associated with the grout.









### An aquifer becomes an aquitard: centrifuge measurement of desaturating sandstone from the constrained zone above an underground mine



Paul Cai<sup>1</sup>, Wendy Timms<sup>1,2</sup>, Martin S Andersen<sup>2,3</sup>, Noune Melkoumian<sup>4</sup>

<sup>1</sup> Australian Centre for Sustainable Mining Practices, School of Mining Engineering, UNSW Sydney, Australia <sup>2</sup> Connected Waters Initiative Research Centre, UNSW Sydney, Australia <sup>3</sup> School of Civil and Environmental Engineering, UNSW Sydney, Australia <sup>4</sup> School of Civil, Environmental and Mining Engineering, University of Adelaide (UoA), Australia

Results

#### Introduction

Effective water management is an important part of designing mining operations. Groundwater flow can affect mine safety, productivity, and potentially impact on the environment, including surface waters and aquifers.

Perched aquifer conditions often develop in the constrained zone overlying underground mines, due to dewatering of the mine workings. An inverted water table marks a transition from saturated un-fractured sandstone to an underlying unsaturated fractured zone.

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Figure 1. Conceptual model of an inverted watertable near the base of the constrained zone above a longwall mine.

#### Objective

The aim of this research was to address a knowledge gap by establishing an empirical function for vertical hydraulic conductivity-saturation (K,-S) and suction ( $\rho$ ) of intact sandstone.



An AllegraX-1SR centrifuge was fitted with custom made drainage cells (n-4) to test discs of sandstone (50 mm diameter, 5 mm thick). The quartz rich sandstone cores were initially saturated to >95% with fresh water. The centrifuge speed was accelerated to provide increasing tension and drainage (300 to 2800 revolutions per minute), with the mass of drainage at the base of each cell measured after each acceleration step.

A form of Darcy's Law was used to calculate hydraulic conductivity K (m/s), for steady state flow Q in a centrifuge permeameter.

0.248 Q  $K = \frac{GR}{Ar_m(RPM)^2}$ 

Where Q (mL/h) is fluid flux, A (cm<sup>2</sup>) is crosssectional area of the specimen,  $r_m$  (cm) is radial distance at the mid-point of the specimen and RPM is revolutions per minute.

In this study, it was assumed that the measured K in shallow freshwater groundwater systems is directly proportional to intrinsic permeability of the porous matrix.

pressure head) in the centrifuge for Test 1 sandstone cores.



Figure 2. Sandstone core sample inside the vacuum chamber during the saturation process



Figure 3. Rock core sample set in aluminium liner and outflow reservoir ready for the centrifuge.

The reduction of  $K_v$  with decreasing saturation (S) was observed for the sandstone (n = 8). On average, relative  $K_v$  values decreased by a factor of 10, as moisture content decreased from 16% (at maximum saturation) to 13%. For several sandstone samples, a small decrease in moisture content of 1-2% was associated with a 50% reduction in  $K_v$  values.



Figure 4. Normalised hydraulic conductivity vs. volumetric water content for Tests 1 and 2 sandstone cores.

#### Conclusion

These empirical relationships could be used to improve numerical models that

An empirical relationship of the volumetric (V) water content  $V=0.15e^{0.02\rho}\,(r^2=0.9)$  was developed as a function of the suction (m H\_2O) applied within the centrifuge. To our knowledge this is the first time such relationships have been developed for consolidated rock. Further research is recommended to verify these observations and to model transient and non-linear drainage processes to calculate actual K values.





### STRUCTURAL EVOLUTION OF THE THIRLMERE AND MOUNT TOMAH MONOCLINES: SOUTHERN SYDNEY BASIN NSW

Timothy McMillan\* University of New South Wales OMB, 159 Barker St, Randwick NSW t.mcmillan@unsw.edu.au Titus Murray Fault Seal 7/66 Hunter St, Sydney NSW 2000 titus@faultseal.com Dr. Wendy Timms University of New South Wales OMB, 159 Barker St, Randwick NSW w.timms@unsw.edu.au

Proposed Structures - NW Southern Coalfields

### **Project Overview**

Review of historical data and new spatial data for targeted field investigations to identify the location and evolution of the Thirlmere and Mount Tomah Monoclines.

#### Summary

The Southern Sydney Basin is a geological region of sub-horizontal conforming strata, including significant coal measures that have been mined for over 100 years. This apparently simple 'layer-cake' geology has overlooked many complexities associated with intrusions and a variety of geological structures. This over-simplification of geology has contributed to uncertainty in groundwater model outcomes, and impacts to surface hydrology and groundwater systems that have occurred at some sites. The aim of this study was to identify and characterize geological complexities within the Southern Sydney Basin, with a particular focus on near surface groundwater and wetlands which could be sensitive to these direct or indirect disturbances.

An initial desk top review of existing drill-hole data, outcrop maps and typical spatial data was undertaken to highlight areas of possible structural inconsistency, as well as areas with a high probability of faults or other structures such as monoclines. This data was then used in combination with field based geological mapping and high quality digital terrain modelling to assist the current development of a series of kinematic (geologically restored) cross-sections.

This has enabled the preliminary modelling of fault propagation folds associated with the inversion of growth faults, which will be important in the development of a framework to better identify and define the geometry of aquitards, associated with the Thirmere Lakes and groundwater surface expression dependent ecosystems (swamps) over the Southern Sydney Basin. This greater understanding of the features around the Thirlmere Lakes area will lead to the development of a structural evolution model that further explains the incision of Blue Gum Creek and the development of Thirlmere Lakes within an entrenched meander.



#### Results

- Two primary sets of possible additional geological structures were identified that could have influenced the incision and entrenchment of the Thirlmere Lakes System.
- Field observations of bedding slips within the Hawkesbury Sandstone were made.
- Very limited evidence of typical faulting structures through the Hawkesbury Sandstone i.e. no observed fault core or direct offset typical found (with exceptions).

#### Hypothetical flow paths around faults



Figure 7: Conceptualisation of groundwater from paths around builts and monocines in the Signery Bash. (1) Flow along built of the within surrounding damaged some within bash increased germeability above that of a traumoning country horo. (2) Fault cross sinte permeability – does the fault prevent across shife ford (3) Vertical flow through damaged zone and / or increase in storage within damaged zone than fault areachasion. (4) Flow through thritie deformed statignarity how how does the brittle deformation refets auter properties?



#### **Project Methods and Techniques**

- Structural mapping and structure modelling to create 2D and 3D preliminary conceptual models.
  - Review of numerous existing drill-hole data, outcrop maps and typical spatial data (Digital Elevation Model (DEM ±0.8m Horizontal, ±0.3m vertical), satellite imagery, digitized geological maps).
  - Interpretation relied on geomorphological principles of stream forms and typical river patterning.