An Interdisciplinary Response to Mine Water Challenges - Sui, Sun & Wang (eds)
©2014 China University of Mining and Technology Press, Xuzhou, ISBN 978-7-5646-2437-8

Tracing Groundwater Flow Paths in Coal Mine by Means of Geophysical and Borehole Flow Data

J. Busse & A. Scheuermann[1], D. Bringemeier[2], L. Li[3]
1 Geotechnical Engineering Centre, University of Queensland, Australia, j.busse@uq.edu.au;
2 Golder Associates Pty Ltd, Milton, Queensland, Australia;
3 National Centre for Groundwater Research and Training, University of Queensland, Australia

Abstract The micropores and cleat network together with large scale fault related and mining induced fractures in a coal seam, provide the principal source of permeability for fluid flow within the seam. To describe the flow behavior of water in a coal mine it is therefore necessary to track the preferential pathways or flow channels in the field. Based on heat pulse flow meter measurements and standard geophysical data flow zones and permeabilities can be located and quantified along a borehole profile.
Keywords flow in fractures, geophysics, field survey, permeability

Introduction

The survey of groundwater flow and its pattern changes due to extraction and the formation of new flow pathways during the mining process is crucial to a safe and environmentally compatible operation of coal mines. Knowledge of coal seam permeability, for the over-and interburden groundwater allows the optimization of mine working designs and methane controls. A combination of results from experimental field work is presented here to examine the behavior of flow underground and to gain an understanding of the hydraulic connectivity between the mine and the adjacent groundwater system. The connectivity in a hard rock aquifer is generally focused along a few dominant pathways, a phenomenon called flow channelling that occurs on all scales (Tsang and Neretnieks, 1998). Due to its chemical structure, in a coal seam small-scale cleats also play a role (Wold et al. 2008). The preferential flow zones provided by faults, fractures and coal seams on a field scale were tracked by Heat Pulse Vertical Flow Meter logging and the additional use of standard geophysical data from caliper, gamma ray, resistivity and density logs.

Field site and methods

Hail Creek Mine

The Hail Creek coalfield is located at the north-eastern margin of the Bowen Basin in Queensland, Australia. The mine lies along the axis of a relatively shallow open fold syncline structure that is approximately 30 km long, and up to 7 km wide. Its hydrogeological properties are determined by this structure, with the primary flow direction of shallow groundwater and surface water following the syncline in a south-eastern direction (Golder Associates Pty Ltd. 2013).

Coaking coal is extracted from two seams, the Elphinstone and Hynds, with an average thickness of 6.4 m and 8.3 m respectively. Over-and interburden consist of layers of sand- and siltstones. Along the north- western flank of the syncline the seams are mined in an open-cut. Possibilities for underground mining in the central part of the syncline are currently being explored (Clark. 2007).

The data presented in this paper was collected as part of the exploration campaign at the extension site northeast of the current pit. Standard geophysical data and flow data by means of Heat Pulse Flow meter have been collected in October 2013, shortly after drilling was completed.

Fig. 1 *Location of Hail Creek Mine*

Heat Pulse Flow Meter

Field investigations by means of the Heat Pulse Flow Meter HFP 2293, manufactured by Mount Sopris Instrument Company have been undertaken. The advantage of this method compared to other borehole hydraulic test methods is the tracking of low flow rates from 0.113 L/min to 3.815 L/min at close downhole measurement spacing. The tools working principle is based on a heat pulse applied to the fluid in the borehole by means of a pulse electric current through a wire grid. Depending on the movement of the water in the borehole the heated water parcel is detected by thermistor sensors placed above or below the grid. Flow （l/min） therefore is a function of the time between the induction of the heat pulse and the detection at the thermistors. To avoid mixture and bypass a rubber disk that seals the flow against the borehole walls is mounted onto the probe. The measurements are performed under ambient and stressed conditions; for the latter injection of water into the borehole is carried out (Paillet. 1998).

Geophysical data

Fractures and cleats form the main pathways for flow in coal seams. Standard geophysical data sets taken during drilling and exploration at the mine site allow an insight into the geological structure in the near vicinity of the borehole. Geophysical logs include density, resistivity, gamma ray, caliper and verticality logs.

Results

The borehole data that is presented in this paper was taken at the borehole 10214R which intersects the Elphinstone and Hynds seam. It is located at 644482.80 (Easting) and 7627493.97 (Northing), with an elevation of 265.27 m and a total hole depth of 334 m. The casing is 40 m deep. The borehole was drilled using a bit size of 99 mm. The Elphinstone seam is located at 239.6 m to 245.7 m, the Hynds seam at 306.8 m to 316 m. At the time of logging the water level in the borehole was 4.22 m.

Borehole 10214 was logged and based on the data collected at the site a flow profile was generated. Measurement spacing varies from 0.10 m to 10 m, depending upon the in- and outflow behaviour along those zones. Where a sudden change in flow rate and/or direction occurs a conductive layer is indicated and the spacing reduced for an exact localisation. Upward flows are given by positive values and downward flows by negative values (Figure 9 . 2) Based on the principle of mass-balance, the average borehole flow rate is calculated for each zone that is delimited by the fractures (Paillet. 1998). The difference of the vertical flow between the zones indicates the amount of in- or out-flow to or from the section of the borehole. A mass balance over all in- and outflow is calculated to verify the data. Depending on its contribution to the total flow, a percentage of transmissivity for each fracture can then be estimated. The mass balance for the borehole 10214 is given in table 1. Note that the zones are numbered from the bottom to the top of the hole.

Table 1 *Flow profile of borehole 10214 (flow values in [l/min])*

Zone no.	Depth (m)		Amb. above	Amb. below	Amb. flow	Inject. above	Inject. below	Inject. flow	Diff. of flows	% of T
	from	to								
5	40.30	41.3	0.00	0.11	-0.11	-4.50	-1.71	-2.79	2.68	59.6
4	79.1	81.1	0.11.	0.02	0.09	-1.71	-0.88	-0.83	0.92	20.4
3	136.0	141.1	0.02	0.00	0.02	-0.88	-0.62	-0.26	0.27	6.1
2	198.5	202.5	0.00	0.02	-0.01	-0.62	-0.09	-0.54	0.52	11.6
1	239.3	241.3	0.02	0.00	0.02	-0.08	0.00	-0.08	0.10	2.3
Σ					0.00			4.50	4.50	100

The inverse modelling of the absolute transmissivities and far field heads is based on the Thiem- Equation of steady state flow in a confined aquifer (Thiem. 1906). Flow in a borehole is driven by two parameters: transmissivity of the rock and head difference between the borehole and the far field aquifer that feeds the fracture. Both parameters are variables of the underlying formula. The transmissivity value does not change, but in order to solve the equation two different values for the head are obtained via ambient and injection testing. The software FWRAP (Paillet. 1998) is designed to calculate the transmissivity (T) and head of each fracture (H). In an iterative process the total transmissivity in the borehole and the head for each fracture that fits the given values are obtained. The program calculates the water flow and head in each zone, the transmissivity for each fracture as well as the mean square difference between the measured and modelled values. As widely found in hard rock aquifers (Singhal. 2008) the data showes descending transmissivities with depth. Results are shown in table 2.

Table 2 *Permeabilities of borehole 10214*

Zone no.	Depth (m)		Part of T_{total}	*T* (m^2/day)	Hydraulic conductivity (m/day)	Intrinsic permeability [mD]	Head (m)
	from	to					
5	40.3	41.31	59.6	0.9	0.891	951.96	4.39
4	79.1	81.11	20.4	0.3	0.149	159.45	3.99
3	136.026	141.064	6.1	0.09	0.018	19.08	3.81
2	198.498	202.528	11.6	0.18	0.045	47.72	4
1	239.3	241.32	2.3	0.03	0.015	15.87	3.8

Geophysical logs are used to verify the in- and outflow zones (fig. 2).The log of the total natural gamma radiation allows an insight into the lithology and stratigraphy. Sand- and siltstone layers are identified using a threshold of 100 API. The borehole diameter in mm's along the profile was given in the caliper log and enabled the visual detection of possible breakout zones or fractures intersecting the borehole. Density measurements allowed the localisation of low density coal seams (1 to 1.5 grams/cc). This is further verified by the use of sonic velocity, where the amplitude and runtime of acoustic waves was dependent on rock density and porosity. Likewise the electrical resistivity of the rock mass, which is up to 2000 Ohm*m was due to highly cleated coal seams.

A comparison of the flow meter data with the geophysical logs showed that in some cases the former provide evidence of flow zones, whereas the later failed to verify this information. This was the case for flow zone five (40.30 m to 41.31m) and four (79.10 m to 81.11 m). For the three flow zones detected at greater depths both flow data and geophysical data indicate an inflow zone. Under ambient conditions upflow of small quantities (below 1 L/min) alternates with zones of no flow. Only for the first coal seam; the Elphinstone seam were flow values detected. It was logged with 0.5 m spacing under ambient conditions to give an averageupflow of 0.0823 L/min. The Elphinstone seam therefore serves as an inflow zone. Under injection conditions no flow could be detected here. The flow profile for the injection conditions showed the outflow of a large portion of the injected water at the end of the casing (zone five). In the following zones four, three and two the injected water is discharging into present sandstone layers. Based on the flow profile, transmissivities and permeabilities have been calculated. The values summed up for each geologic zone are listed in the table 3.

Table 3 *Permeabilities of geologic zones of borehole 10214*

Bore ID	Overburden		Elphinstone		Interburden		Hynds		Fort Cooper	
	T (m^2/d)	*K* (mD)	*T* (m^2/d)	*K* (mD)	*T* (m^2/d)	*K* (mD)	*T* (m^2/d)	*K* (mD)	*T* (m^2/d)	*K* (mD)
10214R	1.47	1178.20	0.03	15.87	--	--	--	--	--	--

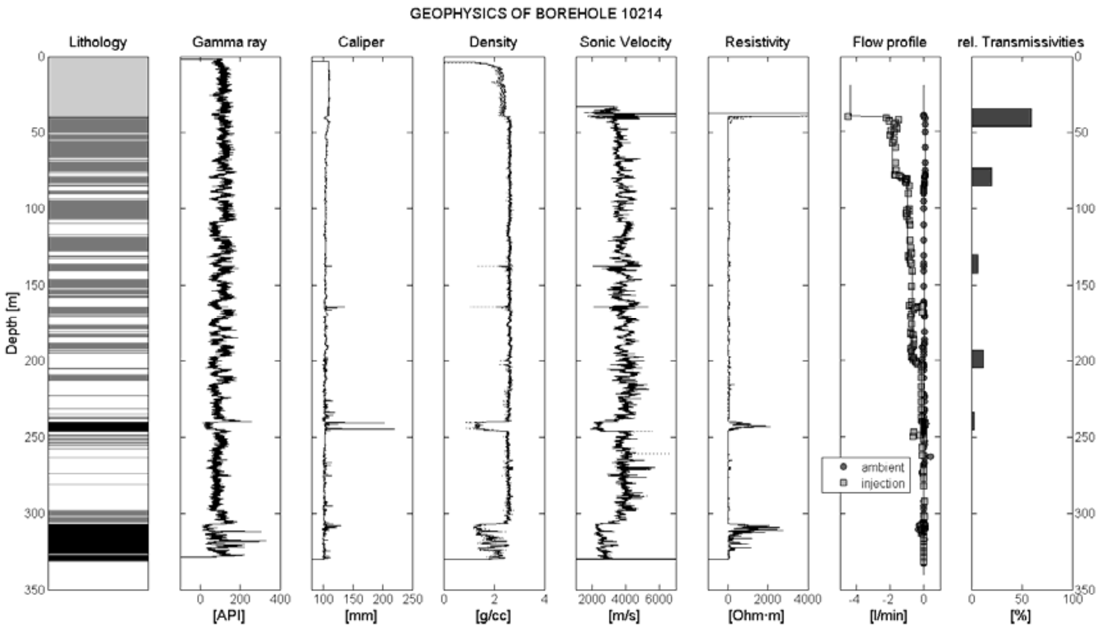

Fig. 2 *Lithology (light grey: casing, grey: siltstone, white: sandstone, black: coal), geophysical and flow meter data - Elphinstone seam at 239.6 m to 245.7 m, Hynds seam at 306.8 m to 316 m*

Conclusions

Measuring the rate of vertical flow in boreholes allows the identification of flow zones provided by faults, fractures and cleats. The data could be further analysed to give an estimation of relative hydraulic gradients and provide an analytical solution of transmissivity and the hydraulic head for flow zones. Individual geologic units can be identified and delineated, as well as potential flow conduits. Therefore the data serves as the base for subsequent numerical modeling and hydrogeological mapping. While the geophysical data gives detailed information on the lithology and can be used to locate possible fracture structures, the flow meter data delivers information about in- or outflow in these zones and allows a quantification of the flow. A combined use of these data is therefore highly recommended. To describe the system further, fracture apertures may be estimated based on the flow measurements in conjunction with ATV logs.

Acknowledgements

The work with the Heat Pulse Flow Meter has been supported ongoing by the expertise of Dr. Fred Paillet. It is funded by an ACARP grant (c20022) and friendly supported by RioTinto and its staff on site at Hail Creek Mine.

References

Clarke G (2007) Documentation of significant geological features evident within Rio Tinto’s Hail Creek Coal Mine. In: MINE, MTSHCC (Eds)

GOLDER ASSOCIATES PTY LTD (2013) Factual report on hydrogeological investigations at the Hail Creek Mine Site. In: MATTERN J (Eds). Rio Tinto Coal Australia Pty Ltd

Monier-williams ME, Davis RK, Paillet FL, Turpening RM, Sol SJY, Schneider GW (2009) Review of borehole based geophysical site evaluation tools and techniques. Nuclear Waste Management Organization, Toronto, Ontario, Canada

Paillet FL (1998) Flow modeling and permeability estimation using borehole flow logs in heterogeneous fractured formations. Water Resources Research, 34, 997-1010

Singhal B (2008) Nature of hard rock aquifers: hydrogeological uncertainties and ambiguities. Groundwater Dynamics in Hard Rock Aquifers. Springer

Thiem G (1906) Hydrologische methoden. JM Gebhardt's Verlag

Tsang CF, Neretnieks I (1998) Flow channeling in heterogeneous fractured rocks. Reviews of Geophysics 36: 275-298