Case Study: Development of an underground depressurisation scheme in an operational mine with reduced pumping capacity

Alastair Black[1], Mark Raynor[1], Thierry Kalonga[2], Laurent Kabiku[2]

[1]SRK Consulting (UK) Ltd, Churchill House, Cardiff CF10 2HH, ablack@srk.co.uk
[2]Kibali Gold Mines, Doko, Province Orientale, DRC

Abstract Groundwater pressure and inflow responses to the systematic opening of underground drain holes in a deep shaft at the Kibali Gold Mine is presented. The hydraulic tests were undertaken when the mine was advancing into areas with higher inflow potential, prior to the construction of the main pump-station. The aim was to estimate the sustained inflow rate from permeable structures and determine the optimum method to reduce flooding risk. Proven connections between drain-holes were reconciled with modelled geological bodies which contain greater water volumes. These analyses were used to advise immediate grouting requirements and determine optimal drain holes to open to aid in depressurization of near term developments.

Key words depressurization, underground, dewatering, hydraulic, testing

Introduction

The procedure described herein was applied at the Kibali underground mine in the DRC. A 750m deep vertical shaft and multi-level off-shaft areas were in active development at the time. Three levels at 530, 685 and 725m below ground were considered within the testing. The geological setting is hard competent rock, with multiple brittle fractures that are typically associated with ironstones and doleritic dykes. A comprehensive description of the site can be found in Randgold (2017), Bird (2016) and Vargas et al.. (2014)

Short term pumping requirements and the expectation of increased inflows was a challenge for the mine as an interim pumping station with a low capacity of 16 l/s was in place pending the development of the full pumping station in excess of 200l/s. The capacity utilised to control seepage at the time of testing was approximately 10l/s with drain holes all closed or 'shut-in'.

The testing in this case study was required to:

- identify areas of higher risk which warranted cover grouting;
- reconcile proven hydrogeological connections with modelled geological bodies anticipated to store larger volumes of water;
- advise on the underground drains to open, fully utilising the 16l/s and which holes would optimally depressurize areas where drilling and blasting was planned; and,
- improve upon the understanding of the rate of flow reduction when drains are opened or features intercepted.

The procedures undertaken utilised basic equipment available at all underground mine sites and the duration of the testing in this case study was 4 days.

High Level test description

The core of the test involved the systematic opening of drain holes while monitoring pressure response in other drain holes within the off-shaft area and monitoring vibrating wire piezometers (VWP) pressure changes around the mine site. As each drain hole is opened the flow rate is recorded and in most, but not all cases, noted to reduce during the duration of the test. These readings collectively are the primary datasets for syn- and post-test analysis.

Ordering of the holes to be opened, and duration to remain open was planned prior to the test. The procedure allows for changes to the timings that holes are open during the test in response to the data being recorded. Such changes would be to maximise the useful data gleaned within the period.

In general the order of holes to be opened was defined from lowest anticipated inflow rates to highest. This permitted the review of the smaller inflows pressure responses which would have otherwise been masked by the overriding signals of the higher yielding drains.

Holes were opened for the maximum duration possible in an attempt to induce pressure responses at greater distances from the drain. The limiting factor for drains to be open was water levels in local sumps and/or the requirement to close all drain holes prior to egress for blasting which in this mine occurs every 12 hours.

Monitoring of all sump levels during the test and a comprehensive understanding of the underground water management system is paramount and maximum permissible levels were defined for each sump. When these level limits were encountered the test was stopped and sumps were allowed to be pumped down. The duration of the test is therefore in part defined by the volume of water storage which is acceptable in areas of the underground mine. Analysis of results considers the rate of reduction in flows over time and the lag and attenuation of the on/off drain hole signals across the monitored locations. Through these analyses the efficiency of connections and rate of potential inflows can be estimated.

General procedure and considerations

Pre Test

Prior to the test an underground survey was conducted to provide input to a site specific procedures document and assist in the preparation of hardware required to fit hoses and gauges or install loggers.

The survey includes (non exclusive list):

- Confirmation of hole names and reconciliation with holes in the geological model
- Note on diameter, thread and whether adapters are required for pressure gauges/hoses;
- Note on whether valves can be opened and closed easily
- Requirements for hoses and their lengths for drain holes which are not plumbed to sumps
- Sump locations, pump types and each pumps operational triggers

- Levels of permanent electrics, generators, rigs and other features which may affect decision on permissible levels for water storage at sumps
- Confirmation of linkages in underground pumping system, rating of pumps and identification of reservoirs which are used as overflows if pumping to surface is exceeded.
- Telemetered alarms for reservoirs
- Details of flow and pressure monitoring which currently exists
- Other local issues e.g. ground conditions and potential for washout / transport of fines to sumps.

The logging interval on all existing VWP installations was reduced from 2 hours to 5 minutes approximately 2 days before the start of the test. The loggers remained at this frequency for the duration of the testing.

Site specific procedures were developed and communicated to all parties operating underground. Shut-in trigger limits for each sump were discussed and agreed with the mining contractors such that the test did not significantly interfere with ongoing activities. The test results in substantially wetter conditions underground than would be tolerated under normal conditions. The written procedure was discussed and circulated during morning meetings to ensure that all stakeholders clearly understood what was planned.

The procedure included stage volume calculations for each of the sumps and basic modelling of how the overall pumping system would respond to elevated water levels relative to normally operations. A basic spreadsheet model was used to identify areas requiring additional pumps and key overflow reservoirs were noted such that hardware could be put in place in advance. This had the effect of reducing impacts to others, permitting the test to run for a longer duration, providing better quality data and reducing the amount of time to drain down sumps after the permitted storage volumes had been used.

Procedures could be updated each day with any revised plans, and re-issued to all stakeholders to aid communication of the unusual activities.

In every planned test the procedure to follow included:

- Morning briefing and confirmation from shaft managers that the tests could proceed as planned
- Start test and continue until specified time in procedures has elapsed.
- If any sump level limit reaches the permissible limit before that time
  -> shut-in prematurely
- If any individual requests for the test to stop or pause -> shut-in prematurely
- Always shut-in when all egress for blasting even if the sumps are fully managing current requirements.
- Basic analysis of data to inform the subsequent shifts test

Syn- test

The start of each shift included confirmation to proceed from shift managers and a briefing of all staff of the shut-in trigger levels.

On initiation of each shifts test, a manual reading of existing shut in pressures were recorded in all gauged drain holes, across all levels of the mine. Pressure gauges were removed from the hole to be opened and hoses fitted. In this case study flow gauges were not available so 55 gallon barrel-fill tests were undertaken. For the first 10 minutes of each test barrel-fill rates were recorded as quickly as possible with flow test frequency decreasing with increased time from opening the valve. During the testing, pressure changes were recorded in the other drain holes, on each of the mine levels, and VWPs automatically logged pressure changes at distal locations. The flow rates are continued to be monitored until either the time allocated for that hole has completed or the flow rate reduces to a steady unchanging volume. If a reduction in flow is noted and the flow reduces to a constant rate further useful information is unlikely to be gleaned from this drain and it was considered better to move onto the next hole early.

In addition to recording flow rates and pressures detailed logs of whether each hole is open-flowing, open-pressure gauged, open-dry or closed is required for test interpretation. An example of the recording of hole status is included in Fig. 1.

				Open/Closed								
	Date		Hole No.	0	1	2	3	4	5	6	7	8
PRETEST				CLOSED	OPEN - Flow	OPEN - Flow	OPEN - Flow	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
PRETEST		NOTES		CLOSED	CLOSED	CLOSED	CLOSED	CLOSED	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
0	29/07/2016 11:00			CLOSED	OPEN - Gauge	OPEN - Flow	OPEN - Gauge	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
00:06	29/07/2016 11:06			CLOSED	OPEN - Gauge	OPEN - Flow	OPEN - Gauge	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
00:08	29/07/2016 11:08			CLOSED	OPEN - Gauge	OPEN - Flow	OPEN - Gauge	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
00:09	29/07/2016 11:09			CLOSED	OPEN - Gauge	OPEN - Flow	OPEN - Gauge	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
00:11	29/07/2016 11:11			CLOSED	OPEN - Gauge	OPEN - Flow	OPEN - Gauge	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
00:23	29/07/2016 11:23			CLOSED	OPEN - Gauge	OPEN - Flow	OPEN - Gauge	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
00:33	29/07/2016 11:33			CLOSED	OPEN - Gauge	OPEN - Flow	OPEN - Gauge	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
00:43	29/07/2016 11:43			CLOSED	OPEN - Gauge	OPEN - Flow	OPEN - Gauge	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
00:50	29/07/2016 11:50			CLOSED	OPEN - Gauge	OPEN - Flow	OPEN - Gauge	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
01:02	29/07/2016 12:02			CLOSED	OPEN - Gauge	OPEN - Flow	OPEN - Flow	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
01:05	29/07/2016 12:05			CLOSED	OPEN - Gauge	OPEN - Flow	OPEN - Flow	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
01:07	29/07/2016 12:07			CLOSED	OPEN - Gauge	OPEN - Flow	OPEN - Flow	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
01:11	29/07/2016 12:11			CLOSED	OPEN - Gauge	OPEN - Flow	OPEN - Flow	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
01:13	29/07/2016 12:13			CLOSED	OPEN - Gauge	OPEN - Flow	OPEN - Flow	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
01:16	29/07/2016 12:16			CLOSED	OPEN - Gauge	OPEN - Flow	OPEN - Flow	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
01:20	29/07/2016 12:20			CLOSED	OPEN - Gauge	OPEN - Flow	OPEN - Flow	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
01:28	29/07/2016 12:28			CLOSED	OPEN - Gauge	OPEN - Flow	OPEN - Flow	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
01:30	29/07/2016 12:30	HS smell starts from drain 3		CLOSED	OPEN - Gauge	OPEN - Flow	OPEN - Flow	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
01:43	29/07/2016 12:43			CLOSED	OPEN - Gauge	OPEN - Flow	OPEN - Flow	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
01:48	29/07/2016 12:48			CLOSED	OPEN - Gauge	OPEN - Flow	OPEN - Flow	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
01:52	29/07/2016 12:52			CLOSED	OPEN - Gauge	OPEN - Flow	OPEN - Flow	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
02:07	29/07/2016 13:07			CLOSED	OPEN - Gauge	OPEN - Flow	OPEN - Flow	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
02:21	29/07/2016 13:21			CLOSED	OPEN - Gauge	OPEN - Flow	OPEN - Flow	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
02:27	29/07/2016 13:27			CLOSED	OPEN - Flow	OPEN - Flow	OPEN - Flow	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
02:28	29/07/2016 13:28			CLOSED	OPEN - Flow	OPEN - Flow	OPEN - Flow	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge
02:29	29/07/2016 13:29			CLOSED	OPEN - Flow	OPEN - Flow	OPEN - Flow	OPEN - Flow	OPEN - Gauge	OPEN - Gauge	CLOSED	OPEN - Gauge

Figure 1*. log of hole status*

The intent of the test is to impose a large stress change on the groundwater system. For this reason already tested holes were not immediately shut-in after the above procedure. Instead, the next, new, drain hole was opened in addition to the previous drain hole(s). This process can be seen in Fig. 1. The flow rates recorded for this test are noted in Fig. 4. Gradually opening holes has the benefit of imposing a greater stress release on the wider system and also can provide valuable insight into drain connections. If the flow rate in previously open holes suddenly drops as the new holes are opened this provides further confirmation of connection (this can be seen in Fig. 4 when hole 3 is opened hole 4's rate drops).
Tests are concluded either at the end of a shift or if one of the procedure shut-in triggers occur. Fig. 2 is an example of water levels approaching a pre-arranged trigger level and the

premature shut-in of drain holes. Fig. 3 is included to show the testing setup at a cluster of drain holes.

A final pressure reading was manually recorded in each of the holes immediately before the end of the test. All drain holes were then shut-in and sumps permitted to drain down. If possible the recording of pressure immediately after shut-in can provide useful pressure rebound data. In this case study this was rarely possible due to the blasting schedule and a desire to keep holes open for as long as possible.

The period between tests while blasting and shift change was in progress could be used for logger download and basic analysis to confirm or revise the plan for the next test.

Figures 2 & 3. *Left: Test terminated early as water levels reached the pre-arranged shut-in trigger level. Right: Example drain holes with manual read pressure gauges and 2 open holes with hoses attached for barrel-fill flow rate tests.*

Post-test analysis

On conclusion of the testing, flow rates for each drain hole, manual read pressures and logged pressures were plotted. Examples are included in Fig's. 4 and 5.

Drain holes which were tapping into hydrogeologically connected lithologies or structures could be readily discerned from contemporaneous pressure responses and/or coupled flow rate changes as drain holes were sequentially opened (e.g. locations 7 and 8 on Fig. 4). Conversely drain holes which showed no pressure or flow response to select test drain holes could be identified as isolated hydraulic systems (e.g. locations 1 and 5 on Fig. 3).

The pressure responses across different levels of the mine could be particularly illuminating identifying substantial structures or lithological formations which were inter connected and could be more efficiently drained by individual holes.

Beyond direct connection analysis from the off-shaft underground measurements, high frequency VWP data recorded the drain down of lithologies previously identified as water bearing. These data aid the estimation of the duration of inflow anticipated from the intercepted groundwater system. Drawdown during the tests and rebound between tests can be seen in Fig 5.
Finally, the inflow rates recorded by drillers at the time of grade control hole completion were corroborated, however, when left to flow the rate frequently, but not in every case, was

noted to drop to a lower more sustainable rate. This was anticipated however the steady rate was previously unknown. This was of particular importance for the locations 7 and 8 holes which were initially recorded as in excess of 20l/s each at 40 bar however in reality stabilised to a more manageable 4l/s.

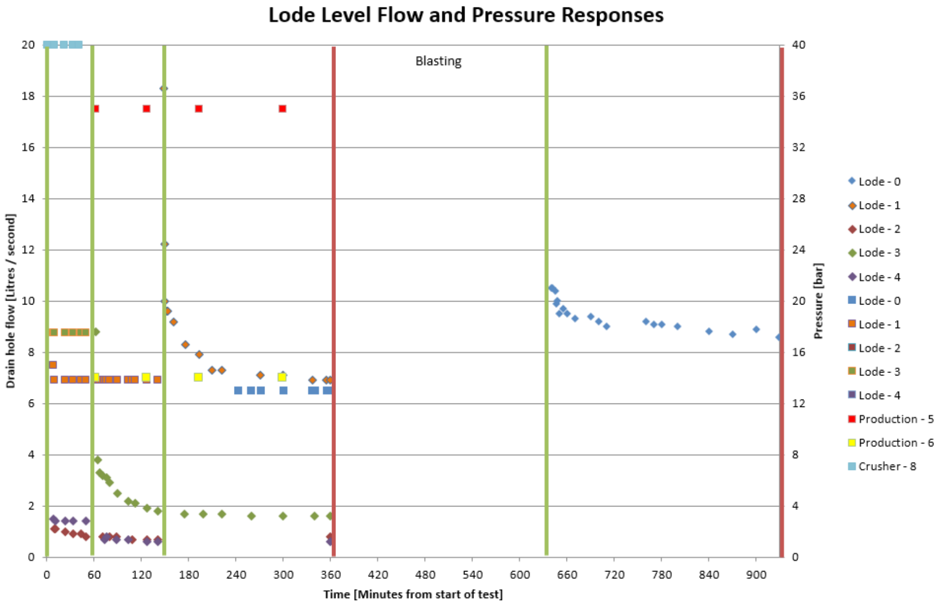

***Figure 4**. Diamonds denote flow rates, squares – pressures. The colour identifies the drain hole.*

Conclusions

Hydrogeological testing via the systematic opening of successive underground drain holes can be undertaken to greatly increase the understanding of hydraulic connectivity and inflow potentials. The test requires appropriate monitoring to be in place and is conducted over a period of a week.

The tests introduced in this case study assist in discerning drain holes in mutually exclusive connected or isolated hydraulic systems. The rate of flow reduction from drain holes and their steady state flow rates were determined. This allowed an assessment of the magnitude and duration of likely inflow events from intercepted water bearing systems. This information was used to develop a grouting and drainage plan that optimally depressurized or sealed areas scheduled for development prior to commissioning of the main pumping station.

The overall dewatering strategy at Kibali is to depressurise the deep workings using dedicated drain holes and water bearing grade control holes. This allows stopes to be pre-drained which greatly reduces complications when the stopes are backfilled with paste. Grouting is used as a last resort where inflows will potentially exceed pumping capacity, or where the location of inflows results in unacceptable impacts on mine production rates. Had the test presented above not been carried out, more extensive grouting would have been required and this in turn would have hampered the depressurisation of the workings as a whole.

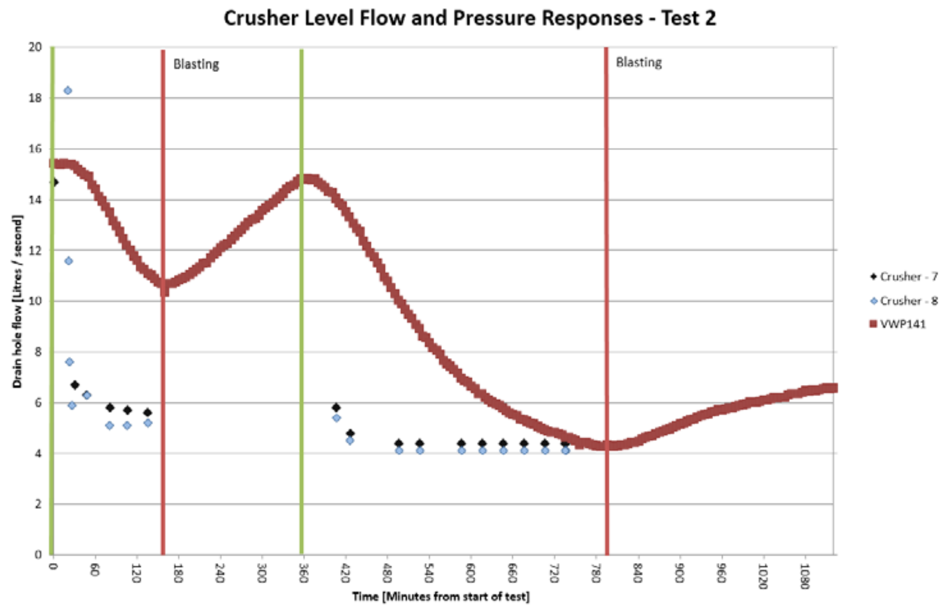

***Figure 5**. Diamonds denote flow rates, continuous timeseries data are VWP pressures monitoring a significant water bearing lithological formation in advance of the area to be mined in the near future.*

References

Bird (2016) Evolution of the Kibali Granite-Greenstone Belt, North East Democratic Republic of the Congo, and Controls on Gold Mineralisation at the Kibali Gold Deposit, Ph Thesis, Kingston University London http://eprints.kingston.ac.uk/37344/1/Bird-P-J.pdf

Randgold (2017) http://www.randgoldresources.com/kibali-gold-mine

Vargas et al.. (2014) Understanding the structural geology, stratigraphy, and mineralization of the Kibali 'orogenic' gold deposit, NE DRC: Key for exploration criteria in complex Neo-Archaean terranes. Conference proceedings of the Society of Economic Geologists, 2014 https://www.segweb.org/SEG/_Events/Conference_Archives/2014/Conference_Proceedings/data/papers/abstracts/0393-000290.pdf