The combined use of spinner flow logging and geotechnical information to investigate the hydraulic properties of fractured rock mass

Rosalind Pedder, Houcyne El-Idrysy

SRK Consulting (UK), 5th Floor Churchill House, Churchill Way, Cardiff, UK

Abstract Spinner flow logging is a technique used to determine vertical variation in hydraulic properties of aquifer formations. Down-hole acoustic televiewer and geotechnical core logging are usually used to determine geotechnical parameters of rock formations. A mine Feasibility Study in West Africa where both of these methods have been implemented allowed a closer insight into the relationship between the structural and hydraulic properties of the rock formations. Combining both techniques provided valuable data that enables a more accurate estimation of pit water inflows and a more cost effective design of the dewatering system and of the pit slope angles.

Keywords Spinner logging, geotechnical logging, fractured rock, hydrogeology, dewatering

Introduction

As part of a Feasibility Study (FS) for an open pit gold mine in Burkina Faso combined hydrogeological and geotechnical site investigations were carried out. The main objective of the investigations was to refine the conceptual hydrogeological understanding of the project area and obtain the required input parameters to (1) estimate potential groundwater inflows into the pits and (2) aid the design of a dewatering system. This paper focuses on how the combined use of down-hole spinner flow logging, acoustic televiewer (ATV) survey and geotechnical core logging can contribute to achieving this objective.

Spinner flow logging is a well documented technique used to determine vertical variation in hydraulic properties of aquifer formations (Molz *et al.* 1989, Hill 1990, Paillet 1998). The combination and comparison of this technique with geotechnical information is sparsely represented in literature, yet can reveal relationships between geological structures and hydraulic properties of aquifer formations, reflecting the magnitude and potential continuity of water-bearing networks of geological structures. This in turn enables a more accurate assessment of the potential variation of groundwater inflow into the pit over the mine life and thus aids the design of more effective water control and management systems.

Site Background

The site is located in the southeast of Burkina Faso in a relatively flat area of sparsely vegetated steppe grassland with a semi-arid climate. The proposed final footprint of the main pit in Fig. 1 is around 9.4 km^2 with an ellipse shape elongated northeast-southwest. The final pit depth is planned to reach 450 m. To the southwest of the main pit a smaller pit of 1.3 km^2 is proposed to have a final depth of about 120 m.

Fig. 1 highlights the proximity of the pit footprint to a river which flows into a large reservoir to the east of the image boundary. Towards the end of the rainy season the northern and eastern pit boundaries of the main pit are located between 1.2 km and 0.5 km from the river respectively. The proximity of the river to the main pit mine raises the question of a potential hydraulic link between the pit and the river, which could possibly lead to in-

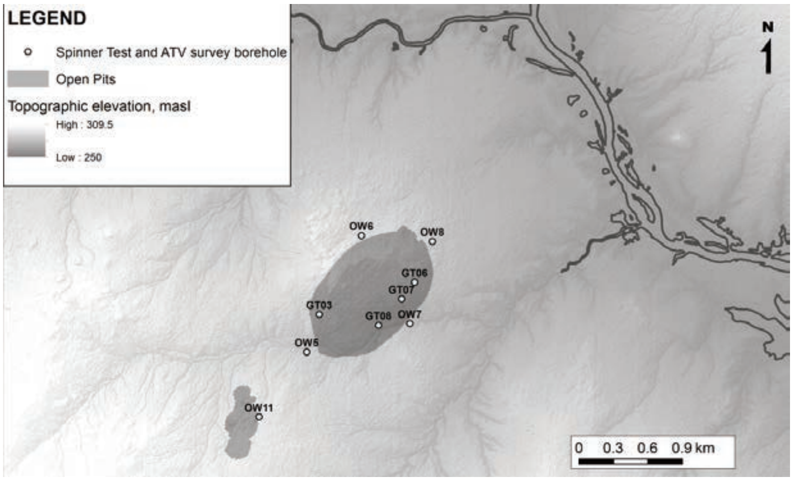

Fig. 1 Location of spinner tests and ATV logs in relation to the pit footprints and the river.

creased water inflows into the pit. Although the spinner tests discussed in this paper contribute to answering this question, this hydrogeological aspect of the FS is beyond the scope of the present paper: an extensive hydrogeological investigation programme has been implemented in addition to the spinner tests presented in this paper.

The local geology is dominated by granitoids. Gold mineralisation is associated with broad alteration systems within quartz schists of varying mineralogical composition. Following a northeast-southwest strike, the geological formations in the ore zone are steeply dipping toward the northwest. Mineralisation is intersected by a series of north-south trending amphibolite dykes between 3–30 m in thickness. The rock mass is fairly competent with low structure density, although there is a 30–40 m zone of weathered material above the more competent rock.

Methods

Spinner logging has been conducted under both ambient (non-pumped) and dynamic (pumped) conditions in addition to structural core logging and ATV surveys in nine boreholes of depths between 220–420 m. Five of the holes are vertical groundwater observation wells used in the pumping tests that have been carried out as part of the FS. The other four holes are geotechnical holes inclined at 65° or 75° into the pit walls in order to intersect any structures that could potentially act as failure planes. Fig. 1 shows the location of the boreholes relative to the pit footprint and nearby river.

Spinner Logging

Each of the nine boreholes was initially logged under ambient conditions (without pumping) by lowering the calibrated spinner sonde down the borehole at a constant speed using an electric winch. The impeller could then detect any ambient flow in the borehole and the depth of occurrence. Subsequently, each borehole was logged whilst pumping at a steady state to induce a flow greater than any ambient flow that might exist. The resulting logs were manually separated into individual flow anomalies which correspond to an inflow at a discrete depth.

Transmissivity for each borehole was estimated from the steady state drawdown and total flow induced by pumping. Where the pumping rate during spinner testing was not capable of inducing enough drawdown for analysis, transmissivity was calculated from airlift recovery tests or from drawdown during pumping tests in adjacent boreholes. To estimate transmissivity for each flow anomaly the percentage contribution of each anomaly to total flow was calculated. The percentage contribution was then applied to the total transmissivity to express the transmissivity of each inflow relative to the total.

ATV Survey and Geotechnical Core Logging

The geotechnical investigations were conducted as part of a small scale structural survey to remove drilling bias created by the resource exploration holes with the primary objective of informing pit slope design. The study was conducted in parallel with the hydrogeological study.

Oriented core was obtained from each borehole. To ensure accuracy in the structural logs the ATV surveys were carried out prior to core logging so that structures could be logged from both sources simultaneously. The ATV survey involved winching the acoustic probe slowly down each borehole so accurate information on travel time and amplitude could be obtained. Open structures were recorded as open joints, open foliations, open cemented joints and shattered zones. Their dip angle and dip direction were calculated in each case. Based on drillhole orientations the impact of sampling bias was considered to be minimal.

Selecting the exact depth of change in flow from the spinner logs requires an element of judgement and the task of correlating such responses with structures in the core and ATV logs needs to be approached cautiously. However, due to the relatively low structure frequency of the rock mass the majority of inflows in the spinner logs coincided clearly with open structures in the ATV logs. In the few cases where there was no open structure that corresponded exactly to a spinner-indicated flow zone, the nearest open structure was chosen and this was always within a few centimetres.

Results

The ambient spinner tests did not detect any ambient flow, so it was concluded that there was no significant hydraulic head gradient between inflow zones. The results therefore suggest the absence of a perched water table at the top of the rock formations or a pressurised confined aquifer at the bottom. However, the impeller has a sensitivity threshold due to friction in the bearings, so if a low vertical gradient exists between the various horizons this may not have been detected.

Spinner flow depths and magnitudes are presented in Fig. 2. The dynamic spinner survey (carried out simultaneously with pumping at constant low flow rate) clearly indicated the top rock horizons as the most hydraulically conductive. The rest of the rock mass can be described as a non-aquifer. However, once again, taking into account the impeller sensitivity threshold it is likely that there may have

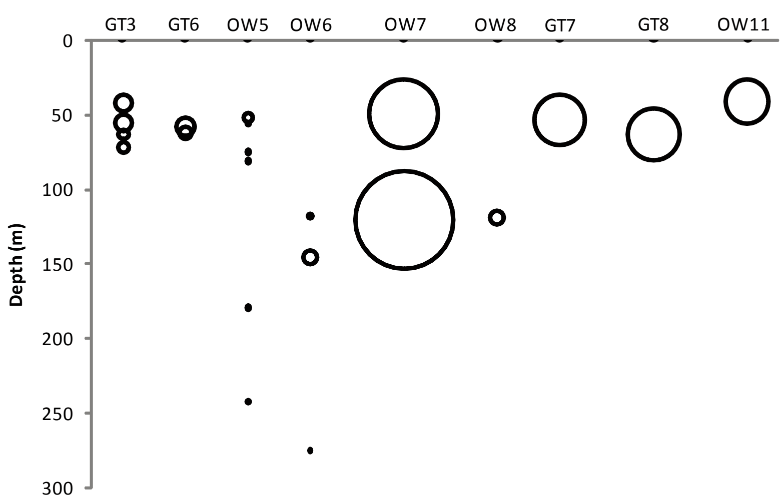

Fig. 2 *Inflow magnitude and depth in each borehole. Each circle represents an inflow. Circle area reflects inflow transmissivity, which has been normalised to the highest transmissivity value in the dataset.*

been low permeability structures or zones in the deep horizons that produced flow below the spinner's detection limit both under ambient conditions and during pumping. It was assumed that the contribution of these zones to the total permeability of the rock mass was insignificant in the context of this study, as micro-flow data was not required.

The spinner test results suggest the existence of a total of 21 inflow zones in nine boreholes. Inflows ranged in depth between 36 m to 276 m, although full depth of most of these boreholes ranges between 300 m and 420 m. Due to the presence of near-surface blank casing in some boreholes the depth of the shallowest inflow is not well constrained. The spinner results show that 67 % of the inflows are located at depths shallower than 85 m.

The five largest circles in Fig. 2 represent inflows in OW7, GT7, GT8 and OW11 whose transmissivity is one or two orders of magnitude greater than the next largest inflow. These high transmissivity inflows are all at depths shallower than 120 m and are all located on the eastern side of the mine pits. Equally, the two deepest inflows in OW5 and OW6 have a transmissivity that is an order of magnitude less than the next smallest inflow and are both located on the western side of the mine pits. However, when inflow transmissivity is plotted against inflow depth there seems to be no correlation between the two. This indicates that, although the occurrence of inflows themselves appears to be controlled by depth, the magnitude of their transmissivity does not appear to correlate with depth. Furthermore, there seems to be no correlation between the total borehole transmissivity and structure frequency or aperture as recorded in geotechnical logging and ATV survey.

Transmissivity values across all boreholes ranged from 0.06 m^2/d at 276 m in OW6 (also the deepest inflow), to 113.5 m^2/d at 120.8 m in OW7. The inflows with the highest transmissivities were found in OW7, GT7, GT8 and OW11 (Fig. 2). These boreholes only had one or two discrete inflow horizons reflecting the relatively competent nature of the rock mass with few open structures.

All inflows were produced by open joints with the exception of two open cemented joints and two shattered zones. Shattered zones are classified as fault zones in geotechnical interpretation. Although joints may appear cemented in the core, the spinner tests revealed that these features may nonetheless act as flow conduits indicating only partial cementation with sufficient connectivity of void space within the joint structure to enable groundwater to migrate.

A comparison has been made with regard to the global dip angles of the inflow structures and the logged joints as recorded from drill cores and ATV survey. The dip angle for 95 % of the structures that were associated with inflows ('inflow structures') was less than 35°. Although the data are insufficient for a robust statistical comparison, visually it is clear from Fig. 3 and Fig. 4 that the dip angles of all open structures (as recorded by ATV survey and drill core logging) are distributed across a wider range than the dip angles of the inflow structures alone. The clustered data in Fig. 4 with a dip angle greater than 30° represent the foliation trending northeast-southwest with the more strongly clustered data representing structures dipping steeply to the northwest, and the more scattered data, structures dipping steeply to the southeast. Based on the results of this investigation the structures corresponding to the foliation are unlikely to be flow conduits. Groundwater flow is predominantly associated with the sub-horizontal joint sets.

The information from the spinner testing and the geotechnical logging were used to inform a three layer conceptual model (Fig. 5) comprising the overburden, the zone in which all inflows were detected ('inflow zone'), and the rest of the rock mass where no inflows were detected. A Radial Basis Function was used to interpolate between known inflow locations to create the estimated inflow zone. The inflow zone thickens from east to west,

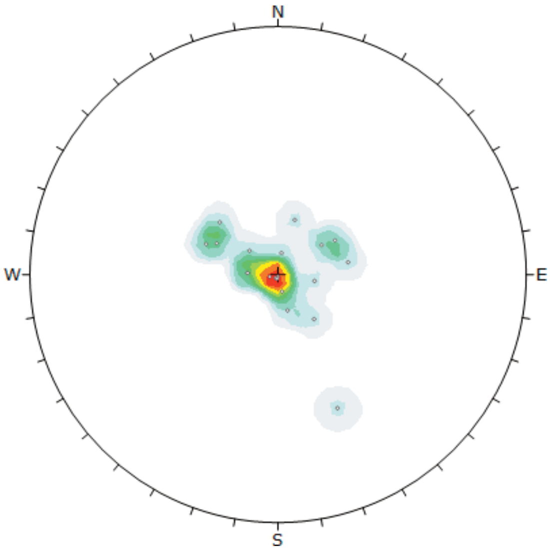

Fig. 3 *Density concentration of poles of structures detected as inflows. A darker colour indicates a higher concentration. Sample size was 21.*

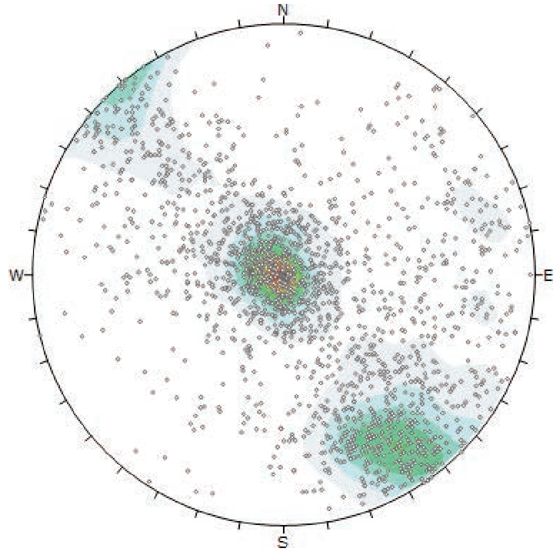

Fig. 4 *Density concentration of poles of all logged structures. A darker colour indicates a higher concentration. Sample size was 3103.*

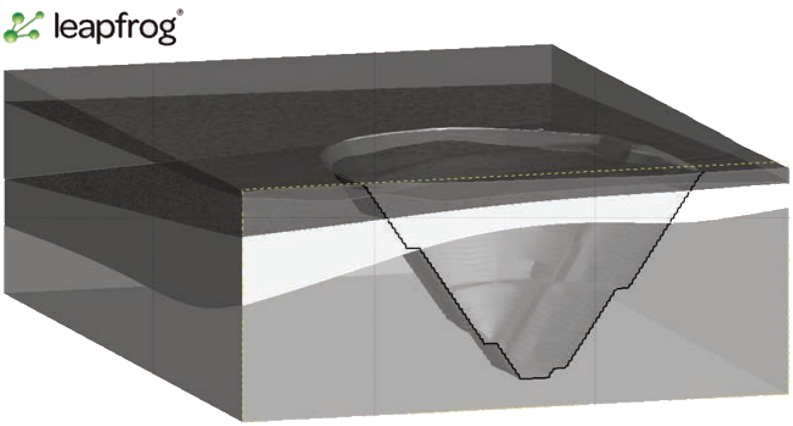

Fig. 5 *Conceptual model block diagram of proposed pit shell with zone in which inflows were detected in white. Weathered zone is dark grey and the remaining rock mass is pale grey. Aspect is towards the north-east and the pit diameter at the line of cross-section is approximately 1km.*

with a narrowing in the centre of the pit, although this narrowing is likely to be caused by the geographical bias of the dataset. The model highlights that, although the highest magnitude inflows have all been recorded on the eastern side of the main pit, they all occur within a relatively narrow range of thickness between 54 m to 120 m depth, and they are often the only observed inflows in the borehole. On the western side of the pit the inflow zone had a greater thickness with depths ranging between 43 m and 276 m. However, the inflows recorded along the western side of the pit have a much lower magnitude. This observed inflow pattern suggests the existence of structure zones of significant storage capacity along the eastern wall of the main pit, which would be drained with high productivity dewatering wells.

Conclusions

Spinner logging, ATV logging and geotechnical core logging were used to investigate the hydrogeological properties of the fractured rock mass at a proposed open pit gold mine in Burkina Faso. For the hydrogeological conceptual model, the spinner test results indicated the absence of a perched aquifer as well as pressurised confined aquifers, and enabled the transmissivity of inflow structures to be quantified. The addition of geotechnical information provided added resolution as to the exact depth of inflow structures, as structure depth could be measured accurately from ATV output and confirmed in the drill cores. This enabled the thickness of the highly permeable zone to be more confidently constrained in the conceptual model. This has important implications for the estimation of groundwater inflows to the pit and for the design of a more efficient and cost-effective dewatering system.

From the perspective of the geotechnical investigation the information from the spinner testing showed that there is a low likelihood of encountering high water pressures in steeply dipping structures that may impact on the pit slope stability. Spinner test results indicate that the majority of inflow structures were sub-horizontal. Sub-horizontal structures with high water pressures are much less detrimental to pit slope stability, as they are unlikely to act as potential failure planes. The combination of both spinner testing and geotechnical logging thus provided valuable input to both open pit groundwater inflows and pit slope stability studies, ultimately leading to more effective mine designs, and may have further reaching implications during the operational phase of the mine.

Acknowledgements

The authors thank Volta Resources and Kiaka Gold SARL for facilitating the research that allowed the production of this paper. Thanks also go to the geophysical logging contractor, LIM, for collecting the spinner and ATV data. Additional thanks go to Mike Palmer and James Haythornthwaite (SRK) for their work with Leapfrog, and to the SRK Geotechnical Engineers for amiably collaborating with this research.

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