Pre-sink shaft safety analysis using wireline geophysics

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Synopsis

During the preliminary design phases and feasibility study of a proposed vertical shaft, a vertical diamond drill-hole is normally drilled on the site. This paper outlines how rock mass characteristics, *in-situ* rock stress, rock strength, hydrological characteristics, and structural parameters can be determined using wireline logging of this borehole. In addition, a rock mass classification scheme is developed, based on published work, and in particular the Q-factor is adapted to assess the stability of raise-bored shafts. The 'stick plot' is introduced, which combines all geotechnical parameters applicable to the stability of a vertical shaft into a colour-coded format where cross-correlations can readily be made on a day-to-day basis during the shaft-sinking process.

Keywords

shaft-sinking, raise-boring, geophysical logging, geotechnical, Q-factor, stability.

Introduction

During the preliminary design phases and feasibility study of a proposed vertical shaft, very little detailed information is available on the rock mass characteristics, *in-situ* stress, rock strengths, and hydrological characteristics for the evaluation of the project. A pre-sink diamond drill-hole is normally drilled on the proposed site and is steered with the use of gyro surveys and wedges to remain within the barrel of the shaft. *i.e.* not to deviate more than 5 m in any direction from the central position.

Geotechnical logging of the core can now take place and parameters such as rock strengths, fracture orientations and dip, *in-situ* magnitude and orientation of the principal horizontal stress field, and positions of water inflow can be determined with the use of wireline geophysics.

Rock mass classification schemes have been developing for over 130 years since Ritter (1879) attempted to formalize an empirical approach to tunnel design and support requirements. Numerous multi-parameter classification systems (Wickham *et al.*, 1972; Bieniawski, 1973, 1976, 1989; Laubsher, 1977; Barton *et al.*, 1974, 1976, 2002; McCracken and Stacey, 1989) have been developed since then. Although most of the systems were developed for the design and support of horizontal tunnels and excavations, McCracken and Stacey (1989) adapted Barton's Q-factor to the stability of raise-boring. Peck and Lee (2008) have also adapted the Bieniawski (1989) and McCracken and Stacey systems to assess the stability of raise-bored shafts.

The choice of the rock mass classification system used is very often client-dependent. However the 'stick plot' technique used here employs modified versions of Barton, as well as McCracken and Stacey, which have been enhanced with the use of wireline techniques and adjusted to various raise-bore diameters.

The purpose of the stick plot is to combine all geotechnical parameters applicable to the stability of a proposed shaft into an easily readable colour-coded format where cross-correlations can readily be made on a day-to-day basis during the shaft-sinking process. A detailed spreadsheet of all parameters is also provided for the use of the rock engineers.

The purpose of this paper is to introduce the stick plot method to the mining and shaft-sinking community as a viable alternative to the usually more esoteric methods of reporting, thus making the information readily accessible to all involved.

The deviated stick plot

The basis of the stick plot technique (Figure 1) is the use of Barton's geotechnical parameters that have been adapted to a vertical tunnel using data derived from geophysical wireline logging. Each individual structure (jointing, fractures, bedding, breakout *etc.*) is identified in the core, and geologically and geotechnically described with exact depth, inclination, and azimuth. This geophysical data is used to

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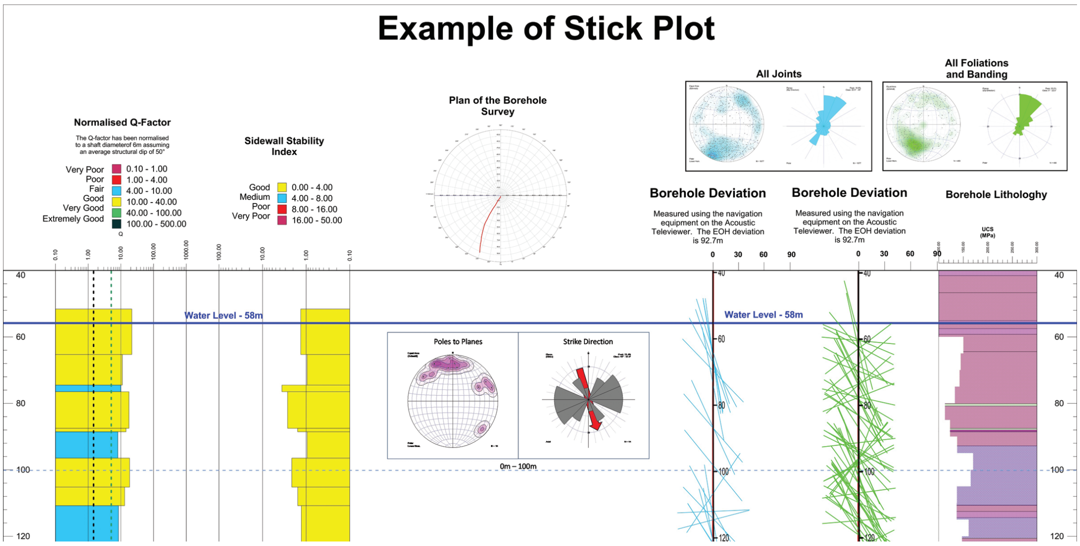

Figure 1 – The shaft ‘stick plot’ showing the normalized Q-factor, the sidewall stability index, fracture orientations and calculated UCS superimposed on the geology

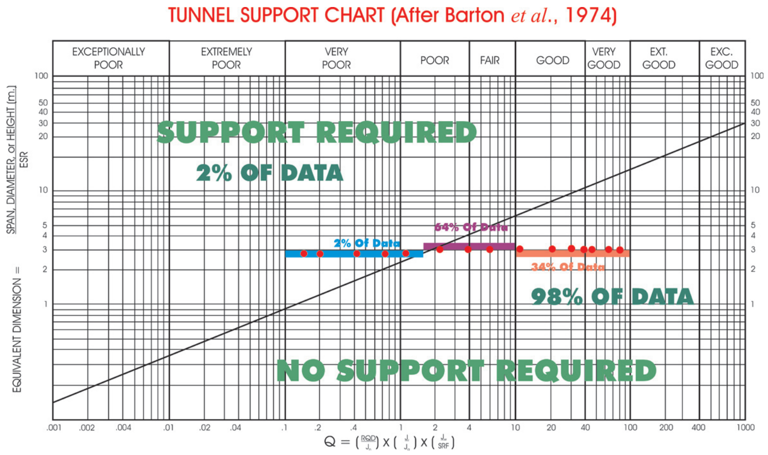

Figure 2 – Barton’s (1974) tunnel support chart showing the the support/no support required for the shaft being evaluated

modify Barton’s, parameters such as joint set number ‘Jn’, joint water reduction factor ‘Jw’, and stress reduction factor ‘SRF’ for conditions in a vertical tunnel.

Both Bieniawski’s and McCracken and Stacey’s parameters are also adjusted using the more precise fracture/joint spacings and orientations derived from the geophysical data. The stick plot poster itself shows only the modified Barton (2002) data with an additional ‘sidewall stability index’. Barton’s (1974, 1976) Q-factor values for support/no support are plotted on the modified Barton bar chart to determine what length of the shaft would require support (Figures 2 and 3). A detailed spreadsheet is also supplied for the use of the rock engineers, showing all calculated parameters.

The parameters shown on the poster are for the day–to-day use of the shaft-sinkers, and include the following:

- Colour-coded modified Barton Q-factor normalized to shaft diameter
- Colour-coded sidewall stability index developed by Andersen Geological Consulting
- Stick plots showing dips of all structures subdivided into sets with the borehole deviation. There can be two or three sets, depending on the dominant structural sets
- Stereograms showing the orientation of the structural sets over 100 m intervals down the shaft. These diagrams show the orientation of sidewall bolting to achieve optimum anchoring
- Calculated UCS plotted in a barchart against the lithological log of the borehole
- Barton’s (1974, 1976) tunnel support charts showing the support/no support required using different Q-factor values (Figures 2 and 3).

Details of modified parameters

- RQD. Having accurately determined the positions of all the structures from the acoustic televiewer (ATV), geotechnical units are determined (where all structural spacings are similar) and the RQD is determined over these units, rather than at fixed intervals. The reason for this is that the RQD zone forms the basis of all of the derived parameters

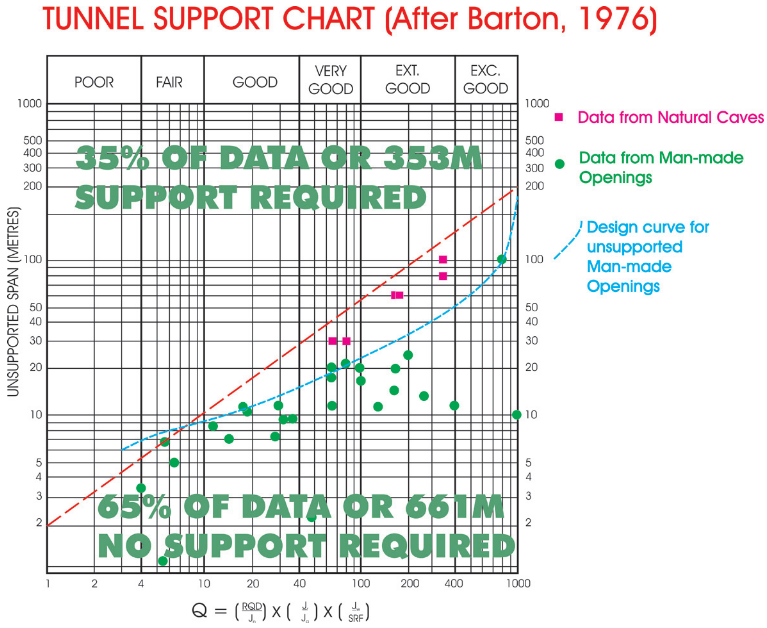

Figure 3 – Barton's (1976) modified tunnel support chart showing his re-evaluation of the support/no support required

- J_n (joint set number). Having measured the structural orientation, stereographic projections are plotted and Jn can then be accurately determined. The zone over which this calculation is done would depend on the dip of the structures and the diameter of the shaft
- J_r and J_a. Each structure is identified on the ATV image so that its exact orientation and depth are known. J_r and J_a parameters are then directly linked to this position. Structural features such as brecciation and orientation of slickensides are also determined. This data then allows for a 'structural domain analysis' to be carried out on the data
- J_w (joint water reduction factor). This factor is linked to the amount of water flowing from the fractures and also to the pressure. Before the water stratification in the borehole is disturbed by inducing water flow, a fluid conductivity log is run in the borehole. The size of the conductivity plume can then be related to the relative water ingress. This data is then interpreted along with physical observations of the fractures in the core, the televiewer classifications, the resistivity response given by the fractures, as well as the response of the full wave-form sonic tool. Following this, a wireline flow-meter can be used to determine the relative water ingress from fractures if a constant water flow is induced in the borehole from surface. This is often not possible as the fractures fill up and there is no flow of water
- SRF (stress reduction factor). Weak zones intersecting the excavation which may cause loosening of the rock mass when the shaft is sunk. This is addressed by the sidewall stability index (SSI). Shear zones are clearly identified by the full-waveform sonic log, where P and S wave velocities of the sidewall are determined. The geotechnical log will also provide information about clay content and chemical alteration
- Rock stress. The orientation of the principal stress can be determined if borehole breakout is visible on the televiewer imagery. The stress ratio can be determined from the geometry of the breakout. If the UCS is calculated over this zone then the value of the principal horizontal stress can be estimated
- Rock strength. The elastic moduli can be calculated from the S- and -P-wave velocities derived from the full wave sonic geophysical log. These would include Young's modulus, Poisson's ratio, bulk modulus, and UCS. The UCS values are dynamic and are usually calibrated against laboratory measurements. The procedure is to take core samples from zones where there is a clean geophysical response, over a range of values and submit them for laboratory UCS determinations. A regression curve is calculated from the resulting data and the USC values are adjusted if necessary.

Sidewall stability index (SSI)

This is a parameter that was developed by Andersen Geological Consulting (2010) in order to quantify the stability of the sidewall of a raise bore. It is essentially an early warning system to alert the operators as to where sidewall conditions have deteriorated and sidewall collapse may occur. The index is not an absolute value, but is a probabilistic determination between 'good' and 'very poor' (Figure 4).

Barton (2002) takes the *frictional component* concept of his Q-factor further by referring to the fact that the ratio J_r/J_a closely resembles the dilatant or contractile coefficient of the friction for joints and filled discontinuities. The relative magnitude of $\tan^{-1}(J_r/J_a)$ approximates the actual shear strength that might be expected of the various combinations of wall roughness and alteration products. Andersen (2010) combined this ratio with the true dip (from ATV) of the

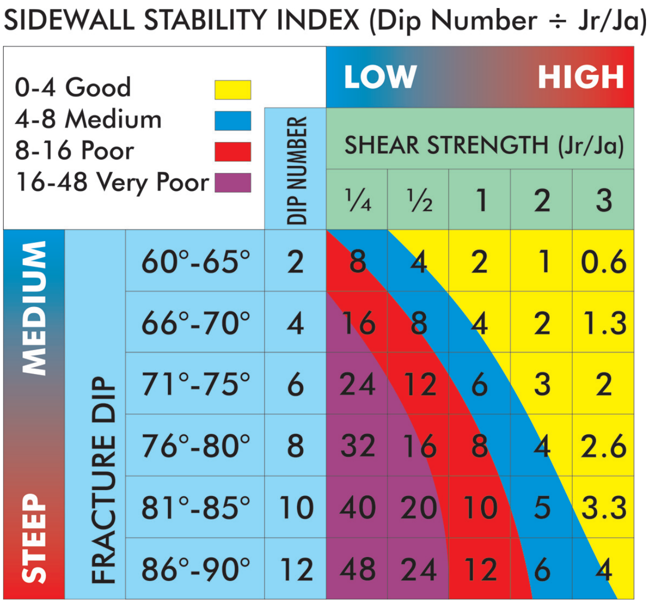

Figure 4 – The sidewall stability index. Matrix showing the calculation of the SSI based on angle of dip of the structure and shear strength derived from Barton's J_r and J_a parameters

discontinuities and produced the sidewall stability index. This index relates to the stability of the sidewall, so dips were ranked from 60° to 90°, with a *dip number* of 2 being allocated to the category 60° to 65°, and 12 for the category 85° to 90°. Any dip less that 60° was given the value of unity. It was considered that dips of less than 60° were less likely to cause sidewall problems during raise-boring than steeper dips. The index has been expanded to include face stability, where fractures with low angles of dip are likely to drop out ahead of the raise bore. Here the dip number is inverted, with the flatter dips being given the higher dip numbers.

The stick plot technique has not been formally published, and was first used for the evaluation of several shafts at Impala Platinum over the period 2002 to 2004, followed by Lonmin Platinum in 2002, Western Platinum in 2003, at Lonmin Platinum's Akanani Project in 2008, De Beers' Venetia diamond mine in 2011, and Lonmin Platinum in 2013. The first public presentation of the technique was at a symposium of the SAIMM's Bushveld Branch in 2004 (Andersen, 2004), followed by workshops given at Wits University, (Andersen, 2008, 2009). The concept of the sidewall stability index was first introduced at an SAIMM conference in 2010 (Andersen, 2010).

Summary of geotechnical results for the accompanying stick plot

The accompanying stick plot (Figure 1) is for the upper 400 m section of a 1 100 m borehole that was drilled for the evaluation of a shaft site. The graphic has been reduced in size for the purpose of publication.

The results below summarize the geotechnical evaluation of this borehole using the stick plot technique for the purpose of sinking a shaft.

Q-factor analysis

The Q-factor was calculated over the entire depth of the shaft borehole using intervals of RQD measurement. As stability varies with shaft diameter, an exercise was conducted to calculate the Q-factor for different diameters of raise bore. Shaft diameters of 6 m, 5 m, 4 m, and 3 m have been used. The Q-factor changes because the joint set number (J_n) becomes smaller as the shaft diameter decreases. The bar chart for the 6 m diameter shaft is shown in Figure 1. Superimposed onto this chart is the support/no support Q-factor value determined by Barton (1974, 1976). If Barton's 1974 value of <1.4 is used, then for a 6 m diameter shaft, it is estimated that approximately 2% (16.1 m) of the length of the shaft would have to be supported. If the 1976 value of about 5 is used then approximately 35% (353.12m) of the shaft would require support. The Q-factor values increase as the shaft diameter decreases. However, there is not a marked change as the fracture/joint dips are generally steeper than 60°.

The Q-factor analysis is used to estimate support/no support for horizontal tunnels, so it should be interpreted in conjunction with the sidewall stability index.

Sidewall stability index

The sidewall stability has been rated over the same intervals as the Q-factor and UCS and is shown as a bar chart on the stick plot. The sidewall stability is rated between medium and good down to a depth of 1006 m, after which there are some poor zones.

It is important to note that the SSI refers to the probability of the sidewall of the shaft collapsing during excavation. However, the normalized Q-factor indicates the blocky nature of the rock mass, which would be caused by the jointing and fracturing in the rock. In a horizontal tunnel this would relate directly to support required, whereas in a vertical shaft it indicates possible rock fragmentation after blasting. The SSI is a better indicator of sidewall stability.

In general the sidewall stability is reasonable but there are distinct zones where the dip of the fractures is greater than 60° and the fractures contain soft filling which could result in sidewall collapse. These zones are classified as poor on the SSI.

Below 860 m the jointing intensity increases and the Q-factor shows zones that are rated between fair and poor with some intervening sections being good. There is one very poor zone where there is a possibility of water inflow.

Overall trend of the structures

The banding and foliation are the most prominent structures present in the borehole. These have a mean strike direction of northwest to southeast, and dip dominantly to the southwest with a small component dipping to the northeast.

The jointing has been separately classified and is also seen to follow the dominant foliation direction, although the dips are steeper with an average of about 75°. A shallower dipping joint set is also present with a northwest to southeast strike and a dip to the southeast.

It was possible to classify dip, oblique, and strike slip faults. The orientations of the strike and oblique slip faults are sympathetic to the jointing. These faults dip at more than 70°. The dip slip faults form a conjugate set striking northwest-southeast and dipping at about 45° to both the northeast and southwest.

Sidewall bolting

A series of stereograms has been calculated over 100 m intervals down the length of the shaft. These show the mean dip and strike of the structures over each section. The purpose of these is to indicate the optimum direction for rockbolting, which is indicated by an arrow.

Groundwater intersections

The shaft will 'make water' from numerous joints from depths greater than 66 m, which is the current static water level. These are shown in column 6 as blue intervals. The driller's log did not indicate any water intersections.

Rock strength analysis

The rock strength values, including UCS, Young's modulus, and Poisson's ratio, were calculated using the P- and S-wave velocities as determined from the full-waveform sonic measurements. The UCS values were overlaid onto the geological log on the stick plot and the other values are available as text files.

Conclusion

Barton's Q-factor system (Barton *et al.*, 1974) was initially developed to assess the design and support of horizontal tunnels and excavations. This system has been adapted for use in a vertical shaft, with structural information being derived from an acoustic televiewer (ATV) geophysical wireline log and Barton's geotechnical parameters described directly from the borehole core at the depths indicated by the ATV log. A colour-coded bar chart is then constructed depicting Barton's classification of rock mass quality between very poor and extremely good, based on RQD domains.

As the stability of the sidewall is very important in shaft sinking, a sidewall stability index (SSI) is introduced. This index is based on the dip of the structures (determined from the ATV) and the shear strength of the structure (J_r/J_a) determined from the geotechnical logging. Again, a colour-coded bar chart is derived, ranking the sidewall stability between good and very poor.

Zones of possible water inflow into the shaft excavation are indicated based on wireline fluid conductivity, differential temperature, and impeller measurements.

Stereographic projections are constructed based of structural measurements made by the ATV. Dominant joint sets are identified that could cause structural failure if their orientation is not taken into consideration when excavating shaft stations or developing shaft bottom orepass raises. These joint sets are shown as graphical projections.

Rock strength parameters are calculated from the wireline velocity and density measurements. The orientation of the principal horizontal stress is determined from the orientation of borehole breakout observed on the ATV image.

McCracken and Stacey's (1989) maximum unsupported span, based on the geotechnical parameters, is also calculated but is not shown on the stick plot.

The 'stick plot' is designed as an easy-to-read graphic for the daily use of shaft sinkers to indicate rock conditions in advance of the sinking. A detailed report discussing the rock engineering parameters is also provided for the rock engineers.

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