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Geotechnical evaluation of coal deposits based on the Geophysical Strata Rating

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ABSTRACT

In exploration programs for coal mining, geophysical logging of boreholes is mainly undertaken to reveal seam locations and the basic lithological section. Through the introduction of the Geophysical Strata Rating (GSR), this paper develops new geotechnical applications for geophysical logs. The GSR is an empirical rating scheme based on P-wave velocity data from sonic logs and estimates of the clay content and porosity derived from natural gamma and density logs. In coal measure strata, GSR values range between 0 and 100, with values of <15 indicating very poor rock and values over 80 representing extremely good rock.

Given that geophysical logging data are obtained at closely spaced intervals within boreholes and that coal measure strata are usually laterally persistent between boreholes, geophysical results such as the clay content and the GSR can be modelled in two- and three-dimensions. This allows geotechnical information to be viewed in a geological context. Examples are provided of the log analysis and modelling. Geotechnical applications in risk identification, hazard assessment and design optimisation are also discussed. These applications exist in both underground and open cut mining.

1. Introduction

For many years, geophysical logging of exploration boreholes has been an integral part of coal exploration. The logs, particularly the density and natural gamma logs, readily indicate the locations of coal seams and other strata in the geological section. In combination with a sonic log, a caliper log and a log of the borehole trajectory, these logs form the basic coal-suite of logs (see for example, Thomas, 2012; Edwards, 2009; Hatherly, 2013 and on-line material provided by Weatherford (2016) and Wireline Workshop (2016)). They are used in coal mining regions around the world.

Given the large petrophysical contrasts that exist between coal and most other rocks, identification of coal seams from geophysical logs is straightforward. As a result, expensive core drilling need only be undertaken in sections of boreholes needing core samples for coal quality, gas content and geotechnical testing. Elsewhere, the geophysical logs allow the geological section to be established, including the locations of marker bands useful for correlation. The logs also provide precise depths to coal seams and allow recognition of intervals where core losses have occurred.

With regard to the geotechnical applications of geophysical logs in coal mining, most efforts are concentrated on estimating uniaxial compressive strength (UCS) from sonic logs. Various relationships between sonic velocity and UCS have been proposed (McNally, 1990; Oyler et al., 2010; Shanmukha Rao and Uday Bhaskar, 2015) but because sonic velocity is a function of the elastic properties of the medium and its density, any relationship between sonic velocity and UCS relies on there being a relationship between the elastic properties and strength. Additional complications arise because the sonic velocity is also affected by fractures in the strata and any anisotropic properties due to bedding. In some ways, the seismic velocity charts for estimating rippability from P-wave velocity as well as rock type (Caterpillar, 2016) are an example of a more robust approach to estimating a geotechnical parameter (rippability).

Given these geological and geotechnical applications for geophysical logs, it is easy to see why they are an indispensable part of most exploration programs. It is therefore appropriate that their role is recognised in the Australian Guidelines for the Estimation and Classification of Coal Resources (Guidelines Review Committee, 2014; Joint Ore Reserves Committee, 2012). What is not apparent, however, is the existence of a prevailing philosophy that depth control, basic lithological identification and UCS estimation are the only significant roles for geophysical logs. Geologists and geotechnical engineers don't tend to regard geophysical logs as a primary data source for providing geological and geotechnical insights in their own right.

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There are probably a number of reasons for this. One is the limited understanding of the fundamentals to geophysical measurements on the part of coal mine geologists and engineers. As well, mining companies don't tend to employ geophysicists and logging matters are handled by specialist logging contractors who are not necessarily familiar with, or involved in the analysis and end-use of the results. Finally, it is human nature that a bird in the hand in the form of a piece of core is regarded much more highly than elusive birds in the bush in the form of 'esoteric' geophysical measurements.

It is in this context that this paper introduces a new approach for the analysis of geophysical logs in coal mining. The approach has mainly been developed in the black coal fields of Australia (NSW and Queensland) and provides integrated geological and geotechnical insights that are only possible from geophysical logs. It does not reduce the need for conventional geological and geotechnical investigations but it provides additional information from the conventional geophysical logging suite which puts geotechnical information into a 3-dimensional (3D) geological context. From this, geotechnical engineers are much better placed to address issues such as roof support, longwall caving, highwall stability and blastability.

In the next section of this paper, a method for the analysis of geophysical logs which provides robust estimates of the clay content and porosity of clastic strata is described. A rock mass rating scheme is then introduced. Named the Geophysical Strata Rating (GSR), it utilises the information from sonic logs and the porosity and clay contents derived from log analysis. These geophysical results are effectively continuous and can be interpolated (modelled) between boreholes. This allows development of 3D models of GSR and other geophysical data. An approach to the modelling of geophysical data is demonstrated in the third section of the paper. Finally, some of the geotechnical applications are discussed.

2. Quantitative analysis of geophysical logs from coal exploration boreholes

2.1. Lithological identification

Australian coal measures contain a range of sedimentary rock types. In addition to coals and carbonaceous siltstones, clastic rocks ranging from mudstone, to fine-grained siltstones, to sandstones and conglomerates are present. Igneous rocks in the form of intrusions, surface flows and ash fall tuffs may also be encountered. The main types of sedimentary rocks that are not present are carbonates and evaporites.

The first step for a quantitative analysis of geophysical logs is to identify coals and other rocks containing carbonaceous bands. These are readily identified on geophysical logs by virtue of their low responses on density, sonic velocity and natural gamma logs. In most circumstances, it is sufficient to identify these from just the density log. Coal will typically have a density <1.9 g/cm^3 and any other carbonaceous materials tend to have densities between 1.9 and 2.3 g/cm^3. Once these rock types are identified, the remainder of the geological section can be inferred to be comprised of mainly clastic rocks with exceptions being tuffs (which typically give very high natural gamma responses), basalts (which typically have high densities, high sonic velocities and low natural gamma responses) and siderite bands (which have high densities, high velocities and thicknesses less than one metre). These exceptions can be identified at a later stage in the analysis once the maximum densities for the clastic rocks and the maximum natural gamma response for the typical claystones and siltstones have been selected.

For the clastic rocks, the usual practice is to regard them as consisting of three components – grains, cements and pores. For the coarser clastic rocks, the grains are often dominantly quartz due to its high abrasivity and chemical stability. In quartz sandstones, the natural gamma responses are low. However, in lithic sandstones which tend to be found in closer proximity to the source rocks and have grains made of rock fragments, higher natural gamma responses may occur. In the finer grained clastic rocks such as siltstones and mudstones, the distinction between grains and cements may be lost because these fine-grained rocks are deposited in quiet sedimentary environments and clay minerals tend to dominate. In these rocks, the natural gamma responses are high.

2.2. Porosity and clay content

Once the coal and carbonaceous materials have been identified, the remaining clastic section of the borehole needs to be analysed to determine the porosity and clay content. These procedures and underlying assumptions are thoroughly described in text books such as Hearst et al. (2000) and Rider and Kennedy (2011).

For the determination of porosity, $ø$, from density, ρ, the standard equation is:

$$\phi = \frac{\rho_{ma} - \rho}{\rho_{ma} - \rho_f} \tag{1}$$

where ρ_{ma} is the matrix density and ρ_f is the density of the fluid occupying the pores (e.g. 1 g/cm^3 in water saturated rocks). In this equation there is an assumption that the density of all of the grains and cements can be assigned a single matrix density. Given that the density of clays tend to be similar to the density of quartz (2.65 g/cm^3), this assumption is acceptable provided the matrix density reflects the density of the dominant mineral. For the Australian situation, any sections of a density log where the observed density is greater than the chosen matrix density, siderite or basalt can be assumed to be present and the porosity can be set to zero.

In the case of the clay content, the volumetric value, V_{shale}, is determined. From a natural gamma log, the standard equation for the clay determination is:

$$V_{shale} \approx \frac{\gamma - \gamma_{sand}}{\gamma_{clay} - \gamma_{sand}} \tag{2}$$

where Υ is the natural gamma measurement and Υ_{clay} and Υ_{sand} are the natural gamma values for the clay and grains indicated by the minimum and maximum values of the natural gamma log within the clastic section of the borehole. Note that here, as is often the case in the log analysis literature, the terms 'clay' and 'shale' are used interchangeably and 'sand' is taken to include all grain materials – quartz and other. While there are more refined equations for the determination of clay content and also equations for determining clay content from neutron and resistivity logs, Eq. (2) is adequate for present purposes. Exceptions may arise in situations where non-radioactive clays are present (e.g. kaolinite) or when there are sands containing heavy minerals with enhanced radioactivity. In these cases resistivity and neutron logs may be of assistance if they are available.

As stated above, volcanic tuff bands may also be present. If it is found that in some sections of a log, Υ is significantly higher than Υ_{clay}, it may be appropriate to label these as tuff bands and set their porosities to zero and clay content to 1.

GSR calculations require estimates for the porosity and clay content for rocks other than coal. Application of Eqs. (1) and (2) is straightforward but the choice ρ_{ma}, Υ_{clay} and Υ_{sand} may require some experimentation if the composition of the clastic rocks is not well understood and if the geophysical logging tools are not accurately calibrated. The following empirical equation provided by Eberhart-Phillips et al. (1989) leads to a method where some guidance can be given to the choice of values:

$$V_P = 5.77 - 6.94\phi - 1.73\sqrt{V_{shale}} + 0.446\left(0.01p_e - e^{-0.167p_e}\right) \tag{3}$$

Here, the sonic (P-wave) velocity, V_p, is measured in km/s and p_e is the effective pressure measured in MPa. This equation was derived from a study of 64 sandstones from onshore and offshore sites across