A ROCK MASS RATING SCHEME FOR CLASTIC SEDIMENTS BASED ON GEOPHYSICAL LOGS

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ABSTRACT

In addition to fractures and joints, compositional factors and bedding influence the strength of clastic sedimentary rocks. Rock mass rating schemes must therefore consider all of these factors.

In this paper, a rating scheme for clastic sediments based on geophysical measurements is described. Geophysical logging allows an approximation of rock composition to be obtained and an assessment of bedding frequency and laminations. Velocity measurements incorporate the effects of fracturing.

The rating requires scores for the intact rock, bedding/cohesion, and defects. These are combined to yield a Geophysical Strata Rating (GSR). Determination of the GSR is objective and repeatable. GSR values are typically between 20 and 80 and can be related to the Coal Mine Roof Rating.

INTRODUCTION

Analysis of geophysical borehole logs provides one of the best approaches to characterizing rocks within boreholes. The techniques have been developed mainly for use in petroleum exploration, but there are also established applications in coal mining, metalliferous mining, groundwater investigations, and civil engineering. For mining, the main application is to provide information on ore quality, geological correlations, and geotechnical properties.

This paper concerns the geotechnical applications in underground coal mining where the characterization of roof and floor strata is important for understanding caving behavior and roof support requirements. The results relate to Australian coal mining conditions where the coals are mainly of Permian age and depths of mining are usually less than 500 m. Roof and floor strata are mainly sandstones, siltstones, and claystones with occasional tuff beds and bands of siderite. Limestones are absent. Given the mainly clastic nature of these strata, the techniques of geophysical log analysis developed for the characterization of petroleum reservoirs are particularly useful.

On the basis of these techniques, Medhurst and Hatherly [2005] proposed the Geophysical Strata Rating (GSR). In this paper, we further develop the GSR and provide examples of its application. The GSR mainly relies upon sonic logging. In this regard, it can be viewed as a refinement of UCS/sonic relationships frequently employed in Australian coal mining. It also has similarities with the approach developed by Barton [2002, 2006] for determining Q-values from sonic, porosity, and depth information. The GSR delivers results on a linear scale similar to the Coal Mine Roof Rating (CMRR) of Molinda and Mark [1994]. It combines separate ratings for the intact rock mass and defects. Beyond consideration of velocity, porosity, and depth, it also considers clay content (shaliness).

Owing to the widespread interest in using sonic velocity in geotechnical investigations, this paper begins with a review of the geotechnical significance of sonic velocity.

SONIC LOGGING

The sonic velocity obtained by sonic logging is a compressional seismic wave (P-wave) with velocity, V_p given by

$$V_p = \sqrt{\frac{k - 4/3\mu}{\rho}} \tag{1}$$

where k is the bulk modulus (incompressibility), μ is the shear modulus, and ρ is the density.

In an isotropic and homogeneous rock body, seismic velocity responds to the elastic properties and density of the medium as might be measured in a rock mechanics laboratory. If the strength of the rock were related to its elastic properties, then the velocity would also be related to the strength. However, when inhomogeneities due to factors such as compositional variations and defects are present in the rock mass, as well as anisotropy in the form of bedding and other directional features, k, μ, and ρ are variable and the interpretation of V_p becomes more difficult. To understand the significance of a velocity measurement, it is necessary to understand the influence of the various causes of inhomogeneity and anisotropy.

In fresh igneous rocks where the porosity is low and the crystals have similar elastic properties, the velocity is largely controlled by fractures and joints. Barton [2006] makes frequent reference to the work of Sjøgren et al. [1979], who correlated RQD with measurements of V_p

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from shallow seismic refraction surveys in Norwegian igneous and metamorphic rocks. As is also reported by Barton [2006], Deere et al. [1967] found a relationship between RQD and the square of the ratio of V_p measured in the field and in the laboratory on intact samples. However, when igneous rocks weather, compositional changes occur and pore spaces develop. Other factors will then influence the velocity.

In sedimentary rocks, particularly those that form petroleum reservoirs, there has been considerable attention given to understanding the relationship between V_p and composition and porosity. Pressure is also an important factor because of its influence on the porosity. While it is not possible to determine exact expressions for V_p, laboratory studies allow development of empirical relationships. For example, Han et al. [1986] report on a study of sandstone samples with fractional porosities, φ, ranging from 0.02 to 0.3 and clay contents, V_{Shale}, ranging from 0.03 to 0.5. Results are given for a number of confining pressures. For example, at 5-MPa confinement, V_p is given by

$$V_p = 5.26 - 7.08\phi - 2.02V_{Shale} \qquad (2)$$

with a correlation coefficient of 0.969.

While this equation shows that porosity has 3.5 times the effect on the velocity compared to clay, the clay content does have a measurable effect. This is illustrated in Figure 1, which shows how velocity varies over the compositional range investigated by Han et al. [1986]. As Han et al. point out, the velocity in a rock with very near-zero porosity and low clay content is significantly lower than the velocity of 6.05 km/s true for quartz aggregates. This implies that just small amounts of clay are able to soften the sandstone matrix and produce a reduction in velocity.

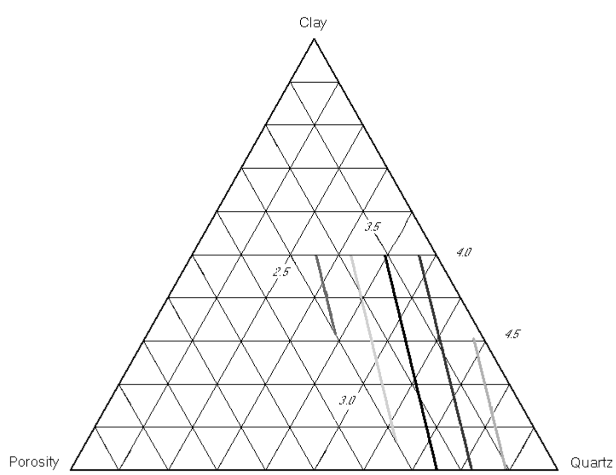

Figure 1.—Ternary diagram showing changes in V_p in sandstone according to porosity, clay, and quartz content at 5-MPa confinement. Velocities are in km/s. Quartz content = 1 – V_{Shale} – φ.

Han et al. [1986] also suggest that for clay to have an effect on the velocity, it has to be either structural (i.e., bonding grains) or laminar (forming discrete layers between grains). If the clay were simply suspended between pores, then negligible affects would be expected. Dvorkin and Brevik [1999] use the separate influence on V_p of clay in the form of cements and interstitial clays to infer the strength and permeability of reservoir-forming sandstones. Similar observations were made in another study by Eberhart-Phillips et al. [1989], who obtained empirical relationships between V_p and φ, V_{Shale} and effective pressure, p_e (confining pressure minus the pore pressure). They observed systematic departures for some sandstones from normal trends, which they attributed to factors such as the shape and size of grains and pores, as well as the degree of compaction.

As an empirical relationship between V_p, composition and p_e, Eberhart-Phillips et al. [1989] derived the equation:

$$V_p = 5.77 - 6.94\phi - 1.73\sqrt{V_{shale}} + 0.446\left(p_e - e^{-16.7 p_e}\right) \qquad (3)$$

By calculating velocity, this equation can be used to provide confirmation of clay content and porosity determinations from natural gamma, neutron porosity, and density logs. It also allows velocity measurements to be checked against the results from these other logging data.

ROCK CHARACTERIZATION FROM SONIC VELOCITY

From Equation 1 it follows that there are relationships between V_p and modulus. If density is known and measurements are also made of shear wave velocity, it is possible to solve for k and μ. However, the strains involved in the measurement of V_p are of the order of microstrains, whereas in rock testing the strains are of the order of millistrains. With these very different orders of strain, it is found that different values of the modulus are obtained.

Both Barton [2006] and Wang [2000] review and discuss these issues and present numerous results. The reason for the difference is attributed to the behavior of pore and crack boundaries. At low strains, these are stiff, but they deform elastically at higher strains and the rock appears softer. In materials such as steel and solid quartz, there is little difference between values. This is also the case at depth (pressures greater than 100 MPa), when pores and cracks are closed. Closer to the Earth's surface, the so-called dynamic modulus obtained by seismic measurements in sedimentary rocks may be twice the laboratory values (static modulus). Wang [2000] also reports that Winkler [1979] found, for the same reasons, there is a strain dependence for V_p.

In the case of the UCS, there is no theoretical basis for relating it to V_p. However, because it is generally observed that stiffer rocks are stronger, empirical estimates of UCS can be made from V_p, provided fracturing is not strongly influencing V_p. Barton [2006] presents comparisons between V_p and UCS and reference is made to a V_p^3 relationship, one that also provides a reasonable first estimate of UCS in Australian coalfields.

As discussed by Medhurst and Hatherly [2005], many Australian coal mines use empirical relationships to estimate UCS from V_p. If a relationship is established for a specific situation where strength does vary with modulus and there is proper consideration of the effects of pressure and fracturing on velocity, this approach can be followed. Situations where V_p is not particularly sensitive to UCS include those involving poorly cemented cohesionless rocks and also shales where moisture conditions influence strength.

For purposes of rock mass characterization, Barton [2002, 2006] developed a graphical approach for determining a Q-value and modulus from V_p, porosity, and depth. As a basis, it uses the hard-rock relationship:

$$V_p \approx 3.5 + \log_{10} Q \tag{4}$$

which Barton derived from results of numerous investigations involving unweathered rocks such as granites, gneisses, volcanic ignimbrite, and competent sandstones, all at depths to about 25 m. To allow for the influence of depth and porosity and to extend the application to other rock types, a normalized value Q_c is introduced whereby

$$Q_c = \frac{Q}{100} UCS \tag{5}$$

The physical basis for this approach is evident from the preceding discussion on the relationship between V_p, RQD, pressure, modulus, and UCS. Variations in V_p due to compositional factors such as the clay content in clastic rocks are not explicitly included. However, Equation 5 does make some allowance for compositional variation because of the relationship between V_p and UCS and because of the strength reduction factors involved in the determination of Q.

The GSR for clastic rocks that is described below similarly uses information on V_p, porosity, and depth to determine a rock mass rating. However, it is based on direct geomechanical considerations of rock strength and includes explicit consideration of the clay content. To determine GSR, geophysical logging data are analyzed. As a minimum, sonic, density, and natural gamma logs are required. Neutron porosity logs can also provide alternative estimates of shaliness and porosity, which will help improve the analysis. A basis for the geophysical log interpretation procedure is given by Medhurst and Hatherly [2005] and Hatherly et al. [2006].

GEOPHYSICAL STRATA RATING (GSR)

Like soil classification systems, sedimentary rocks are amenable to characterization via a description of the grain size and type, amount of pore space, and moisture content. Fortunately, geophysical logs provide a reliable and repeatable measure of such parameters. As discussed, sonic velocity is a key measure that reflects rock stiffness and to some extent rock strength and fracturing, provided changes in mineral composition and porosity can be detected via other log data. At its core, the GSR is based on providing ratings for the quality of the individual beds, their contacts, and frequency.

Rock Score

The rock score attempts to provide a measure of the quality of the individual beds and has three components: strength score, porosity score, and moisture score. The strength score is calculated using sonic velocity and is used as the basic measure of rock competency. Adjustments are then applied to take into account the influence of high-porosity, poorly consolidated materials and the influence of high moisture content. Using an empirical approach, the following relationships have been developed:

$$\text{Strength score} = 20 * V_p - 45 \tag{6}$$

where V_p is in km/s and is corrected for effective pressure via Equation 3.

$$\text{Porosity score} = -5 * X * Y \tag{7}$$

where X relates to the clay content, V_{Shale}, and Y relates to the porosity, φ. If $V_{Shale} > 0.35$, $X = 0$. If V_{Shale} is between 0.25 and 0.35, X is linear between 1 and 0. When $V_{Shale} < 0.25$, $X = 1$. If $\varphi < 0.05$, $Y = 0$. When φ is between 0.05 and 0.2, Y is linear between 0 and 3. When $\varphi > 0.2$, $Y = 3$.

Essentially, the maximum adjustment of –15 occurs when $V_{Shale} < 0.25$ and $\varphi > 0.2$ and reduces to zero when $V_{Shale} > 0.35$ or $\varphi < 0.05$.

$$\text{Moisture score} = -5 * X * Y \tag{8}$$

where X relates to V_{Shale} and Y relates to φ. If $V_{Shale} < 0.65$, $X = 0$. If V_{Shale} is between 0.65 and 0.75, X is linear between 0 and 1. When $V_{Shale} > 0.75$, $X = 1$. If $\varphi < 0.025$, $Y = 0$. When φ is between 0.025 and 0.075, Y is linear between 0 and 2. When $\varphi > 0.075$, $Y = 2$.

Essentially, the maximum adjustment of –10 occurs when $V_{Shale} > 0.75$ and $\varphi > 0.075$ and reduces to zero when $V_{Shale} < 0.65$ or $\varphi < 0.025$.

The final estimate of rock score is therefore given by

$$\text{Rock score} = \text{Strength score} + \text{Porosity score} + \text{Moisture score} \quad (9)$$

Bedding Contact/Cohesion Score

In the Australian coalfields, stronger rocks tend to have stronger bedding. This allows a bedding/cohesion score to be given on the basis of sonic velocity. High-quartz sandstones are assumed to have strongly bound and/or cemented bedding surfaces, whereas mudstones are assumed to have smooth, planar, and weaker bedding surfaces.

$$\text{Cohesion score} = 10 + 5 * X \quad (10)$$

where X relates to V_p, again corrected for effective pressure. If $V_p < 2.75$, $X = 0$. When V_p is between 2.75 and 3.25, X is linear between 0 and 2. When $V_p > 3.25$, $X = 2$.

In the case of hard sandstones, i.e., quartz contents greater than 0.57 and $V_p > 3.25$, an additional component applies:

$$\text{Cohesion score} = \text{Cohesion score} + 5 * X * Y \quad (11)$$

where X again relates to V_p and Y relates to the quartz content. If V_p is between 3.25 and 3.5, X is linear between 0 and 1. If $V_p > 3.5$, $X = 1$. If the quartz content is between 0.57 and 0.67, Y is linear between 0 and 1. When quartz > 0.67, $Y = 1$.

Initial GSR (GSRi)

$$\text{Initial GSR (GSRi)} = \text{Rock score} + \text{Cohesion score} \quad (12)$$

The initial GSR (GSRi) provides a measure of variation in the rock quality of individual beds. In doing so, it not only provides a bed rating, but by the contrast between beds, it also reflects the variation between beds. It is thus possible to obtain measures of bed frequency in laminated strata or to determine the thickness of so-called geotechnical strata units in thicker strata sequences where lithological boundaries are less significant.

Defect Score

In keeping with other rock mass rating schemes, the GSR also needs to reflect the state of the defects introduced by fracturing and bedding. When cores and direct rock exposures are available, ratings are provided by manual logging—an intensive and potentially subjective process. With geophysical logs, acoustic scanner data also allow direct mapping of defects provided they are evident in the borehole wall. However, this is also an intensive and potentially subjective process.

For the GSR, defect information is extracted from the results of the analysis of the geophysical logs. The variability in these is taken to be the indicator of defects. Specifically, rapid changes in V_{Shale} are likely to indicate changes in lithology, while changes in GSRi are likely to indicate that defects in the form of fractures and changes in lithology are present. The variability is thus determined on the basis of the rate of change of GSRi and V_{Shale}.

The *bedding score* is based on the variability in V_{Shale} and is designed to capture the transitions between sandstones and siltstones/mudstones and also the variability within fine-grained units. The mean value and standard deviation of the variability is established over the interval of interest, and a bedding score between 0 and 10 is assigned. A score of 10 indicates that there is no change occurring in V_{Shale}. A score of 0 indicates that the maximum changes in V_{Shale} are occurring at the point in question.

The *fracture score* is based on the variability in the GSRi. The GSRi provides an overall estimate of the state of the rock mass from all available geophysical logging data and therefore captures any influences on the logs of the bedding as well as fractures. Following the work of Priest [1993] on joint frequency, an exponential relationship is used to describe the variability and from this, the likelihood that any particular value of variability is due to a defect is predicted. At each point, a linear score between 0 and 10 is applied on the basis of this probability.

Final GSR

$$\text{GSR} = \text{GSRi} + \text{Bedding score} + \text{Fracture score} \quad (13)$$

EXAMPLES

Implementation

Most geophysical logging data are recorded in the standard LAS (Log ASCII Standard) format.[4] Files begin with a header containing log and borehole information, and point-by-point log data are then supplied in column format. Being an ASCII format, LAS files can be read using standard text editors and imported into databases and spreadsheets such as Microsoft Excel. Visual Basic macros within Excel have been written to interpret the geophysical

[4] An exception arises with image and other data intensive logs, such as acoustic scanners and full waveform sonic logs. For these, binary data formats are used, but unfortunately standard file formats have not been accepted by the logging industry. Proprietary formats prevail.

logs and to calculate the GSR. All data contributing to the GSR are tabulated and can be examined in their own right.

Southern Coalfield, New South Wales, Australia

Figure 2 shows an example of a result from the Southern Coalfield, 60 km south of Sydney. The geophysical logs were initially obtained at 0.01-m spacings up the borehole. To reduce statistical uncertainty, especially in the natural gamma log, the logs were smoothed and resampled at 0.05-m spacings. Data are shown over a 4-m interval near the top of the working seam.

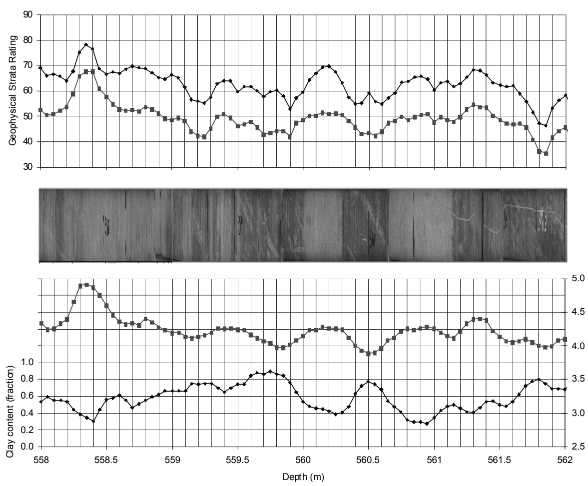

Figure 2.—*Top:* GSR (black) and GSRi (gray). *Center:* Core photograph showing a sequence of sandstones (white) and siltstones (gray). *Bottom:* Sonic velocity (gray) and interpreted clay content (black).

At the base of Figure 2, the interpreted clay content is shown together with the sonic data. Core photos are shown immediately above. There are no fractures evident, and the variations in clay content and velocity can be seen to be due to the changing lithology. In the gray silt bands, velocities are lower and clay content increases. Some of the bands have distinct margins (e.g., the siltstone band between 560.3 and 560.65 m).[5] In other sections, there are gradational changes in properties. For example, there is an increase in clay content and decrease in velocity between 558.8 m and 559.8 m. Here the strata are coarsening upward. At 558.35 m there is a band of high velocity, which is due to siderite. Siderite bands show up in the geophysical logs as thin zones of abnormally high density and velocity. There is also a minor siderite band interpreted to be present at 561.3 m.

At the top of Figure 2 are shown the GSRi and GSR. As expected, the GSRi shows the trends evident in the log data and core. Where there are distinct bands, they are evident as discrete layers. The sandstones have a GSRi of about 50. For the siderite it is 68; in the siltstones, it is about 42. Similarly, the gradational changes in lithology are represented by gradational changes in GSRi. There is also a region of low GSRi at 561.8 m, which is due to low velocity affecting the strength and cohesion score, and high shaliness and porosity, which influence the moisture score.

When the defect score is added to the GSRi to obtain the GSR, the gradational units remain gradational, the GSR at the boundaries of the discrete beds is enhanced (GSR goes relatively lower), and the GSR at the center of the discrete beds is enhanced. Lithological and bedding effects can thus be seen to be incorporated into the rating.

Newcastle Coalfield, New South Wales, Australia

The second example (Figure 3) comes from the Newcastle Coalfield 100 km north of Sydney. Here, results for the 2-m-thick immediate roof of the working seam are shown. From the core, five lithological units were identified and assigned separate CMRR ratings based on their discontinuities and intact strength. The lithologies, discontinuity spacing rating, UCS, and overall CMRR ratings for each unit are shown. The mudstones have lower UCS values than the sandstones. There is a low discontinuity spacing rating in the muddy sandstone in the immediate roof.

Figure 3 also shows the GSRi, GSR, and various defect scores determined from the geophysical logs. From the GSRi, it can be seen that the mudstones tend to have lower values than the sandstones. The fracture score established from the variability of the GSRi tends to be low at the bed boundaries and also in the immediate muddy sandstone with the low discontinuity spacing rating. For the bedding score, lows occur in the vicinity of the bed boundaries. When the bedding and fracture scores are added to the GSRi to produce the GSR, it can be seen that the relativity between the various beds is maintained and there are decreases in GSR at the bed boundaries and in the fractured muddy sandstone. While the absolute values of the GSR differ from the CMRR unit ratings in the sandstones, there is quite reasonable overall correlation between the CMRR unit rating and the GSR.

[5]Geophysical logs necessarily sample the rock mass over a finite interval of about 10–20 cm. For this reason, none of the rock boundaries appear abrupt.

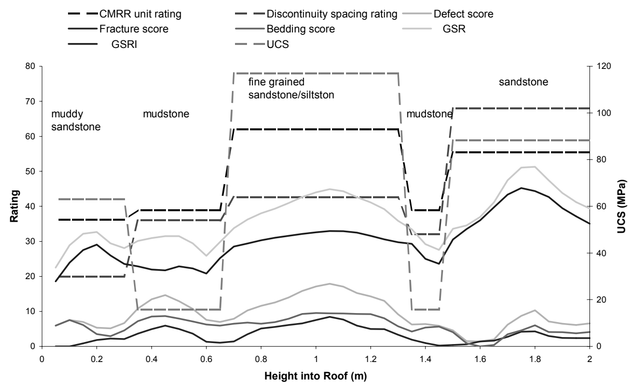

Figure 3.—Comparison of GSR and CMRR. The sample interval in the geophysical logs is 0.05 m.

DISCUSSION AND CONCLUSIONS

The GSR is designed to be a rock mass rating system based on geophysical logging data for clastic strata typical of coal mining regions. It has some similarities to the method proposed by Barton [2002, 2006] for determining Q-values from geophysical data, but it allows for the variations in seismic velocity that can occur as a result of changes in lithology from clay-rich rocks to sandstones. Such changes in lithology also change the geotechnical properties of the strata, and the GSR is designed to accommodate these.

The elements of the geophysical log interpretation behind the application of the GSR have been confirmed through the analysis of many geophysical logs from the coalfields of Australia, and the main structure of the GSRi is in place. Fine-tuning of the various scores, particularly the two defect scores, is now underway through comparisons with independent geotechnical ratings. The CMRR is the obvious scheme against which these comparisons can be made. Once these are completed, a more definitive GSR is likely.

Another area where work is under way concerns the effect of clay on rock properties. Earlier reference [Dvorkin and Brevik 1999; Eberhart-Phillips et al. 1989] was made to the effects of interstitial clay and clay in the form of a cement on seismic velocity. Following the work of Katahara [1995], it is possible to identify from natural gamma and porosity logs in shaly sandstones the presence of interstitial clay, clay cements, and laminar clay. On the basis of these considerations, refinements to the moisture and porosity scores are likely.

As a rating scheme, the GSR assigns a single value to every depth point. However, the component scores and interpreted geophysical data leading to the GSR have direct geotechnical and geological significance. Examination of these provides insights into the geotechnical properties of the strata and could also be used as input into numerical modeling investigations.

Geophysical log analysis and the GSR are not expected to totally replace manual geotechnical logging. As with any form of remote sensing, there will always be the need to provide ground truth. Anomalous regions identified by the GSR analysis should also be independently investigated to verify geotechnical conditions.

The benefits of the GSR should also be obvious. It is objective, repeatable, inexpensive to conduct, and representative of the state of the rocks as they are in the ground. Data from holes drilled for exploration purposes are also potentially available for analysis, thus supplementing the geotechnical database. By virtue of the fact that the GSR delivers a continuous assessment, it also provides insights into characteristics of rock units that may not be evident from manual logging, where properties are assigned across discrete geotechnical units. Bed and defect boundaries are also highlighted through the process.

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