Coal Operators' Conference

Faculty of Engineering and Information Sciences

2013

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GEOTECHNICAL MODELLING BASED ON GEOPHYSICAL LOGGING DATA

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ABSTRACT: Computer modelling of coal seams and their properties is standard geological practice for both underground and open cut mining. It is based on correlations of coal seams made between boreholes and the interpolation of relevant coal seam properties on the basis of the inferred coal seam boundaries. In the case of geotechnical studies, this same approach is not followed because there are insufficient geotechnical test results to form a basis for modelling and the geological models do not typically create boundaries for interburden rock types. Instead, geotechnical models tend to be based on coal seam geological models with test results shown as point data in the interburden intervals. This situation can be improved if geophysical logging data are used as the basis for geotechnical modelling. Appropriately analysed, these logs provide continuous measurements of lithological and geotechnical properties. In the case of natural gamma data, an analysis to show the variations in clay content allows sandstones to be separated from finer grained siltstones. If geophysical strata rating values are determined from the geophysical logs, they provide a measure of rock quality. From these analyses, 3D models showing interburden properties as well as boundaries of the relevant rock types can be created and used as a basis for mine design and control of geotechnical hazards.

INTRODUCTION

In both underground and open cut coal mines, there is a need for on-going developments in technologies which allow management of risk and the maintenance of high levels of productivity. In this paper an approach to the characterisation and modelling of rock masses using conventional borehole geophysical logs is described.

At many coal mines, geophysical logs, primarily natural gamma, density and sonic logs are obtained in most exploration boreholes. These geophysical logs provide objective measurements of rock properties which are at great detail. Two useful rock properties that can then be derived are the clay content, which indicates basic stratigraphic variations between rock types such as sandstone and siltstone, and the Geophysical Strata Rating (GSR), which is a measure of rock quality.

Within a borehole, the geophysical logs are usually acquired at cm intervals. These more than adequately sample the vertical variations in the geology. Provided also, that the exploration boreholes are spaced at intervals which adequately sample the lateral variations in the geology (typically at spacings of a few hundreds of metres), the geophysical results can be modelled in 2D and 3D to provide a view of the lithological and geotechnical properties of the strata that are present.

GEOPHYSICAL LOG ANALYSIS

Through ACARP funded research, an approach to the analysis of geophysical logs that allows robust estimates of the porosity, clay content and rock quality within a borehole has been developed. The porosity is best determined using density logging results and clay content can be determined from a natural gamma log or from neutron porosity or resistivity logs, provided the density porosity is also available. In the case of the rock quality, the GSR provides a measure which is based on depth corrected sonic logging data and the values of the clay content and porosity obtained from the other logs. Hatherly *et al.* (2009, 2010) provide more detailed accounts of the approach to geophysical log analysis and the basis of the GSR. An example of the results that can be obtained are shown in   Figures 1 and 2.

Figure 1 shows a suite of geophysical logs from a borehole at an open cut mine and their geological interpretation. Two coal seams are present. These can be readily identified as the intervals where there are low densities, low natural gamma responses and low sonic velocities. The boundaries of the coal

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seams can be accurately picked from the density log. Values of about 1.95 t/m^3 typically represent the upper density limit for a coal seam.
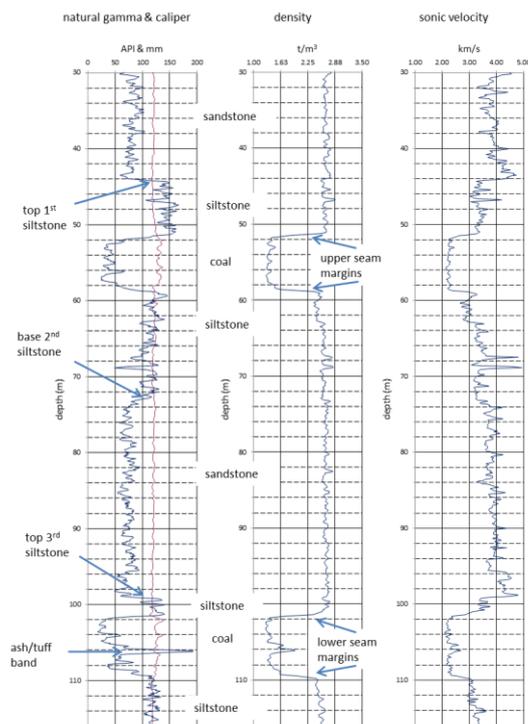

Figure 1 - Example of geophysical logs obtained from an exploration borehole. These logs allow identification of the major rock types present - coal, sandstone and siltstone. A tuff band is also present in the lower coal seam.
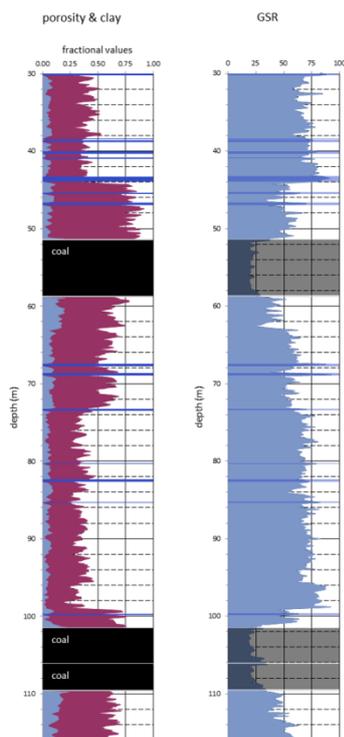

Figure 2 - Interpretation of the geophysical logs from Figure 1. On the left, the porosity is shown in blue and the clay content is shown in red. The clay content is lower in the sandstone than in the siltstone. GSR values are higher in the sandstone than in the siltstone.

Both coal seams are bounded by layers of siltstone. Siltstones typically have higher natural gamma signatures than coal and sandstones. The boundaries between coal and siltstone, and siltstone and sandstone can be sharp or gradational, but in the case of the data shown in Figure 1, the siltstone boundaries are reasonably sharp. The regions with relatively low natural gamma signatures represent sandstone. The actual value may depend on whether the sandstone is quartz rich or more lithic. In the case of lithic sandstones, the individual rock grains can be clay rich and create a situation where the natural gamma response is higher. Another feature of the natural gamma log in Figure 1 is the spike that occurs in the lower coal seam. This spike is due to a tuff band in the coal seam.

The sonic log values show the expected behaviour. As demonstrated by McNally (1990) and Ward (1998), sonic velocities can be empirically related to UCS. In Figure 1, the coal seams have the lowest sonic velocities and are weakest, the siltstone layers identified on the natural gamma logs have intermediate sonic velocities and intermediate strength. The sandstones have the highest velocities and are strongest. Occasional sharp spikes in sonic velocity and density are due to siderite bands.

Figure 2 shows the interpretation of these logs. The porosity and clay contents are derived from the density and natural gamma logs. The GSR values are derived using the procedure described in Hatherly *et al.* (2009 and 2010). The main features in the porosity and clay interpretations are the higher proportions of clay in the siltstone units and the higher porosities in the siltstones at the base of each of the coal seams. These higher porosities are possibly indicating that the siltstones beneath the seams are carbonaceous and, as a consequence, the overall density is lower. As far as the GSR determinations are concerned, the coal has a GSR of about 20, the siltstones have GSR values in the range 40 to 55 and the sandstones have GSR values of about 55 to 80.

MODELLING

Given the detailed information on rock properties that can be obtained from the geophysical logs, interpolation of the data between holes allows development of 2D and 3D models of the subsurface. However, it is first necessary to provide guidance as to how the various layers are linked between the holes. If this is not done, a result such as that shown in Figure 3 might be obtained. Here, a 2D section which passes close to 4 boreholes (including the borehole used for Figures 1 and 2) is shown. The section line is in the dip direction and it is clear that the interpolation has not been able to link the geology between the holes.
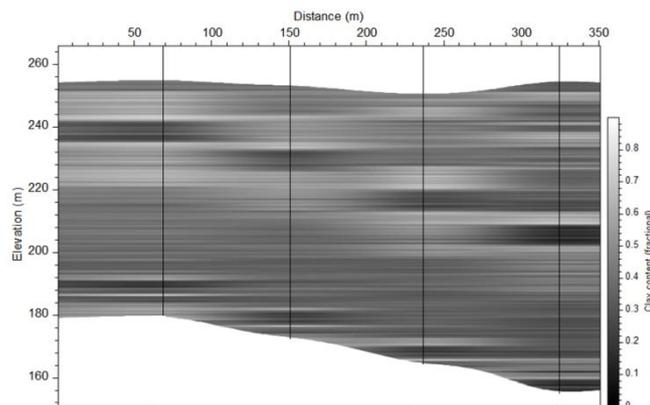

Figure 3 - A model of the clay content determined without any guidance as to how the layers present in the four boreholes should be correlated. In this section, the coal seams should be dipping from left to right. Without guidance, the coal seams show step-like structures which are clearly incorrect.

As shown in Figure 1, the layering and the positions of the boundaries can be established through an examination of the geophysical logs. If the position of the main boundaries is determined in each hole and then interpolated between boreholes, these can be used to provide guidance for the modelling.

Figures 4 and 5 illustrate the process. In Figure 4, the layer boundaries were picked in each hole and then interpolated between the holes. Each boundary was established independently. They can then be used

to constrain the interpolation of the geophysical parameters between holes. In this 2nd stage of the process, only the data from between the boundaries in each of the boreholes is used when interpolating values for that layer between holes.
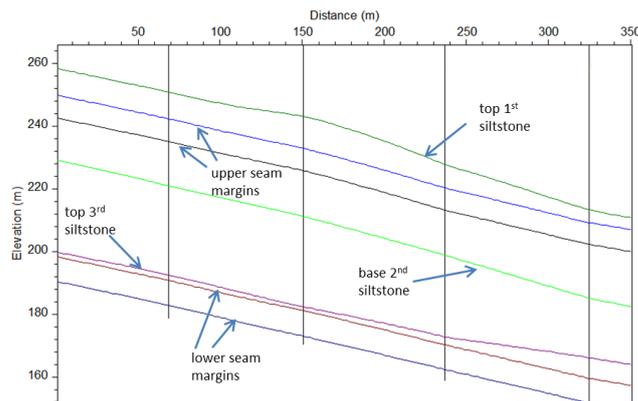

Figure 4 - Layer boundaries determined from geophysical logs from the four boreholes and interpolated between the holes. Once positions of the boundaries are established, they can be used to guide the interpolation of the geophysical data between holes.
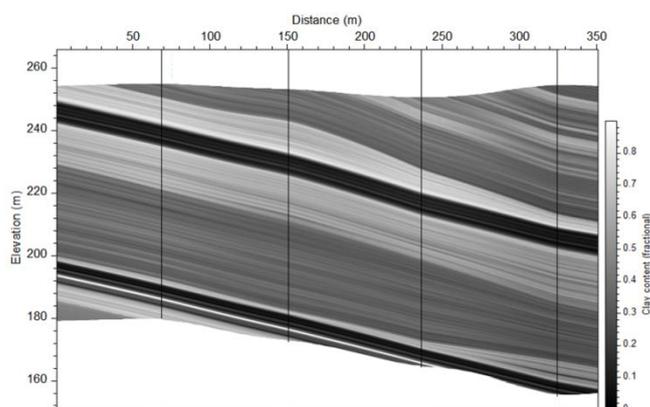

Figure 5 - A model of clay content for the same section as Figure 3 but with the layer boundaries of Figure 4 used to guide the interpolation of the clay contents determined in each borehole

Figure 5 shows the resulting model for the clay content. In contrast to Figure 3, the layering is continuous and it can be seen that the values of the clay content assigned to each layer is properly representative of the layers. Furthermore, within the layers, subtle variations in the clay content are propagated between holes. Given that the geophysical data is being honoured at the boreholes, this indicates that within many rock units, there are numerous consistent geophysical features present in adjacent boreholes. The lateral variability in the rock units can thus be explored in considerable detail.

When the GSR is modelled along the same section line, the results shown in Figure 6 are obtained. As shown in Figure 2, the coal seams have low GSR values, the siltstones have the intermediate values and the sandstones have the highest values. As with the model of the clay content, subtle features in the rock quality are also propagated between holes.

Figures 4, 5 and 6 all show results in 2D section view. If the modelling is conducted in 3D, sections can be created along arbitrary lines and data can be examined in plan view. Plan views can be particularly useful if values are taken parallel to a horizon of interest, as might be the case where there is interest in the rock properties at a certain interval within the roof or floor strata of a coal seam.

An example of a result in plan view is shown in Figure 7. This shows average GSR values for a 6 m interval immediately above the lower coal shown in the previous figures. Also shown on Figure 7 is the position of the profile line for the 2D sections. It can be see that the region of lower GSR on the right of

Figure 7 coincides with the region to the right of Figure 6 where the siltstone overlying the lower coal seam is thicker. Plan views therefore provide an indication of the lateral extent of the units of interest.
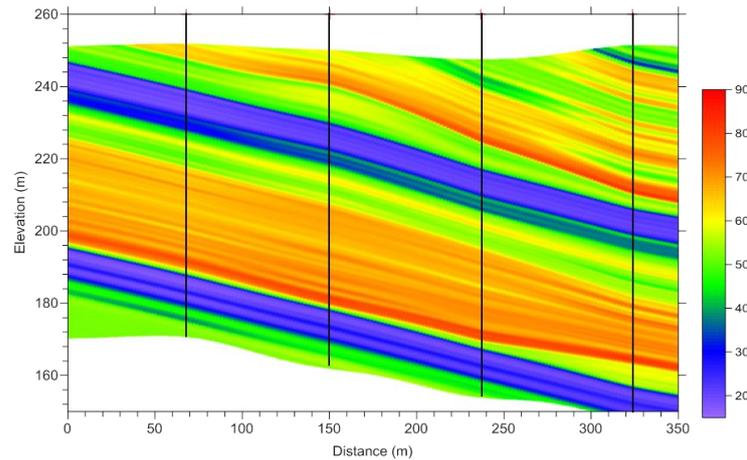

Figure 6 - The GSR model for the same section as Figure 5. Again the layer boundaries of   Figure 4 have been used to guide the interpolation of the GSR data between holes.
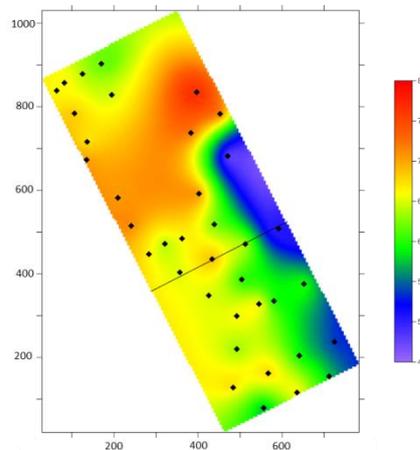

Figure 7 - GSR data in plan view, taken from a 3D model which covers the region of the section line in Figures 3 to 6. The GSR values shown here are averaged over a 6m interval, immediately above the lower coal seam. The section line for Figures 3 to 6 is shown by the thin line. Diamonds indicate borehole locations. The region where the siltstone forms the main part of this interval has lower average GSR values. The region where sandstones predominate has the higher values.

DISCUSSIONS

The approach to geotechnical evaluation described in this paper has the advantage of being based on objective geophysical logging measurements. It also draws on the extensive database provided by exploration drilling programs and the geophysical logging that is undertaken in those holes. Once established, the models of GSR and other petrophysical parameters provide a context for geotechnical observations from core testing, logging and monitoring. They facilitate the development of good geotechnical understanding.

Applications that exist in both open cut and underground mining include:

- Highwall design and the understanding of highwall failure.

- Blast design.

- Predicting and understanding floor heave.

- Longwall caving behaviour.

- Determining roadway support requirements.
- Preparation of hazard plans.

More industry-wide experience is required for these applications to develop. Research is working towards developing tools that allow direct quantitative use of the approach in specific mine design problems. It is hoped that in future years, 3D geotechnical modelling will become just as much a part of the mining process as geological modelling is today.

CONCLUSIONS

Australian coal mining is accustomed to conducting geophysical logging in exploration boreholes. As aresult, a very large database of geophysical logs is available at most mines. Through a quantitative analysis of these logs and determination of GSR values, it is possible to create 3D models of the subsurface which contain detailed information about the occurrence and properties of the strata that are present. These models allow an unprecedented view of geotechnical conditions and have numerous applications in both open cut and underground mining.

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