Assessment of development roadway roof conditions at an operating underground coal mine using neural network analysis

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ROOF CONDITIONS AT AN OPERATING
UNDERGROUND COAL MINE USING NEURAL
NETWORK ANALYSIS

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ABSTRACT: Considering that the majority of Australian longwall mines are currently roadway development constrained, understanding of the key geotechnical parameters that determine the roadway roof behaviour is often critical to the success of modern longwall operations. Crucial to improving this understanding is geotechnical characterisation. This process typically evolves with time and experiences at any underground coal mine and is necessary to understand the variation of the rock mass across a mining area. Based on local experience it is possible to improve forecasting of how similar geotechnical areas will behave and subsequently, the types and densities of support required to maintain roadway serviceability.

There are numerous methodologies to characterise a rock mass and determine geotechnical domains using site-based data, which can vary from a simplistic single variable back analysis to more complex multivariate approaches. In a relatively isotropic and benign roof environment, simplistic models have been proven to be effective to provide an acceptable understanding of the change and variability in the rock mass and associated roof behaviour. However, with more challenging, weaker rock masses, where there are multiple independent features driving roof behaviour, the more complex statistical based back analysis approaches are more appropriate in order to accurately define different geotechnical domains. In this case study at Grosvenor Mine, a novel application of complex multivariate statistics in the form of a neural network analysis is shown to provide a useful and significant improvement in forecasting of the as-mined roadway conditions. This example indicates that in complex and challenging geotechnical environments, the application of complex analyses to characterise and understand the ground conditions is a promising potential area of further research, particularly with the advances being made in artificial intelligence more broadly.

BACKGROUND

Grosvenor Coal Mine is located near the township of Moranbah in Queensland’s Bowen Basin, approximately 150km west of the coastal city of Mackay. Grosvenor (GRV) mine, as with three other longwall mines in the vicinity, extracts the Goonyella Middle Seam (GMS) and has a mine life in excess of 25 years. The GMS ranges in thickness from 4.2 to 5.6 m thick across the GRV lease which is at the lower end of the thickness spectrum of existing GMS mines. Conventional underground development commenced in 2014 following completion of the mine access drifts with a tunnel boring machine. The ground conditions experienced at GRV have been highly variable, with certain areas proving challenging to develop due to weak rock masses and stress driven roof deformation, which is not typical of existing GMS longwall mines. The deformation usually occurs soon after development, biased to the central portion of the roadway and is typically in the form of a buckling immediate roof with associated centreline cracking, roof bagging/sagging, and elevated levels of roof extensometer Tell-Tale (TT) displacements. This deformation is typically experienced in the Cut Throughs (C/T), due to being adversely orientated to the major horizontal stress. In contrast, the headings are orientated almost parallel

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to the major horizontal stress, with improved conditions experienced as a result. Examples of typical C/T roof deformation and Tell-Tale (TT) displacement are illustrated in Figure 1 and Figure 2.

Figure 1: A Typical C/T deformation

Buckling of centre span and associated centreline cracking and roadway sagging

<100mm coal beam revealing weak/jointed carbonaceous siltstone unit

Figure 2: A Typical C/T displacement vs time

Prior to commencement of mining at GRV, initial geotechnical characterisation was based on the geological distribution of coal plies and seam splits, as the adjacent Moranbah North mine had encountered significant ground control difficulties in the vicinity of an upper seam split. This seam split was also present at GRV across a broad area referred to as the seam split zone. The GMS at Grosvenor is made up of five main plies, moving sequentially from ply-1 to ply-5.
starting at the top of the GMS. In the seam split zone, ply-1 gradationally splits away from the remainder of the GMS, up to a maximum of 5m above the ply-2 with carbonaceous stone interburden between the plies. As such, where ply-1 is logged more than 200mm away from the GMS, it is classified as “Domain A”. Domain A trends across the centre of the lease in a broad NWN/ENE direction, with the areas outbye and inbye classified as “Domain B Shallow” and “Domain B Deep” respectively (see Figure 3) implying a similar geotechnical environment either side of Domain A.

Figure 3: Grosvenor geotechnical domains

After several kilometres of development had occurred in all three geotechnical domains, it was observed that the original boundaries did not correlate as strongly as expected with the ground conditions experienced. As mining progressed and more experiences were gained, several key variables were identified that determine the development roof behaviour other than the distribution of coal plies. As such, a project was instigated to review the available data with a view to incorporating these factors into defining the geotechnical domain boundaries. Although several factors had been identified, the variables were independent of each other, and the combined influence of each on excavation behaviour was a complex interaction. In an attempt to cater for this complexity, a statistically based Neural Network (NN) analysis was tested. Within a NN, algorithms are used via machine learning to define a relationship between the identified variables and the outcome (development roadway roof behaviour).

NN’s are currently widely used across a range of different industries to establish patterns and relationships in datasets as a form of artificial intelligence with the use currently expanding at an exponential rate in conjunction with the expansion in collation and storage of data. Existing examples include international airlines analysing past food consumption and using NN to predict food usage on long-haul flights thus allowing for optimisation of food inventory and minimising fuel burn. Another everyday example is banks detecting fraudulent transactions based on past purchasing habits. Although growing rapidly in other industries, and no doubt being developed in house at many large organisations, there are currently only a few published examples of NN’s utilised in mining applications. A relevant example was developed by Rankine (2004), in which a NN was produced for the prediction and optimisation of cement backfill at BHP’s Cannington Mine in north-west Queensland. Broadly, the benefit of a statistical machine learning based approach, such as NN, to understanding datasets is that instead of computers being given explicit instructions on how to analyse data, i.e. closed form, they are given a set of rules. This allows self-training and the ability to iteratively learn from datasets and gain insight
that would otherwise remain hidden. The potential for finding additional insight is ongoing as further data is collected over time and incorporated into the NN (ADL, 2018).

MODEL PARAMETERS

Overview

The premise for parameter selection is to be as least subjective as possible to drive repeatability and consistency into the project. As the final model is aimed at forecasting difficult roof conditions in development, three potential measures of outcome were explored. The first was a qualitative estimation of the roof conditions, i.e. good, moderate or poor. However, as these measures are highly subjective, it was disregarded. A rating system was also considered, based on several observable features such as excessive extensometer movement, centreline cracking, both presence and magnitude, TARP level, etc. However during the project it was also identified that the identification of these features still introduced unsuitable levels of subjectivity into the data gathering process.

The third option, and that selected for use as the sole dependent variable (outcome in the NN), is total roof extensometer displacement. It is acknowledged that there are certain limitations when using roof extensometer data as an indicator for roof behaviour, including; installation quality with respect to monitoring height and anchorage, anchorage slippage, absence of lateral displacement (shear), variance in instrument placement (location in roadway in relation to where deformation is occurring) and lack of insight into the failure mechanisms due to a single data point. However, as GRV has a very high density of monitoring devices (approximately 25 m spacing), and subsequently a large number of data points, it was hypothesised that meaningful relationships can be determined, and obvious outliers identified and addressed, despite these limitations.

Based on the experience at Grosvenor and Moranbah North Mines, the following six independent variables have been identified as influencing roof deformation (convergence):

- Roof unit thickness
- Primary roof bolt length
- Long tendon type
- Long tendon spacing
- Roof Unit 1 composition
- Roadway stress environment.

All the above parameters are readily available from existing downhole geophysical logs, underground mapping, rock mass characterisation, engineering calculations and geotechnical design. As such the model can be developed, implemented and updated without the need for a significant amount of additional work to be performed or specialist skills.

Roof unit thickness

Due to the range in seam thickness and nominal development cut height (3.6 m), the immediate overlying strata above the working section at GRV comprises of coal (plies 1 and 2 of the GMS) followed by a transitional sequence of carbonaceous mudstone and siltstone into bedded siltstones and sandstones. The thickness and composition of the immediate roof changes significantly across the lease in geological terms; however, by utilising physical measurements from borehole geophysical logs, three discrete geotechnical units (ROF1, ROF 2 and ROF3) can be readily determined. Using physical measurements, rather than geological logs which may vary between geologists based on logging, much greater consistency is achieved.
Although in reality the excavation height will range between 3.6 m to 4 m above seam floor, for standardisation, the cut profile has been selected as 3.9 m above the GMS floor for determining the base of ROF1 (cut roof horizon). This assumes 0.3m of coal left in the floor which is the targeted development horizon at GRV.

ROF1 refers to the “clean” coal overlying the cut profile and is identified where the density log is relatively low and consistent (<1.5 g/cm³). The thickness of ROF1 displays a typical pattern of variation along the gateroads, initially approximately 0.6 m thick (Domain B Shallow), thinning to less than 0.1 m in areas in the centre of the gateroads (Domain A), before thickening to >1m at the inbye end of the panels (Domain B Deep).

Above ROF1 lies ROF2, a mainly carbonaceous siltstone which is transitional in nature and characterised by weak contacts between units. This unit is typically highly bedded and laminated, and forms a weak rock mass, evidenced by both low material strength (uniaxial compressive strength or UCS) and diametral point load strength. This also varies significantly in thickness along the gateroads, showing a typically inverse relationship to ROF1. Generally, where ROF2 is at its thickest (> 3m), ROF1 is at its thinnest. It is within this zone (Domain A) that the most challenging roof conditions are encountered in development. As the thickness of both ROF1 and ROF2 appear to correlate well with experienced conditions, they have been included as independent variables for the model. An example of the picked ROF units can be seen in Figure 4 from borehole DDG190R.

![Figure 4: Picked roof units](image)

The variation in these ROF units across the GRV lease is readily determined from the geophysical logs. Figure 5 through Figure 7 show a representative borehole log (density, sonic derived UCS and gamma) from each of the geotechnical domains at GRV. Note the variability in ROF thickness for each domain. While the evolution of the ROF units has continued over
time, it is evident that other variations of note occur in each domain, essentially creating sub domains, however these have not yet been incorporated into the NN.

**Figure 5: Geophysical logs (Domain B Shallow)**

**Figure 6: Geophysical logs (Domain A)**
One variation worthy of note is the change in gamma response for ROF 1 between Domain B Deep and Domain B Shallow, with Domain B Deep having a much lower response. This is mainly driven by the banded nature of the coal in Domain B Shallow and “clean” coal in Domain B Deep, indicating that the domains are not similar, in both lithology and behaviour. A thick clean coal beam is associated with increased roof stability at all GMS mines and GRV is no exception to this characteristic. The gamma content of the coal is discussed further below. Figure 8 and Figure 9 show the thickness distribution of ROF1 and ROF2 respectively across the lease.

Figure 8: ROF1 thickness (m)
Various lengths of roof bolt have been utilised at Grosvenor. The initial bolt length was selected as 1.8m, however 2.4 m bolts have been utilised on install roads and in some particularly poor areas, and recently there has been a wholistic change to 2.1 m roof bolts. In general, it is recognised within the industry that the longer bolts will provide improved roof stability and behaviour, with the 2.1 m bolt length most common. However, individual sites must assess the benefits of a longer bolt with the disadvantages such as costs, equipment limitations (clearance, ergonomics) and the need for additional resin cartridge lengths to encapsulate a longer bolt.

The benefit of a longer bolt can be explained mechanistically with the following equation after Canbulat and Van Der Merwe, 2009.

\[
\tau_{MAX} = \frac{1}{2} \rho g \left( h + h_1 \right) L
\]

Where,

- \( \tau_{MAX} \) is the maximum shear stress within the bolted beam
- \( \rho \) is the density of material (kg/m\(^3\))
- \( g \) is gravitational acceleration (m/s\(^2\))
- \( h \) is the built beam thickness (m)
- \( h_1 \) is the height of softening (m)
- \( L \) is the beam width (m)

Increasing the bolt length will increase the built beam thickness (h), as such reducing the maximum shear stress within the bolted horizon. This concept is shown visually in Figure 10, which has been generated using a consistent height of softening of 5 m and a 5.4 m roadway width. Based on this assessment, changing from a 1.8 m bolt to a 2.4 m bolt can result in a reduction in maximum shear stress by 18%.
Long tendons

Two distinct types of cable bolts have been utilised at Grosvenor, due to varying strategies of strata control. The first type was an 8m end anchored cable bolt, with the top 2 m resin anchored and the bottom 2.5 m near the collar post grouted, leaving a 3.5 m free length in the cable. Due to the free length in the bolt, it behaves as a softer support unit accommodating greater levels of roof movement for the same applied load. The other type of cable that is now routinely used is an 8m full column grouted cable bolt. This type of cable is the most commonly used for roadway development in Australia. This is an active, stiffer support unit due to the fact that the cable is tensioned with resin on installation and the remaining length of the cable is encapsulated with cementitious grout post drivage.

As each cable is designed to control the roof by different methods, one aimed at accepting a higher level of roof movement, and the other trying to prevent movement, the installed cable type will have a significant impact on both the allowable tell-tale displacement and the magnitude experienced.

Long tendon density

Fundamentally the density of ground support installed based on spacing, length and capacity (ultimate tensile strength) has been shown empirically to have a positive correlation with roadway stability irrespective of the type of support utilised (Frith and Colwell, 2009). Based on the findings of Frith and Colwell (2009), a higher density of primary cables should provide a higher level of reinforcement, leading to lower levels of roof deterioration.

Roof unit 1 composition

As discussed previously, the current domain nomenclature implies that the areas inbye and outbye of Domain A are the same apart from cover depth. However, development experiences have proven that this is not the appropriate interpretation. Domain B Shallow which is present in the first 10 to 15 pillars of the first five panels is located at relatively lower depth of cover (180-250 m) and typically behaves favourably on development in the headings. However,
isolated cut-throughs have converged significantly (>50 mm). In contrast, Domain B Deep conditions are considerably improved in both headings and cut-throughs, despite the depth of cover being twice that of Domain B Shallow (350-420 m). As mentioned in the preceding section, although both domains have thick coal roof, upon further investigation, a significant difference in the composition of ROF1 across the lease is evident, with the Domain B Shallow ROF1 exhibiting significant clay banding that is not present in Domain B Deep. This banding and stone infill are variable and are likely to contribute to the variable behaviour of roadways in Domain B Shallow, i.e. increased delamination and roadway convergence. To quantify this difference, the median gamma value for ROF1 is determined. The gamma log is sensitive to the higher levels of radiation from thorium adsorbed by the clay minerals and potassium content. As the banding in the coal at Grosvenor is typically clay based, the gamma log provides a reasonable indication of how strong and persistent the clay banding is (Kansas Geological Survey, 2017). The median gamma content for ROF1 is shown in Figure 11.

![Figure 11: ROF1 median Gamma (API)](image)

Roadway stress

Intuitively, a weak roof environment at depth, such as that at GRV (low strength/stress ratio), is highly sensitive to changes in either parameter. To minimise the portion of roadway exposed to elevated levels of in situ horizontal stress, the gateroads at GRV are aligned approximately parallel to the major horizontal stress (033⁰), as such the cut-throughs are subject to higher stress concentrations in the roof and floor on development than the headings. This assumption appears to have worked in practice as even in the weakest roof areas, the headings experience far lower amounts of roadway deformation than cut-throughs, with total displacements >10mm rare compared with >50 mm common in the adjacent cut-throughs. As the magnitude of the horizontal stress acting across the roadway has shown to have a dramatic influence on roof behaviour, it has been included as an input for the model.

The following equation has been used to determine horizontal stress acting in each roof unit, after Nemcik et al, 2005:

\[
\sigma_H = \frac{\nu}{1-\nu} \times \sigma_v + E \times TSF_H
\]

(2)
where:

- $\sigma_H$ = Major horizontal stress (MPa)
- $\nu$ = Poisson’s ratio
- $\sigma_V$ = Vertical stress (MPa)
- $E$ = Young’s Modulus (GPa)
- $TSF_H$ = Tectonic stress factor for major horizontal stress component

The values for $\nu$ and $E$ for ROF 1 and 2 have been determined based on averaging site wide laboratory data. There is some level of variability for these values across the lease, however for simplicity the mean of each ROF unit is used. After determining the mean stress acting in each unit, a weighted average in the bolted interval was calculated to determine the ratio of the major and minor horizontal stress to vertical stress. Once these ratios were calculated, it was possible to determine the total magnitude of the horizontal stress acting across each roadway orientation using the following equation, as summarised by Hoek, 1980:

$$\sigma_R = \frac{\sigma_H + \sigma_h}{2} - \frac{\sigma_H - \sigma_h}{2} \times \cos(2\beta)$$

(3)

where:

- $\sigma_R$ is the resultant horizontal stress
- $\beta$ is the difference in orientation between the roadway and the major horizontal stress

After calculating the horizontal stress for each roadway analysed, a graph can be produced showing resultant stress against depth of cover, to gain useful insight into the distribution of stresses in both headings and cut-throughs, for the expected variation in the ROF unit thickness. This can be seen in Figure 12.

**Figure 12: Resultant roadway stress along gateroads**

The graph above shows that there is a gradual increase of the stress with depth of cover, however the trend begins to reverse at the ~350 m mark despite cover depth continuing to increase inbye. This observation coincides with a thickening of the less stiff ROF1 unit from Domain A to Domain B Deep, with the lower modulus coal attracting less stress, resulting in a lower resultant stress value. This lower level of stress applied to ROF1 is suspected of contributing to the improved conditions in the inbye areas of the gateroads (Domain B Deep).

RESULTS
Model fit

A total of 139 cases were used to develop the model using the NN approach. This consisted of 111 training cases and 28 cases to test the model on. The utilised software provides inbuilt analytical tools to identify the quality of the model generated in order to determine how accurately the dataset can be represented by a given model.

For the testing cases, mean absolute error was 4.2 mm with a standard deviation of 5.2 mm. This is a relatively good fit, indicating that on average the model can predict the values from the testing database within 4 mm, and that a meaningful relationship has been developed between the indicator variables and the dependent variable (total tell-tale displacement). This relationship is illustrated in Figure 13.

The red line represents a perfect case of actual tell-tale movement equalling predicted, and the blue line the trend of the data set. The correlations are very similar, although the predicted tell-tale movements tend to be lower than the actual for elevated levels of displacement (>50 mm). This may be due to the limited data points at higher overall displacements and suggests that the model may somewhat underestimate at higher displacement levels. It is noted that as the roof displacements gained from this model are currently used to identify different geotechnical domains, it is assessed that minor variations will be managed in the development TARP.

Although this analysis is useful for determining model fit, it does not suggest how accurate it is against points outside the training database. As such, the software also runs an analysis on the predicted vs actual for the testing cases, which were excluded from training the data set. This can be seen in Figure 14.

![Figure 13: Predicted vs Actual TT movement (training cases)](image-url)
This graph shows a similar trend as Figure 13, with a reasonably close relationship at the lower tell-tale movements, however, the predicted displacement again tends to be lower than the actual at the higher levels. The residuals of this data set can also be plotted, which shows quantitatively the errors in the model based on actual data, as displayed in Figure 15. The residual refers to the difference between the actual and predicted values. The higher the residual, the further the predicted value is from the actual, and provides an indication of the model's precision.

The above figure shows that in 75% of the cases the residuals are less than plus/minus 10mm of the actual measurement. At the higher magnitude displacement levels, i.e., in the remaining 25% of the cases, the residuals lie between plus/minus 20mm of the actual. Based on the preceding graphs and analysis, it is reasonable to conclude that the model is suitable for the purpose of identifying different domains that are likely to be subject to higher levels of deformation in comparison to other areas.
Modelled Tell-tale Data

Long sections for two gateroads have been generated, comparing the maximum cut-through tell-tale displacement to the modelled tell-tale data.

![Figure 16: Maingate 102 long section](image)

![Figure 17: Maingate 103 long section](image)

It is evident from these long sections that there can be significant localised variation between adjacent cut-throughs in terms of total displacement that the model cannot replicate. The cut-throughs are typically 125m apart, and it is clear from the tell-tale data that the overlying lithology and/or other operational factors vary over this distance. Borehole spacing, which is what 4 of the 6 indicator variables are based on, are often spaced further than 125m. This is a limitation for capturing the localised variations occurring in the rock mass at this scale and subsequently limiting the precision of the model.
The Maingate (MG) 102 long section also confirms the observation in the previous section that the high levels of tell-tale movement do not appear to be repeatable in the model. Yet the model does show a distinct zone of elevated displacement consistent with the actual data within Domain A, indicating that different zones can be identified with the predicted values.

The overall trend for both panels of actual vs. modelled displacement are reasonably similar, indicating that the model could be used to identify zones at increased risk of high levels of roadway convergence prior to mining.

**Tell-tale displacement prediction in MG104**

The predicted tell-tale displacements for the entire length of MG104 can be seen in Figure 18, with the actual data plotted in blue up until ~2600m chainage (CH). Note that at the time of the model development, the face chainage was approximately 900m. The model indicated that the roof conditions were expected to be reasonably consistent until approximately CH1500m (close to 15 C/T), where a sudden increase in roof convergence was expected. It is considered that this increased convergence will be driven by a combined effect of the thickening of ROF2, thinning of ROF1, and increase in horizontal stress in the immediate roof due to the higher stone content. The elevated levels of displacement were expected to continue to approximately CH2400m (23 C/T), where the model predicts a significant reduction in roof deformation, largely based on a thickening of the ROF1 unit. Pragmatically this analysis would suggest that poorer conditions and more frequent TARP triggers would be expected also from 1500-2300CH, as well as likely poorer conditions in the gate end roadways during LW retreat.

It can be seen that the actual vs modelled tell-tale displacement varies rather significantly in magnitude in the identified weak zone. However, the underground observations closely matched the forecasted conditions as stated above, in that between 15 C/T and 22 C/T, significant deterioration was observed, with frequent TARP responses and additional support required to maintain roadway serviceability. Again, this confirms the previously stated findings that the model cannot replicate exact tell-tale displacement magnitude or variability, however it can correctly forecast the poor zones typical to Domain A along the gateroad length.

![Figure 18: MG104 long section (actual vs modelled TT displacement for C/Ts)](image)

**CONCLUSIONS**
Based on the analysis detailed above, this project has successfully defined a relationship between a set of independent variables, and the total recorded displacement of a roadway under development loading conditions with the total displacement used as a proxy for ground conditions. This model is based on actual data from an operating underground mine site and has been successfully used to improve the forecasting of tell-tale displacements in future roadways at this mine site. This allows for improved operational planning that otherwise would not be possible based on existing methods of geotechnical characterisation. As with any system that incorporates actual data, this NN model can and should be updated as additional information becomes available.

It is found that the model’s accuracy is acceptable. However, at the higher ends of the predicted tell-tale movements, the model somewhat underestimates the displacement. As such, the model should not be used to assess the exact displacements in a roadway under given conditions. It is recommended that this model should only be used as another tool to identify geotechnical zones within panels that are likely to encounter more difficult ground conditions in comparison to other areas. These zones can be used in lieu of the existing geotechnical domain boundaries. Improved ground characterisation when communicated to the workforce clearly prior to mining, will increase the likelihood of the appropriate support densities and TARP responses being implemented, while also assisting the mine planning process to predict cut rates that reflect realistic targets.

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