## Experience in the Application of Computer Modelling to Coal Mine Roadway Design in Weak Rock

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**Abstract:** A summary of the weak rock failure process is presented to demonstrate the application of computer modelling to coal mine roadway design.

The weak rock failure mechanism was chosen because its discovery required a design tool (modelling) that was not bound by a preconception of the results. Modelling was used to decode the relative influence of the geological and geotechnical factors.

It is emphasised that computer simulation techniques are best applied in a practical sense if accompanied by field measurement and observation. The field measurements are used as both a means of validating the initial model and to confirm that actual events are within design expectation.

*Key Words*: computer modelling, roadway design, weak rock

## Introduction

Many of the geological and geotechnical factors contributing to the behaviour of a roadway can be measured with reasonable accuracy. However, it is the complex interaction of these factors that leads to a potential array of different failure mechanisms, demanding flexibility in reinforcement design and recognition of the most appropriate reinforcement strategy to employ.

This paper outlines field and analytical work leading to the discovery of a failure process operating in weak rock environments. A 'weak rock' case study is presented to demonstrate the application of roadway modelling as a design tool by the resolution of the various competing geomechanical influences.

The characteristic signatures of the weak rock failure process are discussed together with the essential prerequisites for the initiation and propagation of the failure process. Reinforcement and roadway design strategies are discussed.

## **Model Validation**

Model validation is the process by which the simulated roof and reinforcement behaviour is checked against the actual field behaviour. If suitable validation is achieved under known conditions, then predictions of behaviour under future loading conditions (during longwall extraction for example) can be made.

A range of field measurement, monitoring and observational data accompanies the initial development of a numerical model to simulate roadway behaviour. These include rock testing, extensometry, stress measurement, measurement of roof bolt behaviour and visual identification of failure processes.

The rock testing process includes determination of both the strength characteristics of the strata units and the strength properties of the bedding within each unit and the interfaces between units.

The field aspects used to check model validity include:

- Magnitude of deformation
- Height of softening into the roof.
- Depth of softening into the rib.
- Location of strain horizons.
- Maximum bolt loads.
- Distribution of bolt loads developed across the roadway.
- Failure mechanisms.

Some examples of model validation against actual field data are provided in Figure 1. The examples come from a range of geological environments and include investigations into bolt capacity and bolt length. More detailed discussion regarding the results from the weak rock environment is presented below.

Typical roof extensometer output from a moderate strength laminite roof is shown in Figure 1c. The process of strata failure through excessive horizontal stress, stress redistribution and new failure higher into the roof is well understood and well documented (eg. Gale et al, 1992). Validation of this type of failure process has been achieved on many occasions and includes correlation with extensometry, instrumented bolts and measurement of stress redistribution.

## Weak Rock Case Study

## Field Characteristics

## Roof Behaviour

The examples of model validation shown previously included extensometry and instrumented bolt data from a weak rock environment (Figure 1a) and for comparison, a typical moderate strength laminite environment (Figures 1c).

The major difference between the two is the height of softening versus roof displacement as shown in Figure 2. In weak roof environments, the height of softening can exceed 7m (the limit for a sonic probe extensometer) whilst the total roof displacement is less than 15mm. This contrasts with stronger roof environments



Fig. 1(a) – Modelled versus field behaviour – weak roof



i) Comparison of bolt capacity.



Fig. 1(b) - Modelled versus field behaviour - moderate strength roof



Fig. 1 (c) Modelled versus field behaviour - laminite roof

where at least 60mm of roof displacement would be expected before the height of softening reached these levels.

The disturbing consequence of this variation in behaviour is that 15mm of roof movement is not detectable to the naked eye, however experienced, whereas 60mm of movement would focus the attention of mine personnel (through visible deformation) and produce a remedial response.



Fig. 2 – Height of softening versus roof displacement, weak rock versus laminite roof

## Roof Bolt Behaviour

The monitored roof bolts from the weak rock environment (Figure 1a) exhibited low bolt loads in response to the low level of movement (<2mm) within the immediate roof. Essentially the immediate roof has remained intact and the reinforcement has not significantly contributed to the level of (in)stability achieved. This aspect was confirmed after an increase in bolt density did not change the height of softening or affect the total roof movement.

In contrast, the roof bolts have developed very high reinforcing loads in the moderate strength, high deformation roof. In this type of failure process, the reinforcement aspects such as bolt density and bolt capacity have a major impact on the final roof integrity.

## Visual Observation

Severe roof instability, often leading to collapse, over the area of investigation was restricted to driveage in one direction only. The driveage at 90° to the problematic roadways was excellent.

Anecdotal evidence from colliery personnel indicated that the only precursor to roof collapse was minor to moderate rib spall. The roof essentially remained flat prior to and even during collapse.

Most importantly, once collapse had occurred, a shear or gutter was observed in the roof approximately 1 to 1.5m into the rib. In other words, at some stage the gutter had developed beyond the ribline.

This is in stark contrast to typical failure in stronger roof environments where significant visible sag or other modes of roof deformation are often observed well before roof collapse. Guttering is usually observable within the confines of the original roadway opening.

# Summary of Field Characteristics of Weak Rock Failure

The measured and observed roadway and roof bolt behaviour requires that a model (numerical, theoretical or otherwise) of the weak rock failure mechanism must explain the following:

- What is the process that softens strata to significant heights (>7m, often up to 12m) whilst the total roof movement remains low (<15mm)?
- How does a gutter form beyond the confines of the original roadway opening?
- What is the significance of rib deformation prior to roof collapse?
- Why is the driveage direction of importance?
- Why don't the roof bolts have a more significant role?

The following sections outline the model established and addresses issues regarding the roadway behaviour under longwall extraction conditions and strategies to manage problematic conditions.

#### Weak Rock Failure Mechanism

Numerical modelling was used to help identify the most important issues regarding the weak rock failure mechanism and to determine the most appropriate strategies to manage problematic areas.

A roadway model was developed following measurement of rock property data (including the strength of interfaces), measurement of bolt load transfer characteristics (short embedment pull tests) and stress measurement.

Output from the model representing areas of strata softening developed on driveage is shown in Figure 3 (the figure is an excerpt from a video presentation shown at this conference). Note that softened strata could be either overstressing of the material itself or slip along bedding. Bolt loads developed are also shown.



Fig. 3 – Flac output of strata softening about the roadway on driveage – weak rock

The good correlation of the field extensionerry and roof bolt behaviour with the modelled results has been discussed under the Model Validation section.

Figure 3 reveals some important aspects governing the weak rock failure process, namely:

- A zone of bedding shear extends from the corner of the opening into the roof at a high angle (approximately 70° from horizontal).
- Another zone of bedding shear extends into the roof, initiating approximately 1m into the rib and extending into the roof at the same high angle, in an en echelon fashion.
- The rib has failed through overstressing and most importantly, predates the formation of the second zone of bedding shear.

The formation of the second and subsequent zones of bedding shear is the defining feature of the weak rock failure process. These zones of bedding shear develop and extend into the roof whilst the immediate roof (above the opening) remains essentially intact, complete with lightly loaded roof bolt system.

Under circumstances where the zones of bedding shear develop on both sides of the roadway and connect, a large trapezium shaped block of roof strata is created which can mobilise towards the opening. If rib softening is allowed to occur, then the trapezium shaped block can move directly down as an intact unit, finally collapsing as the rib is displaced. A gutter or shear would be observed beyond the ribline.

Figure 4 is an excerpt from the second video presentation showing the modelled behaviour during longwall extraction for the case where no secondary reinforcement was installed.



Fig. 4 – Strata softening anticipated during longwall extraction without secondary reinforcement – weak rock

The softening about the roadway during longwall extraction indicates the initiation of further zones of bedding shear higher into the roof (>12m) and further from the rib. Each successive deformation episode contributes to an 'en echelon' pattern of high angle zones of bedding shear.

## Weak Rock Failure Mechanism Summary

There appear to be two major requirements for this type of failure process:

- The rib strength must be significantly exceeded.
- The shear strength of bedding planes and weak interfaces in the roof strata must be significantly exceeded.

The concept is shown in Figure 5.



Fig. 5 – Prerequisites for "weak rock" failure mechanism

Factors that influence rib deformation can be grouped into those effects that increase vertical stress and those effects that reduce coal strength as listed below:

- Depth of cover.
- Structural fabric of the coal such as cleat.
- Roadway width.
- Behaviour of the roof strata.
- Proximity to goafs/other roadways.
- Roof/rib reinforcement.
- Redistribution of stress as a consequence of previous deformation.

Factors that influence bedding plane shear in the roof can be grouped into those effects that increase shear stress on the bedding planes and those effects that reduce shear strength as listed below:

- The roadway profile (rectangular or arched).
- Extent of rib softening.
- Proximity to goafs/other roadways.
- Roof/rib reinforcement.
- Redistribution of stress as a consequence of previous deformation.
- Water.

Note that both rib deformation and weak bedding planes or interfaces are required for this failure process. Zones of bedding shear will not develop beyond the riblines if the ribs are intact. Similarly, failed ribs will increase the likelihood of bedding shears developing, however the shear strength of the planes must be significantly exceeded.

A parametric study was undertaken using the roadway model to establish the sensitivity of aspects such as coal strength (affecting rib deformation) and bedding strength (affecting bedding shear propagation) on the failure process.

Any aspect that increases rib deformation (for example, longwall abutment or low capacity rib bolting) or any aspect that increases the shear stress on bedding planes will exacerbate the weak rock failure process.

It should be noted that the term 'weak rock' initially referred to a material of low strength. Under circumstances of high stress, a stronger rock may also exhibit 'weak rock' failure mechanisms.

# Weak Rock Reinforcement Strategies

The discovery of factors controlling the weak rock failure process provides a platform to develop suitable reinforcement and mine design strategies.

# Rib Reinforcement

The important function of rib reinforcement cannot be overstated. The post failure strength of the rib coal is highly dependent on the capacity and stiffness of the rib reinforcement system. Both the capacity and strength of the rib bolting system should be maximised and used in conjunction with a high capacity rib meshing system.

Low stiffness, low strength rib bolts may provide nominal skin restraint but would not be expected to reduce the depth of rib softening.

# Roadway Profile

The roadway model was used to evaluate the effect of an arched roadway profile on the development of the high angle zones of shear. The arched profile would be expected to reduce the magnitude of shear stresses on the bedding planes, particularly about the (old) corner area. The extent of softening about an arched roadway on driveage is shown in Figure 6. The results demonstrate that an arched profile would be expected to significantly reduce both the extent of rib deformation and the height to which the bedding shears would extend into the roof. Other variations of the arched profile were not studied, however this is considered to be an area of future research.



Fig. 6 – Softening expected about the roadway using an Arched profile

# Roof Reinforcement

The golden rule in reinforcement is to install the bolts where the action is happening. In these circumstances, angled roof bolts designed to intersect the zones of bedding shear would be considered an appropriate strategy. It is emphasised that under typical moderate strength environments, angled roof bolts may not contribute to roadway stability. Characteristic features of the weak rock failure process should be identified before applying this strategy.

Under circumstances where primary roof bolts are not expected to provide sufficient roof stability, there appears to be no alternative to longer tendon reinforcement. Again applying the golden rule of reinforcement, high capacity, high stiffness tendons installed in the area of strata softening would be appropriate. Individual requirements should be assessed on a site by site basis, using the roadway model to evaluate various long tendon strategies.

## Conclusions

Simulation of roadway and reinforcement behaviour has been successfully used over a wide range of geological and geotechnical environments. The simulation process is not restricted by any preconceived ideas for the failure process; this opens the way to the discovery of new failure mechanics.

The application of roadway modelling to the mechanism of weak rock deformation was invaluable. Whilst the general failure process may be deduced from field observation and measurement, the relative influence of the various competing factors could only be resolved through the modelling process. The failure process was found to be closely linked to the extent of rib deformation and on the shear strength/shear stress relationship of bedding and interfaces between geological units.

The field measurements (extensionerry and instrumented bolts) provided both a means to validate simulated behaviour against actual behaviour and also provided a means to establish if mining is within a weak rock environment.

An understanding of the failure process provides a basis to evaluate reinforcement and roadway design strategies. The roadway computer model fast tracks this process.

#### References

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