Rockbursts and Seismicity in Mines

Dynamic rock mass response to mining

Fifth International Symposium on Rockburst and Seismicity in Mines Proceedings

Johannesburg 2000

Technical Editors

Dr. G. van Aswegan
Dr. R.J. Durrheim and W.D. Ortlepp

Integration of deterministic modelling with seismic monitoring for the assessment of rockmass response to mining: Part I Theory

T.D. Wiles, R. Lachenicht and G. van Aswegen
p. 379-387

Integration of deterministic modelling with seismic monitoring for the assessment of rockmass response to mining: Part I Theory

By T.D. Wiles[+], R. Lachenicht[++] and G. van Aswegen[++]

Deterministic numerical modelling allows one to predict the rockmass response as a result of advancing mining. While the effect of geologic features such as faults or changing lithology can be readily incorporated into the model, often the location, orientation and behavioural characteristics of such features is uncertain. This can result in modelling results of low reliability and hence of limited use to mine operators.

This paper details the methodology of how seismicity can be used to identify and characterize critical flaws in our rockmass. Whether these flaws are critically oriented joints, or a local bends, waves or offsets in a fault, their location and behavioural characteristics can be quantified. Through the Map3Di direct back-analysis procedure, this technique allows us to bring our model to a state most representative of the in situ conditions observed via seismicity.

We can then incorporate the flaws into our deterministic model such that the behaviour characteristics of the flaws are calibrated to match the observed response. For example, we can build a model with a fault that has the exact heterogeneous shear strength distribution required to bring about slip distribution observed from the seismicity. From this state we have best chance of making accurate predictions that closely match in situ behaviour.

The accompanying paper examines the practicalities and potential benefits of this approach through study of several case studies.

[+] ISS International
[++] Mine Modelling Limited

Introduction.

Up until about 40 years ago, the only deterministic models available were for the design of simple columns, beams and cables. Engineering design was limited to gravity-loaded arches and buttresses. By combining these simple equations, numerical models for pin-jointed trusses and towers were developed. However, for any more complex shapes there was no alternative expect for expensive and time-consuming scale model testing.

With the advent of computers in the 1960's, deterministic numerical modelling tools rapidly became the primary design tool in all fields of engineering. It quickly displaced scale model testing almost out of existence owing to its flexibility and cost effectiveness. A very large number of designs could be examined at reasonable cost. This allowed for true engineering optimization of design. Without this tool it would not be possible to design modern bridges, cars, internal combustion engines, jet engines, aircraft, rockets etc. Deterministic modelling works, and works very well.

Note that in spite of this development, airplane wings still broke off, turbine blades snapped, and bridges collapsed. Close examination revealed that the most common form of failure resulted when a crack had grown to a critical size then propagated in an uncontrolled manner causing structural failure.

Deterministic modelling can be used to determine the exact circumstances required for failure. The critical crack size and loading conditions necessary for structural failure can be determined. Deterministic models can even be used to predict how fast cracks will grow and how long it will take for a crack to grow to critical size.

Never the less, deterministic models cannot predict when such a failure will occur. This is because cracks form from randomly distributed microscopic flaws under load. No two turbine blades will have the exact same random distribution of flaws. Hence cracks will form at different locations, different orientations and at different times. As a result, these cracks will grow to critical size causing structural failure at different times in the load history of the turbine blade.

It is the formation of these cracks from microscopic flaws is not a deterministic process, i.e. not predictable.

The only solution aeronautical engineers found to this problem was to conduct repeated detailed inspections to detect the formation of cracks. Once the cracks have been detected, their behaviour is reasonably predictable. Deterministic modelling can then be used to determine how long (this could be measured in number of loading cycles or time under load) it will take for a crack to grow to critical size. The only real limitation to safety is the cost of inspections. More frequent and more detailed inspections will prevent more failures, but at ever increasing cost and diminishing returns.

The fact that helicopters fly at all is a tribute to this technology. Helicopters are literally flying fatigue machines requiring enormous maintenance and frequency of inspection. However, without these inspections they would not be viable at all.

By analogy, one can consider rockmass response. Deterministic models can be used to make consistent reliable predictions. The mechanism of a rockburst is well understood and can be simulated. Deterministic modelling can be used to determine the exact circumstances required for a rockburst to occur. Certainly no one would deny that a rockburst is a deterministic event. Never the less, deterministic models do not seem to be able to predict when a rockburst will occur.

This is likely for the same reasons as above. By use of modelling one can determine that there is adequate stress to cause failure and sufficient energy available (low system stiffness) to drive a violent failure process. However, the exact time that failure will occur cannot be predicted: probably because this depends on random flaws in the rockmass. These flaws may be a critically oriented joint, or a local bend, wave or offset in a fault. Under the exact same conditions failures will occur at different times. At one location, the failure may occur early in the mining sequence due to some critical flaw, while at another location failure may occur much later in the mining sequence owing to a lack of a critical flaw. The real problem with accurate prediction is in identifying and characterizing the contributing factors.

We would like to be able to apply the same methodology used in the aeronautical industry. If we can detect and characterize flaws, then we are in a position to use modelling to determine if and when these flaws will become critical. The problem here is detection. In a wing strut or a turbine blade the location of important flaws is confined to stress concentration points and can normally be detected using some visual enhancement or x-ray technique. A limited number of critical points are responsible for the majority of failures. It is relatively easy to focus attention on these points.

In mining the problem is not so straightforward. Flaws are most likely embedded deep in the rockmass and distributed over a very broad area. It is probably hopelessly expensive to try to actively search for these. One hope is that microseismic activity will betray the presence of such flaws in some way.

Before pursuing this discussion further let's review the application of deterministic modelling in the mining industry.

Deterministic modelling in a uniform rockmass.

With recent advances in computer power and developments in modelling technology it is now practical and affordable to conduct complex mine wide simulations on desktop computer systems. Models can incorporate the combined effect of thousands of stoping units. Backfilling and structural support elements can be readily accommodated to any desired detail. Cracks, flaws, joints and faults of any desired size and shape can be accurately simulated.

Deterministic modelling works, and works well in other engineering fields. The author firmly believes that accurate predictions can be made in the mining environment provided that all contributing man-made (mine openings) and geologic (faults and lithology) features are incorporated and properly characterized.

Mine openings probably make the largest contribution to the rockmass response. Fortunately these are generally well known and can be readily incorporated into a suitable model.

It is readily demonstrated that for a competent rockmass under fairly uniform conditions that the rockmass can be characterized via systematic back-analysis. With sufficient calibration, the variability of the rockmass can be quantified and predictions can be made with consistent known reliability at least as good as the inherent rockmass variability.

To reinforce this concept let's consider a real example (Wiles, 1998). Consider several pillar bursts that occurred at Inco's Creighton Mine over several years of mining. For each rockburst, a Map3D numerical model was run to determine the stress state at the time and location of the burst. If we plot all of these stress predictions on a set of σ_1 versus σ_3 axes we obtain the following.

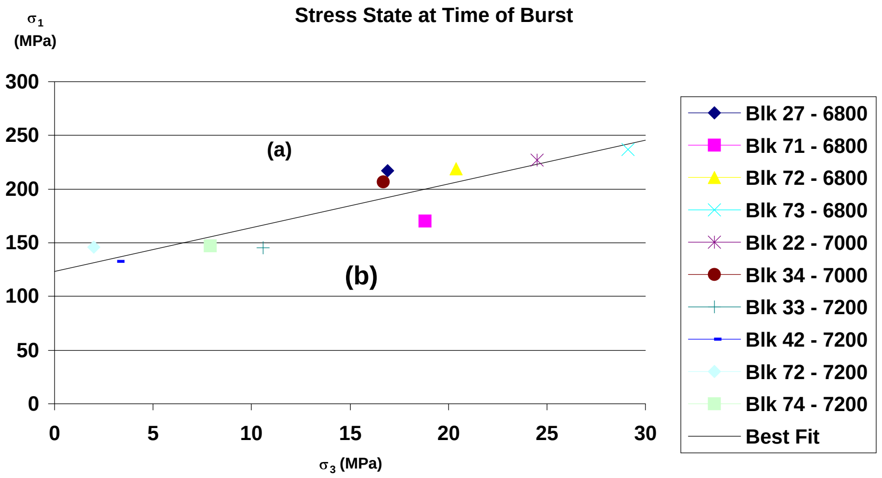


Figure 1 - Correlation between the stress state at the time of each burst and a simple linear strength criterion.

This figure illustrates that there is a strong correlation between the stress state at the time of each burst and a simple linear strength criterion. The coefficient of correlation of this data is 0.90. Let's state this in a different way. If you calculate the difference between the stress state for each pillar and the best fit line, then take the mean of these errors, you find that the mean error in prediction of σ_1 is approximately 14 MPa. This gives a coefficient of variation of about ±7%.

It is evident that for this particular example, the stress state predicted from numerical modelling is a very reliable predictor for the time and location of pillar bursts. Certainly you would not expect pillars with stresses states (a) or (b) to burst at this point in the mining sequence. Simply because they are a lot more than 14 MPa away from the best fit line. In the actual mining, many pillars achieved the indicated stress state without bursting. Some of these yielded non-violently simply because there was insufficient energy available to drive a violent failure process. This was indicated by a high loading system stiffness (low local energy release density) at these locations. Others probably yielded with the blast and hence were not classified as bursts.

This type of calibration is not a trivial exercise. Many back-analysis examples must be investigated and modelled. The variability of the rockmass must be quantified. This requires a large amount of engineering effort. Note that the back-analyses constitute a test of the reliability of the predictions. It is through these back-analyses that the quantitative reliability is established. This does two things for us: it gives us a calibrated model to make forward predictions with, and through repeated back-analyses allows us to test how well our model matches previously observed behaviour.

Model calibration through back-analysis gives us the confidence to make forward predictions with an assured reliability.

If some still have a problem accepting the idea of reliability of predictions let's take this same data one step further. The above data was collected during the silling out phase at each level of the mining. Subsequent to this, the mining progressed in a series of 4.6 m high horizontal cuts forming a crown pillar with ever diminishing size. As the crown pillar became narrower, the stress increased until is failed. Owing to its size, the failure generated a magnitude 3.6 seismic event and resulted in ground displacement of more than 200 m^3.

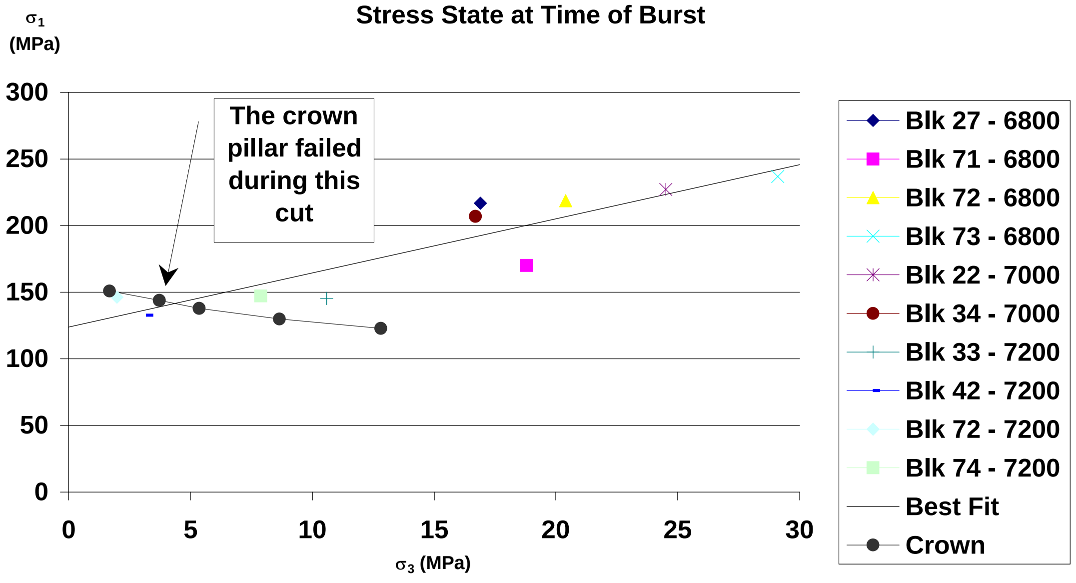


Figure 2 - Crown pillar failure prediction.

An obvious question is "can the strength characteristics determined from the silling be used to predict when the crown pillar will fail?". By superimposing the stresses in the core of the crown pillar on this data we see that the failure occurred exactly as the stresses in the core of the pillar crossed the strength envelope determined from the sill pillar back-analyses.

Although this back-analyses calibration process is expensive and time consuming, it works very well. This constitutes the state of the art in the application of deterministic modelling to rockmass response predictions. It is really an application of the tried and true "observational approach to design".

Deterministic modelling in a non-uniform rockmass.

The above procedure assumes that the strength is homogeneously distributed throughout the rockmass. Hence, the reliability of our predictions can only be assured if the rockmass uniformity is maintained. This breaks down when mining progresses into other lithological units, or into areas with varying competency or non-uniform geology. By definition, such areas have high variability and hence the reliability of any predictions will be low. Accurate predictions of rockmass response will not be possible unless either the calibrations are repeated to accommodate the changing conditions, or the changing geologic features are incorporated into the model.

If one conducted sufficiently detailed in situ investigation to characterize the location and response of contributing geologic features, these could be incorporated into the model and reliable predictions could be made. Modern numerical models are fully capable of simulating the effects of changing lithology, faults and dykes. Successful applications have been made where major structures have been incorporated into the model. In such cases considerable effort was made to define the structures location, orientation and behaviour. It was found that the structure's location and orientation were absolutely critical to the success of the modelling program (Wiles, 1992, Wiles and Nicholls, 1993, Bruneau, 2000).

Most often faults are oriented so that they are in critical equilibrium with the far field stress state. Any disturbance of the stress state in the vicinity of the fault can cause deformation on the fault. Local bends, waves and offsets in the fault become critical factors in defining their response.

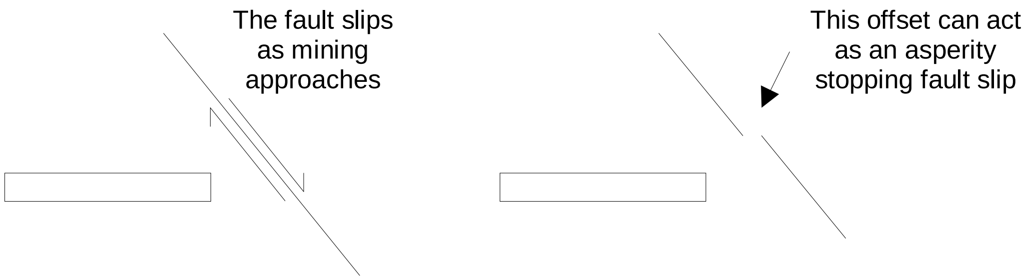


Figure 3 - Importance of detailed knowledge of geological features.

This example clearly illustrates why detailed knowledge of geological features is so important when one is attempting to simulate their behaviour. If we were not aware of the offset in the fault, our simulation would give incorrect results since we could not know that the fault would hang up.

Unfortunately, most often the detailed location and orientation of major faults can vary from poorly know to practically unknown and most often their behavioural characteristics are poorly understood. The location of minor faults and sub-structures are generally not known and not characterized at all. Rockmass lithology can change rapidly from place to place and is often unknown as well. Detailed in situ investigation is generally not cost feasible primarily because of limited access.

This creates a stalemate: although we have a tool (i.e. deterministic modelling) that we know can provide the desired predictions of how the rockmass will behave in the future, we do not have the necessary input data to accurately define the geology. Obtaining this data through in situ investigation is just not practical or affordable.

Without the required input data the above "observational approach to design" cannot be used.

We are faced with several alternatives. We could try to obtain the necessary funding required for is situ investigation. This is the approach taken in most civil engineering projects. For high rise building foundations, hydroelectric tunnels and dam foundations, a full 10% of the budget is often allocated to site investigation. In mining this is probably a hopeless effort owing to the enormous costs involved. Although 10% of the budget would probably be sufficient, I doubt anyone would authorize this expenditure.

Alternatively we can consider modifying the above approach. It is unlikely that any real alternative to the "observational approach to design" will be found, as this is the foundation upon which engineering is based.

Finally we can attempt to obtain the required input data by some other more cost-effective means.

Use of seismic monitoring data for “trail and error” model calibration.

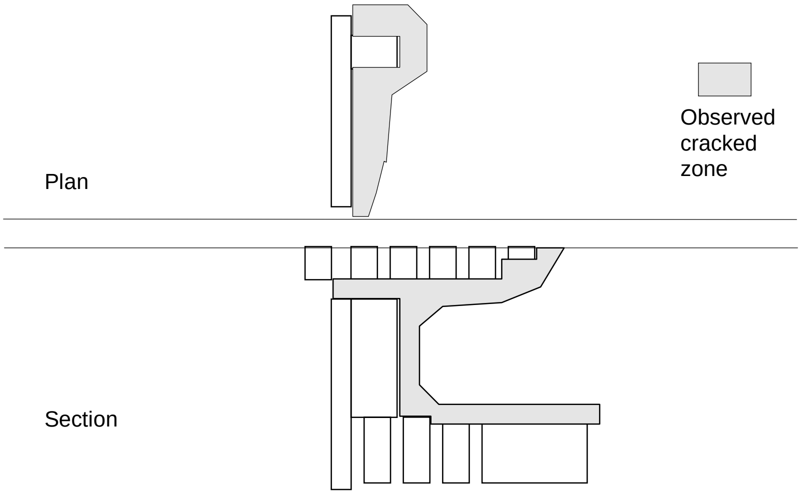
Seismic monitoring is a tool that provides a wealth of information on rockmass behaviour. If we could characterize the location, orientation and behavioural characteristics of important geologic features such as faults and dykes from seismicity, we would have valuable input data required for deterministic modelling.

Some would argue that since part of the rockmass behaviour occurs aseismically (this of course is heavily dependent on your network sensitivity, very sensitive networks are now capable of monitoring magnitude – 2 crack/creep type events), we cannot achieve this goal. I would argue that it is also true that part of rockmass behaviour occurs seismically and hence in the very least, part of rockmass can be characterized. Also, it may be that the lack of seismicity is a most important indicator in itself, as this could reveal the presence of an asperity. Certainly the hope is that microseismic activity betrays the presence of all or at least the most important flaws in some way.

There are many ways that seismicity can be used to obtain input data for deterministic models.

First of all, seismicity provides a timeline of when activity occurs with respect to the advancing mining. This timeline can be used to conduct repeated back-analyses required to characterize behavioural properties. For example, the movement on a fault or yielding in an abutment indicated by seismicity provides the opportunity to conduct back-analyses and hence characterization of behaviour properties used in the model. This has already been used to determine the extent of fracture zones around mine openings and as a robust indicator of local stress orientation.

In a study undertaken at Inco’s Creighton Mine observable cracking was closely monitored (Landriault, 1989). Several kilometres of boreholes were drilled and repeatedly video taped with a borehole camera over several years of mining as illustrated below.



Plan and section showing observed mining induced cracking zone.

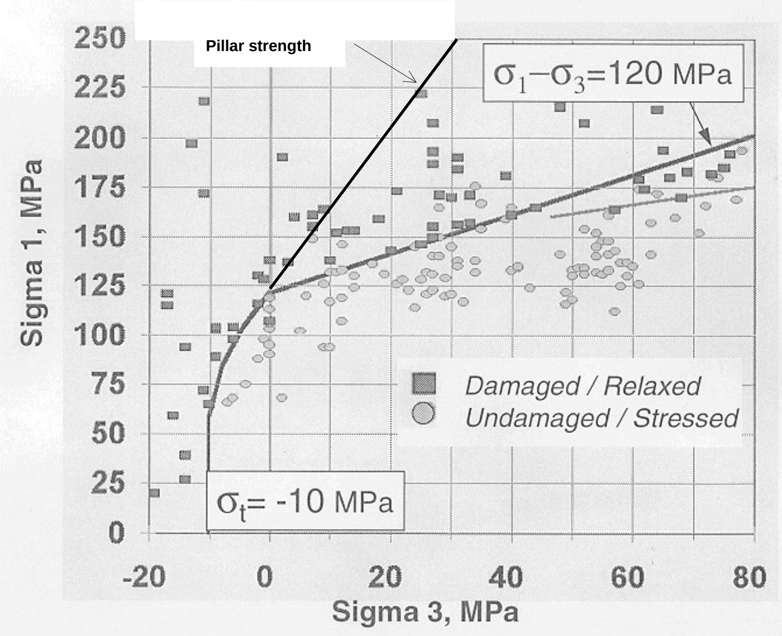
(Landriault, 1989).

Figure 4 - Plan and Section showing mining induced cracking zone
(Landriault, 1989).

Note that the observed cracking was not associated with unstable ground behaviour but just the presence of mining induced cracking of the rockmass and spalling in the boreholes. This cracking is probably responsible for the majority of the seismic activity.

The same mining sequence was modelled elastically using Map3D, and a large number of stress predictions were made both in the observed damaged zones and outside of these in the intact zones. These results are shown in the following figure.
These results clearly show that over a very wide range of confinement, the fracture zone around mine opening consistently extends only to a depth where

σ_1-$\sigma_3 \geq$ 120 MPa.



The stress predictions can be divided into two zones corresponding to the observable cracked and uncracked rockmass.
The dividing line shows no dependence on confinement i.e. a zero friction angle.
(Diederichs and Fidelis, 1998)

Figure 5 - Stress state required for cracking (Diederichs and Fidelis, 1998).

In the example illustrated below, seismicity was used to determine the far field stress orientation. Multiple stress analyses were conducted on the same geometry, but with many different orientations for the far field stress. By finding the best match between contours of maximum shear stress ½(σ_1-σ_3) and observed seismicity, the orientation of the far field stress can be inferred.

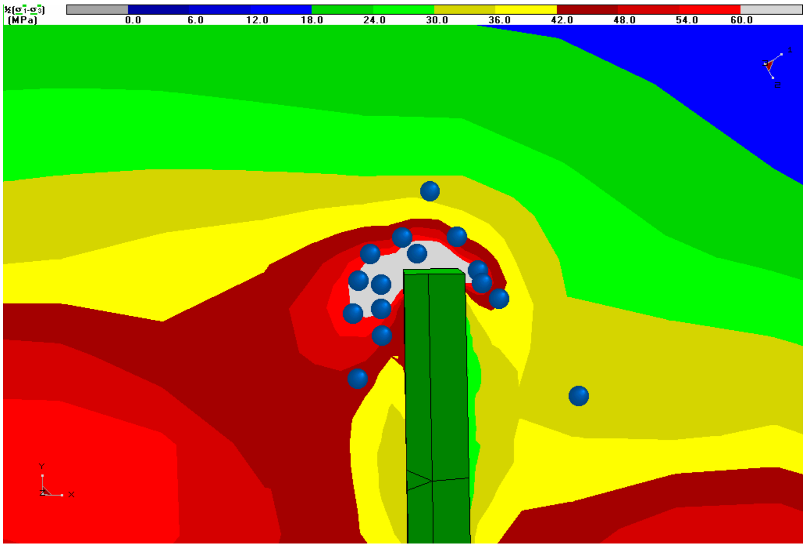


Figure 6 - Far field stress orientation determined from seismicity.

Far field stress orientation can also be inferred by looking at the orientations of the most seismically active structures across the mine.

A second way that seismicity can be used to obtain input data for deterministic models is by classifying events. If one can distinguish between events whose source lies in the "intact" rockmass versus those that can be associated with local jointing or alternatively a major fault or dyke, back-analyses can be used to characterize the individual properties of each of these (i.e. "intact" rockmass, local jointing, major fault or dyke).

In the example illustrated below Beck (1998) calculated the stress state at the location of each seismic event. The local shear and normal stresses at the orientation of each of three know joint sets were then determined. By comparing these local stresses to a strength envelope it was found that events could be classified as being either associated with one of the three joints sets or not.

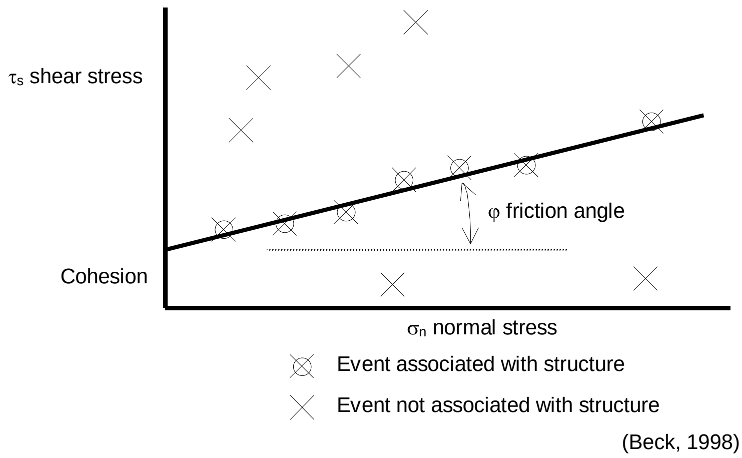


Figure 7 - Association of seismicity with structure (Beck, 1998).

Finally, once the events associated with structure were removed, the remaining events could be classified as emanating from the intact rockmass, and hence good indicators of the extent of fracturing around mine openings. These results are illustrated in the figure below.

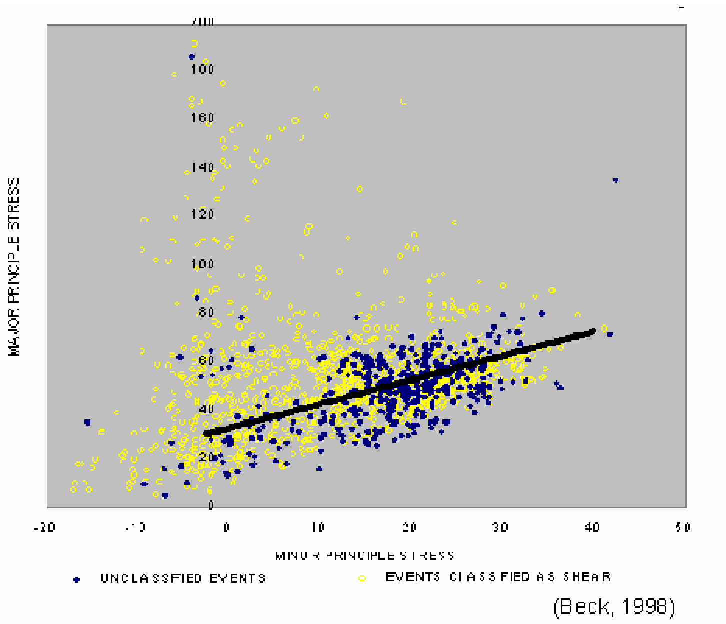


Figure 8 - Stress state required for seismicity (Beck, 1998).

A third way that seismicity can be used to obtain input data for deterministic models is by using their locations to define the location and orientation of geologic features. For example a plane could be fit through a set of seismic data that were classified as belonging to a fault structure. Such features could then be incorporated into the model and calibrated using the seismic timeline as described above. This provides the opportunity to quantify the behavioural properties and the variability of various features.

This point must be emphasized since this procedure constitutes identification of flaws in the rockmass. Microseismic activity can be used to identify the location, orientation and behaviour of these flaws.

At this point we are once again in a position to make predictions with consistent known reliability using deterministic modelling.

Microseismic monitoring provides us with cost effective method of obtaining data for input to our deterministic model.

As noted above, calibration is not a trivial exercise. For a fault slip calibration one would define the location of the structure from intersections, seismicity and geological interpretation, then through a process of trial and error, find the model parameters (far field stress state orientation and frictional strength of the fault) that provide the best match between the observed fault slip response and that predicted by the model.

This would have to be conducted repeatedly as new seismic information is collected. Continual analysis is required to quantify and update the location, orientation and behaviour properties as mining progresses into new areas with varying competency and non-uniform geology. This requires a large amount of engineering effort, obviously at considerable cost in terms of manpower. Perhaps we can take this procedure one step further and reduce the amount of the engineering effort by automating the calibration process in some way.

Use of seismic monitoring data for direct model calibration on a fault.

Model calibration can be viewed as a two-fold objective:

- First we would like to bring the model to a state most representative of the currently observed conditions. In other words, we would like the stresses, strains and displacements in our model to match those observed in situ.
- Secondly, we would like to characterize the behaviour of all contributing man-made and geological features. From this state we have the best chance of making accurate predictions that closely match in situ behaviour.

Model calibration normally proceeds by a trial and error determining the model parameters that give us the best match with observed behaviour. This does two things for us: it gives us a calibrated model to make forward predictions with, and through repeated back-analyses allows us to test how well our model matches previously observed behaviour. This gives us the confidence to make forward predictions with an assured reliability.

The most time consuming part of calibration is the trial and error evaluation of model parameters since this requires a large number of repeated analyses and considerable engineering time for organization and evaluation. This step can be avoided if an alternative calibration approach is adopted. We could directly impose the currently observed in situ conditions into the model.

Consider the difference between a model where we have adjusted the parameters for a best match with observed in situ conditions, and one where we have directly imposed the currently observed in situ conditions into the model. If this latter technique is executed correctly the model will be in the same state as the trial and error calibrated model described above. This can be done by quantifying the displacements implied by the observed seismicity and imposing this in the model.

For a fault slip calibration one would define the location of the structure from intersections, seismicity and geological interpretation (as before), then integrate the effect of the seismicity associated with the fault to determine the distribution of slip on the fault surface. This slip is then applied directly into the numerical model as a prescribed non-homogeneous shear discontinuity. The slip is accumulated as seismicity occurs and used to further load the model.

In the figure below, the location of a fault structure has been defined and is shown with the seismicity.

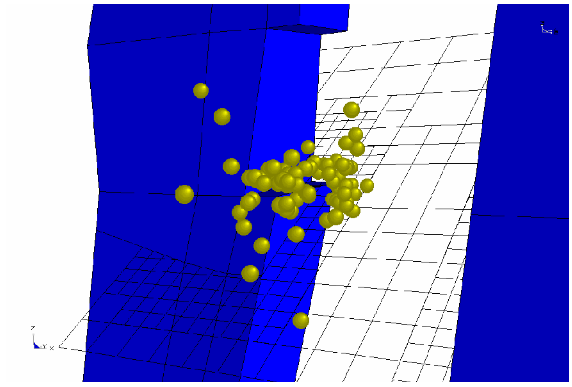


Figure 9 - Seismicity around a fault structure.

The seismicity associated with the fault is then integrated to determine the distribution of slip on the fault surface.

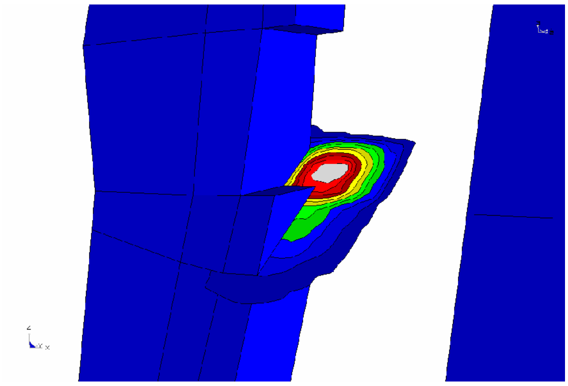


Figure 10 - Fault slip profile indicated by the seismicity.

This slip is then applied directly into the Map3Di numerical model as a prescribed non-homogeneous shear discontinuity. A stress analysis can now be conducted to determine how the stresses, strains and displacements are affected by the deformation indicated by the seismicity. In the figure below, a model has been run without the fault. However, the slip implied by the seismicity has been incorporated. In this figure, the excess shear stress

$$\tau - \sigma_n \, tan(\varphi)$$

at the location of the fault surface is presented (with a 20° friction angle).

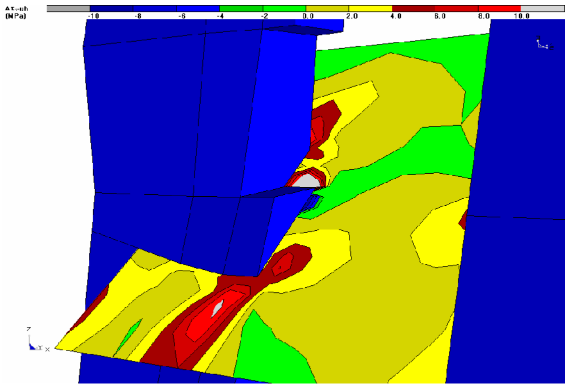


Figure 11 - Excess shear stress on a fault structure.

The results show that over most of the fault surface, there is little or no excess shear stress and hence no further potential for slip at these locations. However at a few locations (to the front and right of the left most stope) there is still considerable excess shear stress. This suggests that the fault is hung up at these locations. There is considerable potential of slip yet the seismicity tells us that this has not occurred.

Note that by applying this procedure we have bypassed the trial and error back-analysis stage and thus reduced the amount of engineering effort required to calibrate our model. Once the prescribed shear discontinuity is applied we have by definition a model that matches previously observed behaviour, and we are in a position to make forward predictions.

By calibrating our numerical model using seismic loading we can actually bring the model into an initial state much closer to in situ conditions then we could ever hope to achieve by the trial and error approach. Non-uniform slip distributions over a fault surface, derived from the observed seismicity, have been directly imposed into the numerical model. The amount of trial and error required to determine the shear strength distribution that would result in a perfect match to the seismically implied slip would be formidable.

We can now take this procedure one step further. We can use these results as a direct back-analysis method. This would proceed by subdividing the fault into small elements. By specifying the slip in each of these elements, we can now back-calculate the shear strength in each element that is required to bring about the specified slip

$$\varphi = tan^{-1}(\tau/\sigma_n)$$

We are now in a position to build a model with a fault that has the exact heterogeneous shear strength distribution required to bring about slip distribution observed from the seismicity. This is illustrated in the figure below where the friction angle distribution necessary to resist slip is presented.

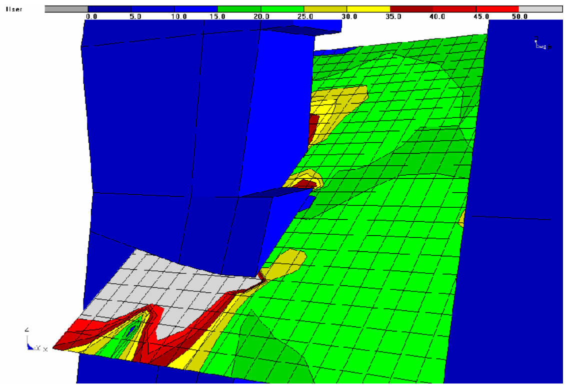


Figure 12 - Frictional angle required to resist slip.

The results show that over most of the fault surface, a nearly constant friction angle of approximately 20° is required. However in front of the left most stope a very high value is required to resist slip. This suggests that the fault is hung up at this latter location. It is likely that an asperity due to some local bend, wave or offset in the fault is responsible for this.

With the model built in this way, at this point we have a model that not only matches previously observed behaviour, but is also calibrated with the exact strength distribution required to evolve to this known state. This does two things for us: it gives us a calibrated model to make forward predictions with, and through repeated back-analyses allows us to test how well our model matches previously observed behaviour. This gives us the confidence to make forward predictions with an assured reliability.

I think it is clear that the resulting model is far better calibrated to observed in situ conditions than one could ever hope to achieve by using a best-fit homogeneous strength assumption. A homogeneous strength assumption would not allow for simulation of the observed asperity.

Once again it must be emphasized that, this procedure constitutes identification of flaws in the rockmass. However, in this case microseismic activity is not only being used to identify the presence of these flaws, but also characterize the behaviour and impose the effect implied by the seismicity into the model.

Use of seismic monitoring data for direct model calibration in 3D.

There is no real reason why the seismicity needs to be integrated over a fault surface to apply the seismically implied slip. Instead of using a plane, one could consider subdividing the volume into a three-dimensional array of voxels. Then integrate the effect of the seismicity occurring in each voxel to determine the strain that is implied. The Map3Di numerical model has the capability to incorporate this strain as a prescribed non-homogeneous strain distribution. As before, the strain could be accumulated as seismicity occurs and used to further load the model. Any fault slip type behaviour would then arise naturally as a consequence of this procedure.

This may be the most desirable approach as it avoids imposing our preconceived notions regarding expected failure mechanisms, and allows the seismic data to dictate whatever failure mechanism is observed. This could include unexpected three-dimensional deformations that do not conform to fault slip interpretations. Observation of these effects in the model might lead to increased understanding of the rockmass response and identification of mechanisms leading to failures.

This latter approach would require that we have a lot of confidence in our seismic data since we must rely totally on accuracy of the location and characteristics used to determine the deformation imposed into the numerical model.

Accurate predictions of rockmass response to mining.

Let us now return to our discussion regarding accurate predictions of rockmass response to mining. This of course includes the use of deterministic modelling in prediction of when and where failures (including rockbursts) will occur. One of the major obstacles to success so far has been the simple fact that we could not characterize the location, orientation and behaviour characteristics of the critical flaws in our rockmass. Without incorporating these flaws into the model, accurate deterministic predictions are simply not possible.

Recall that in the aeronautical industry that once they overcame this obstacle they found themselves in the position of being able to use deterministic models to make accurate predictions provided they could detect and characterize flaws with sufficient detail and frequency. We may be in the same position now.

By use of modelling one can determine that there is adequate stress to cause failure and sufficient energy available (low system stiffness) to drive a violent failure process. If we can then characterize the location, orientation and behaviour characteristics of the critical flaws in our rockmass and input this information into our deterministic models we should be able to greatly enhance the accuracy of our predictions.

With this added information, we should now be able to resolve why under the exact same loading conditions failures are observed to occur at different times. For example at one location we could predict that the failure will occur early in the mining sequence due to some critical flaw at that location, while at another location we would predict that failure will occur much later in the mining sequence owing to a lack of a critical flaw at that location.

Several examples of how this technique has been applied in mine environments are presented in the companion paper “Integration of deterministic modelling with seismic monitoring for the assessment of rockmass response to mining: Part II Applications” (Lachenicht, Wiles and van Aswegan 2001).

There are many reasons to be enthusiastic about this approach. Adding quality information to any model can only improve the accuracy of the predictions of the model. The integration of deterministic modelling with seismic monitoring offers crucial data regarding local variability and sensitive features such as key blocks or hung asperities. Taken together this clearly enhances our deterministic prediction accuracy of rockmass response to mining.

Never the less, there are many potential pitfalls that still need to be addressed.

We need to demonstrate that by incorporating the flaws into the model we can in fact make accurate predictions of failure times. It is possible that the interactions of multiple flaws will be too complex to resolve. Hydrogeologists have been working on complex models of ground water seepage for some time now with little success. Recent work by Napier (1997) has demonstrated that this complexity can be resolved. Their models show that complex arrangements of flaws can be successfully modelled to yield realistic macroscopic behaviour. Early successes in the companion paper (Lachenicht et al, 2001) suggest we are on the right track.

Catastrophic failures often occur in a mode similar to a domino effect where the whole mechanism is inherently unstable. In such cases failure initiation is so sensitive that it is impossible to build a comprehensive enough model to make accurate deterministic predictions. I believe this is the current feeling in earthquake predictions. Although weather predictions fall into this same category, they have improved markedly in recent years. This is primarily because weather modes are now calibrated with real time input data of local conditions. This approach is very similar to the calibration approach proposed above.

All of this depends on accurate and thorough detection of critical flaws in our rockmass. We need to demonstrate that we can characterize the location, orientation and behaviour characteristics of the critical flaws using seismicity. Our hope is that microseismic activity will betray the presence of such flaws in some way.

This paper details the methodology of how seismicity can be used to identify and characterize critical flaws in our rockmass. Whether these flaws are critically oriented joints, or a local bends, waves or offsets in a fault, their location and behavioural characteristics can be quantified. Through the Map3Di direct back-analysis procedure, this technique allows us to bring our model to a state most representative of the in situ conditions observed via seismicity.

We can then incorporate the flaws into our deterministic model such that the behavioural characteristics of the flaws are calibrated to match the observed response. The author's believe that a model that is calibrated in this way has the best chance of making accurate predictions that closely match in situ behaviour.

References:

Beck, D. Observations of mining induced seismicity at BMS #12 Mine, Department of Mining, Minerals and Materials Equipment, University of Queensland, St. Lucia, Queensland, Australia, 1998.

Bruneau, G. 2000, The influence of faulting on the structural integrity of the X41 shaft, Copper Mine, Mount Isa, Australia, MASc Thesis, Dept. Mines and Metallurgy, Laval University, Ste. Foi, Quebec, Canada.

Diederichs, M. and Fidelis, personal communication, Geomechanics Research Centre, Sudbury, Ontario, Canada, 1998.

Lachenicht, R., T.D. Wiles and G. van Aswegan, 2001, "Integration of deterministic modelling with seismic monitoring for the assessment of rockmass response to mining: Part II Applications", RASIM 5.

Landriault, D., Simulation of Bulk Mining at Depth with Backfill - Field Monitoring Program Year Two, INCO Limited Report To Canmet Project No. 6-9033, 1989.

Napier, J.A.L., "Three dimensional modelling of seismicity in deep level mines", CSIR Division of Mining Technology, Johannesburg, South Africa, 1997.

Wiles, T.D. 1992, Numerical analysis of hangingwall fault response at the Casa Berardi Est Mine, Mine Modelling Ltd. report, PO Box 637, Mt. Eliza, Vic., Australia, 3930.

Wiles, T.D. and D. Nicholls, 1993, "Modelling discontinuous rockmasses in three dimensions using Map3D, First Canadian Symposium on Numerical Applications in Mining and Geomechanics, Montreal, Canada.

Wiles, T.D. 1998, Correlation Between Local Energy Release Density and Observed Bursting Conditions

At Creighton Mine, Mine Modelling Pty. Ltd. report, PO Box 637, Mt. Eliza, Vic., Australia, 3930.