

Coulomb Stress Triggering for Seismic Hazard Assessment of Geological Structures in Underground Mines

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ABSTRACT

ABSTRACT: The concept of Coulomb Stress Triggering has been used widely in crustal seismology to gain insight into the probability to experience earthquakes following the occurrence of historical earthquakes. The key idea is to estimate static shear- and normal- stress changes on faults. Such estimates plus assumptions regarding internal strengths along fault contacts are used to calculate so-called Coulomb Failure Stress (CFS). Published results indicate that the majority of aftershocks fall within areas of increased CFS (typically around 1 bar), while earthquakes are delayed in areas of decreased CFS. The same concept is in use in the South African underground tabular mining environment, but referred to as Excess Shear Stress (ESS). Average ESS levels as well as increase in ESS due to mining reflect the probability of triggering large events, and hence may be used for mine seismic hazard assessment. A case study of stress triggering from the underground tabular mining environment is discussed, where input information is known to a fair degree of accuracy, and the main features of the seismic source mechanism is understood. This should serve as a reference case against which other similar studies may be compared, aiming to improve mine seismic hazard assessment.

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1 INTRODUCTION

Coulomb stress triggering in earthquake mechanics is concerned with quantifying stress changes along crustal faults due to historical earthquakes. This should lead to an advance or delay in time of future earthquakes, either on the same fault or other faults in the area. Although there are indications that dynamic ground motion is an important potential trigger, the starting point is to consider static stress changes. This requires knowledge of fault plane orientations and sense of slip, and then applying an appropriate technique to estimate stress changes following an earthquake. Apart from the impact of historical fault slip, there is also a constant loading of faults due to tectonic movement at a particular loading rate. The above two aspects can be considered to determine the recurrence time for earthquakes in a particular earthquake prone area.

In the underground mining environment the same general conditions exist, but different in magnitude and time scales. Large mining induced tremors are in most cases due to mining spans increasing in areas of geological disturbances. Geological structure contacts are loaded at a rate determined by the mining rate (expressed for example in terms of tonnes of rock extracted per month). The input required for such studies is more readily available than for earthquake studies, since the geological structures are mapped underground to some degree of accuracy, and mine production data is known accurately. Elastic numerical modelling can then be used to estimate stress changes along the structure contact surfaces, and this can be used to assess the progression of seismic hazard associated with the structures.

For this paper a case study from the underground mining environment is considered where stress changes offer an explanation of one mining tremor triggering another. In the study area geological structures and the in-situ stress state are known to a fair degree of accuracy allowing calibration of model parameters with some confidence. Results are also given from the same

study area indicating how the concept can be applied for routine mine seismic hazard assessment.

1.1 Coulomb friction

The basis of the concept dates back to the end of the 18th century, when the famous Charles de Coulomb experimented with blocks sliding on each other under an applied shear and normal force. Coulomb friction was defined as:

$F_f \leq \mu N$, where

F_f is the maximum possible magnitude of the shear force exerted, or in the static case the frictional opposing force,

μ is the coefficient of internal friction (an empirical property of the contacting materials), and

N is the normal force exerted between the surfaces.

For surfaces in relative motion, μ_d is the coefficient of kinetic (dynamic) friction, while for surfaces at rest relative to each other, μ_s is the coefficient of static friction.

For practical implementation in rock mass continuum the forces are rather considered through normal and shear stresses acting on discontinuity planes.

In earthquake seismology the term *Coulomb Failure Stress* is used, and the latest methods use the analytical solutions of Okada (1992) to study the interaction between so-called *source* and *receiver* fault planes. In the underground mining environment, the advent of digital computers allowed the estimation of surface stresses on geological structures subject to mining excavations at depth. The term *Excess Shear Stress* was introduced in 1988 by Ryder (Ryder, 1988).

1.2 Coulomb Failure Stress for earthquake forecasting

Coulomb Failure Stress (CFS) is derived from Coulomb friction for a fault plane as follows:

$$CFS = \tau + \mu(\sigma_n + P), \quad (1)$$

where

CFS is the Coulomb Failure Stress,

τ and σ_n are the shear stress and normal stress respectively stress ($\sigma_n > 0$ implies tension),

μ is the friction coefficient, and

P is the fluid pore pressure.

The failure criterion is then given by the change:

$$\Delta CFS = \Delta \tau + \mu(\Delta \sigma_n + \Delta P) \quad (2)$$

The important issues are the changes in shear and normal stress components, which depends on the field stress and orientation of the fault plane at the potential nucleation point. The potential for fault slip is not only determined by an increase in shear stress (the driving stress), but also a reduction in normal stress (the clamping stress). Positive ΔCFS indicates an increased potential for slip, and hence earthquake promotion, while negative ΔCFS indicates earthquake delay.

Many studies have been done since the early 80's for earthquakes in Chile, Japan, Turkey and California USA, amongst more. Usually crustal fault zones slip laterally under tectonic forces, and are influenced by other historical earthquakes either on the same fault, or other faults, whether parallel or not. Depending of the geometry and sense of slip, stress changes either enhances (triggering) or delay (stress shadows) future ruptures.

Some examples may be quoted from studies following the 1992 M7.4 Landers earthquake in the San Andreas fault system, California USA (King, 1994). Four moderate earthquakes collectively caused a CFS increase in the area of the future Landers epicentre, as well as a large area along the rupture zone, by approximately 1 bar. This increased CFS along a fault approximately normal to the Landers fault zone by 3 bar, subsequently triggering the Big Bear earthquake 3 and a half hours later. The Landers and Big Bear earthquakes in turn increased CFS along another prominent fault segment in the area by 2 – 6 bar.

A useful parameter that can be estimated is the change in statistical recurrence time, which is obtained simply by dividing the CFS change by the pre-earthquake loading rate.

Apart from studying specific faults, general seismicity rates can also be investigated by calculating stress changes on optimally oriented planes, i.e. the plane orientation showing the maximum CFS prior to an induced stress change. This has been found to correlate well with increases or decreases in seismicity rates.

1.3 Excess Shear Stress for geological structures in underground mines

Although the same parameter, Excess Shear Stress (ESS) (Jager & Ryder, 1999) for a geological contact surface in an underground mine is defined rather as the amount by which the shear stress exceeds the shear strength:

$$ESS = \tau - (C + \mu \sigma_n) \quad (3)$$

where

τ is the shear stress,

and $C + \mu \sigma_n$ is the shear strength, with

- C the contact cohesion
- μ the friction coefficient
- σ_n the normal stress (in this formulation $\sigma_n > 0$ implies compression, as is the usual convention in the mining environment).

The most common scenario in the deep level underground mining environment is normal faulting driven by a predominantly vertical major principal stress. Fluid pore pressure is usually ignored.

The required surface stress components are obtained from elastic numerical modelling software, in which the mining excavations are simulated using a graphical interface, and fault plane orientations are inferred from geological mapping. For mine seismic hazard assessment the parameter can be applied in three ways: (i) compare different structures with each other, (ii)

view the progression of seismic hazard posed by a structure in time, and (iii) use an approximation method to estimate the potential seismic release (Jager & Ryder, 1999).

2 COULOMB STRESS TRIGGERING IN A TABULAR GOLD MINING OPERATION

This analysis considers two tremors that occurred in a South African tabular gold mine at 3000 m depth below surface. Figure 1 shows the mining layout and some information on geology and seismicity. The longwall mining method is used, and in this case five panels are mined in the reef strike direction, i.e. to the east.

A M2.4 (moment magnitude) tremor occurred on 26 May 2003 at 04h07. This was recorded by an in-mine seismic system, triggering 17 geophone sensors. Waveform processing revealed a second seismic event within the recorded waveforms, triggering milliseconds later. The seismograms were processed accordingly, and a M2.8 event at a location approximately 300 m away was suggested.

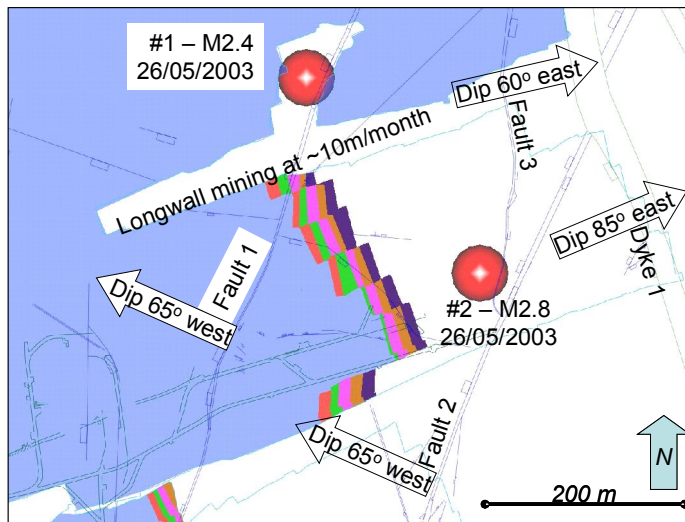


Figure 1. Plan view picture showing the area of interest. The four geological structures modelled are annotated, with the arrows indicating their dip and dip directions. The two seismic events of interest are shown as spheres. Longwall mining advances to the east at a rate of approximately 10 m/month.



Figure 2. Perspective view showing the boundary element model. The structure geometries can be seen, as well as two field point grids used in the analysis. These grids are vertical, and intersect Faults 1 and 2 perpendicularly. Fault 1 and 2 dips to the west, Fault 3 dips to the east while Dyke 1 is sub-vertical.

The seismic events are shown in Figure 1, together with geological mapping in the area - these structures are potential seismic sources.

The first event is conceivably associated with slip on Fault 1, with the remnant pillar causing high shear stress. Even though mining is at some distance to the south, shear stress would have increased gradually, eventually leading to slip on this fault.

The second event was almost certainly triggered by the first, due to the immediate response. Although there is some ambiguity regarding the location of the second (overlapping seismograms), there was significant damage in a drive approximately 100 m below reef, hence co-seismic slip at that position is undeniable.

2.1 Seismic information

The two events initiated within 0.085 seconds, hence an almost immediate trigger. Both located some distance below the reef horizon, but this is subject to an error in depth due to the planar seismic sensor array.

Important source characteristics in this case are estimates of the source size and stress level. The following stress and strain related seismic parameters were supplied by the seismic data base:

Table 1. Seismic source parameters*

Event, HK-Moment Magnitude	Apparent Stress [MPa]	Apparent Volume Radius [m]	Log(M)	log(E)
#1, M 2.4	5.7	44	12.7	8.9
#2, M 2.8	1.5	130	13.4	unknown

* Van Aswegen, 2003

Apparent Stress reflects the average stress level in the source during the rupture, while Apparent Volume is an indication of the source size in terms of the radius of a spherical volume of inelastic deformation. M and E denotes Seismic Moment and Energy respectively. A detailed discussion of the seismic parameters can be found in Van Aswegen, 2005.

These parameters are not absolute estimates of the source stress level and deformation, but are model dependent. However, they indicate an important distinction between the two sources. The first (M2.4) was evidently under much higher stress but with limited source size (high Apparent Stress and Seismic Energy), while the second (M2.8) shows the opposite characteristics, i.e. low stress and large source size. The source characteristics are significantly different despite the fact that they are both normal slip on similarly oriented geological structures.

2.2 Numerical modelling

The boundary element numerical modelling package, Map3D, was used to simulate the mining geometry in sufficient accuracy. This included the full mine, monthly mining steps around the area of interest, backfill, and undulating surfaces approximating the geological structure contacts. This elastic boundary element program solves for tractions on all model boundary elements, from which shear and normal stresses can be calculated. Furthermore, the stress tensor and 3D elastic displacements can be calculated at any requested field point.

Figure 2 shows the actual boundary element model, for a slightly bigger area, as well as the two field points grids incorporated for analysis.

2.2.1 Model in-situ stress state

Stress measurements were done in 2000 in the mine shaft pillar (~3000 m to the west). The Map3D package was used to find the input stress-state yielding outputs similar to the measured directions. Sub-sequent to this, detailed studies were also done using information from an extensive drilling program on the same mine, but approximately 1.5 km to the south. Breakouts were photographed along the drill-holes and from this stress orientations and magnitudes was estimated (Heesakkers, 2006).

The outputs from the abovementioned two methods were consistent, and were used as starting point for the current study. Apart from the stress orientation and magnitude, ESS on a fault is also determined by the contact surface friction coefficient.

A combination of the above parameters was sought to give a plausible picture in terms of a potential seismic source, i.e. a 'lobe' of positive ESS. The stress state used in this study is given in Table 2:

Table 2. Input stress state

Principal stress component	Plunge, [degrees] from	Trend, [degrees] clockwise	Gradient [MPa/m]
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	horizontal	from north	
σ_1	68	344	0.0272
σ_2	20	168	0.0252
σ_3	5	240	0.0130

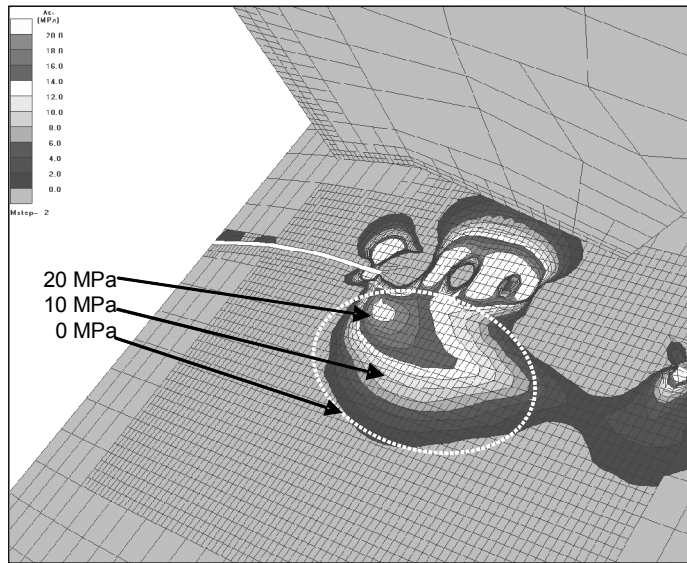


Figure 3a. View looking east onto Fault 1, from below the longwall advancing to the east. Contours of positive ESS on the structure are shown. The ellipse delineates an area as a potential seismic source for the M2.4 event. ESS is high (exceeding 20 MPa) over a relatively small area (~140x60 m).

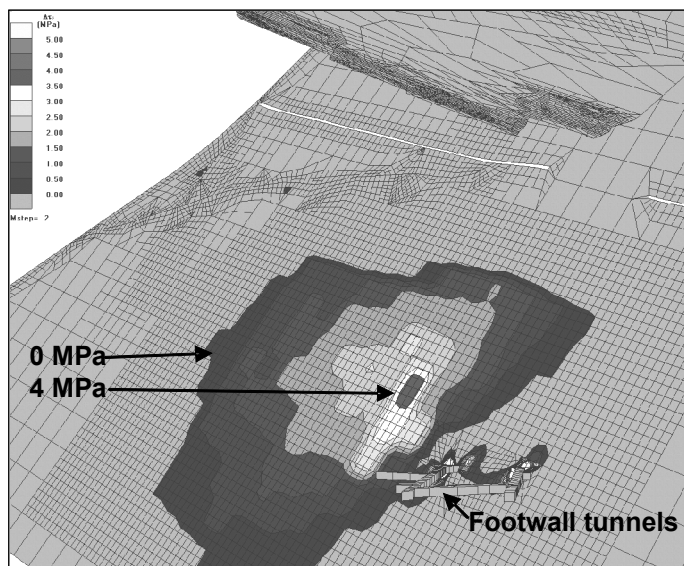


Figure 3b. Contours of positive ESS on the structure is shown (view looking east, from below the mining). The contours of positive ESS delineate a potential seismic source, with a maximum of approximately 4 MPa. The diameter of this area is approximately 220 m.

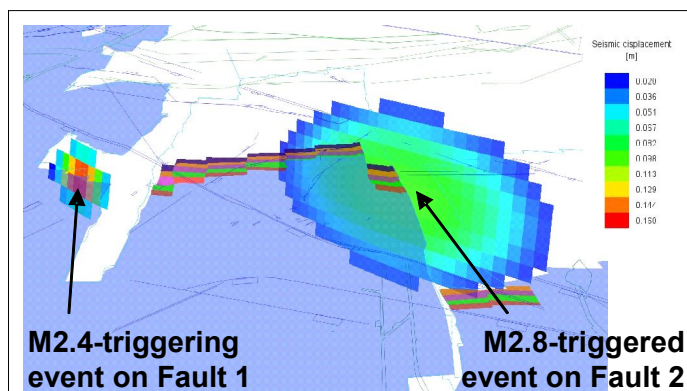


Figure 4. The source areas for seismic integration. The M2.4 event has a small source size, but large seismic displacement (max 18.8cm at the centre), while the M2.7 has lower seismic displacement (max 8.5cm at the centre) but over a larger area.

2.2.2 Model parameter assumptions

The friction coefficients were important parameters together with the input stress state. The calibration entailed finding a combination of parameters yielding positive ESS on the faults as possible sources for the events that occurred. Non-linear fault slip (a feature in Map3D for displacement discontinuity elements) was also modelled on Fault 1 and 2, and this can be translated into modelled seismic moment. For this non-linear analysis the residual (post-failure) friction coefficient was also considered, since this determine the total slip. Although not a robust calibration of fault strengths, it was attempted to find a set of credible parameters, in line with industry-accepted values.

The following model parameters were used:

Table 3. Elastic numerical modelling parameters

Host rock Young's Modulus:	70 GPa	
Host rock Poisson's Ratio:		0.2
Fault 1 & 2 Cohesion:	0 MPa	
Fault 1 Peak (static) Friction angle:	26.0°	
Fault 1 Residual (dynamic) Friction angle:	24.0°	
Fault 2 Peak (static) Friction angle:	20.0°	
Fault 2 Residual (dynamic) Friction angle:	14.5°	

2.2.3 Modelled seismic sources

From a modelling point of view, the potential seismic source may be viewed as the area on the geometrical model of the structure where ESS is positive. In the elastic model, the structure boundary elements do not fail in shear, but ESS will be positive since the shear stress exceeds the shear strength.

Modelled ESS on Fault 1 and 2 is shown in Figures 3a and b respectively. ESS is contoured on the structure boundary elements – note that the contour ranges are different. The modelled seismic event for the M2.4 is a relatively small area, but under high ESS (exceeding 20 MPa), while for the M2.8, the ESS level is lower (less than 5 MPa), but a larger spatial area is positive.

The source characteristics for the modelled seismic events are therefore consistent with the seismic parameters in terms of the stress level and source size (Section 2.1). For the first (M2.4) event, the high ESS on Fault 1 is caused by the historical pillar abutment to the east of the structure. The mechanism is normal fault slip, with a small area yielding at high slip velocity. For the second event (M2.8), a larger area was under positive ESS. The mechanism is again normal fault slip, but a larger area yielded at a lower slip velocity.

2.2.4 Seismic integration

Seismic integration is the procedure of integrating seismic displacement as a field loading effect into the boundary element numerical model. This is done through a special version of the Map3D program, viz. Map3D-seismic integration. Integration can be done in 3D by specifying strain associated with cubical volumes, or in 2D, by specifying the actual distance of shear displacement along a model displacement discontinuity element (the planar boundary elements used to simulate cracks). The effect of this integration is twofold, viz. it reduces stress within the integration source, and it causes static stress changes outside. In the current case, it is used mainly to assess stress changes on Fault 2 due to slip on Fault 1, around 380 m away, although the same can be done on the other faults in the area.

The integration procedure requires an estimate of the seismic source in terms of the source area and distribution of shear displacement across the source area. The slip direction may also be

specified, but due the lack of specific information on this, the numerical model infers slip in the direction of shear stress.

The slip to be integrated is given in terms of a seismic parameter called Seismic Displacement, which is an estimate of co-seismic slip across a structure contact surface. The method of Hofmann et al., 2001, is used. An estimate is made of the planar source area of the shear slip seismic event, and a displacement profile (distribution of slip radially from the centre to the radius) is assumed. The source area and displacement profile allow estimation of the maximum displacement at the centre. The seismic source shape is furthermore assumed to be elliptical with eccentricity 0.5 and with the long axis aligned with the reef plane. This is an approximation for a gravitationally driven slip distribution on a normal fault.

The displacement distribution for integration into the boundary element model is shown in Figure 4. For the M2.4 event, the planar source area has dimensions of 136x68 m (long and short axes respectively) with a maximum displacement of 18.8 cm at the hypocenter. For the M2.8 event, the planar source area has dimensions of 400x200 m (long and short axes respectively, with the maximum displacement at the hypocenter estimated at 8.5 cm.

2.3 Results

2.3.1 Source of the first event (triggering event)

It is firstly attempted to understand more about the stress interaction between rock mass and Fault 1. For this reason a vertical plane-grid (see Figure 2) was placed at the modelled source position, intersecting the fault perpendicularly. Since the plane-grid intersects the fault perpendicularly, the maximum in-plane and minimum in-plane stress can be used to study the effect of the rock mass on the fault.

Figure 5a shows maximum in-plane stress causing high shear stress on a particular area on the fault, and Figure 5b shows minimum in-plane stress causing low normal stress on a slightly different area on the fault. The combined effect is then viewed efficiently through ESS on the fault, as shown in Figure 3a. This is a simulation of the seismic source of the M2.4 event.

Table 4 gives the calculated values from the modelling output for the area of maximum ESS on the fault (model hypocenter), and for the larger area of positive ESS, prior to the triggering of the M2.4.

Table 4. Calculations of surface stress components on Fault 1 prior to the M2.4

Spatial filter	Shear Stress [MPa]	Normal Stress [MPa]	ESS [MPa]
Model Hypocentre (maximum)	54.5	75.6	17.7
Positive ESS (average)	39.0	62.5	8.7

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2.3.2 Source of the second event (triggered event)

Again a field points grid intersecting Fault 2 perpendicularly is used to learn more about the interaction between rock mass and the fault.

In this case, the nature of the loading is different. Figure 6a shows the maximum in-plane stress, i.e. a predominantly vertical maximum stress (essentially virgin stress). In this case, there is not a particular area under higher stress, as was the case with the first event. However, the effect of the mined out area above can be seen through the minimum in-plane stress, approximately

horizontal and east-west trending. This is shown in Figure 6b. The resulting ESS picture on the fault is shown in Figure 3b, with that being a simulation of the seismic source of the M2.8 event.

The point of maximum ESS is approximately 150 m away from the longwall face at the time; hence the occurrence of this event was probably unexpected. There was significant damage associated with this event in the tunnels visible in Figure 6.

Table 5 lists the calculated surface stress components.

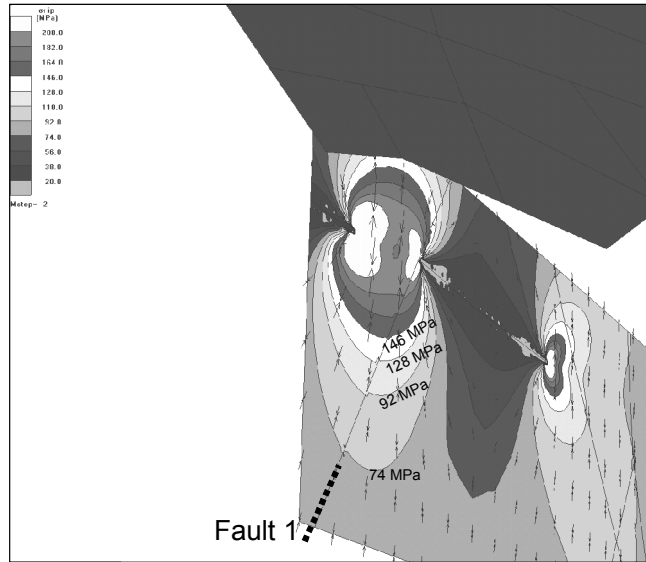


Figure 5a. View looking north-east onto the field points grid at the first seismic event. Contours and vectors of maximum in-plane stress is shown. The abutment causes high stress on the fault at an acute angle, and hence high shear stress.

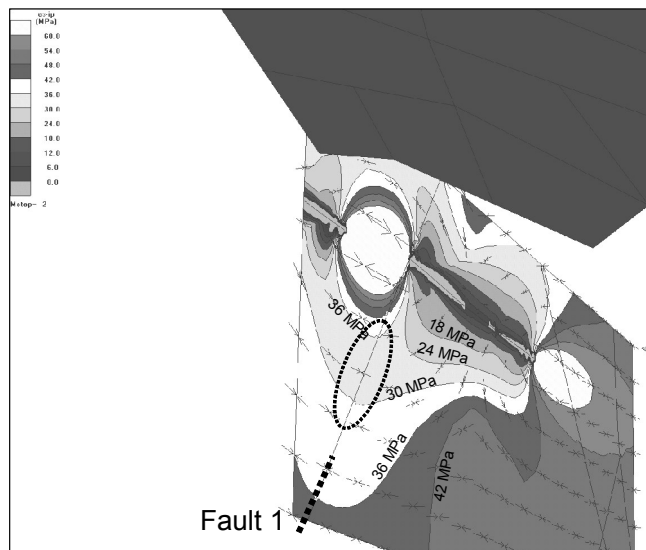


Figure 5b. The same view as above, with contours and vectors of minimum in-plane stress. The ellipse delineates an area of low horizontal stress and hence low normal stress on the fault.

Table 5. Calculations of surface stress components on Fault 2 prior to the M2.8

Spatial filter	Shear Stress [MPa]	Normal Stress [MPa]	ESS [MPa]
Model Hypocentre (maximum)	21.4	52.5	2.3
Positive ESS (average)	21.0	54.6	1.1

2.3.3 Stress triggering

The stress change on Fault 2 due to slip on Fault 1 is now analysed. Figure 7 shows contours of calculated change in ESS. It is important to consider stress changes within the area of positive ESS, as indicated in the figure. The shallower part of the fault (within the potential source region) experienced an increase, reaching a maximum of 0.8 bar, while the deeper part experienced a decrease in ESS.

Roughly half of the seismic source experienced an ESS increase, with the average prior to triggering estimated at 1.1. However, for this fault, the ESS increase due to the mining of May 2003, is calculated as 1.6 bar. This suggests that the M2.8 event was not triggered only due to the stress transfer from the M2.4, but also by the significant impact of the advancing mining. It appears that the fault was in general at a critical stress state, and could have triggered at any time. Importantly though, the additional loading from the M2.4 occurred almost instantaneously over a relatively large area. Dynamic loading will also have played a role, but such effects are not considered here.

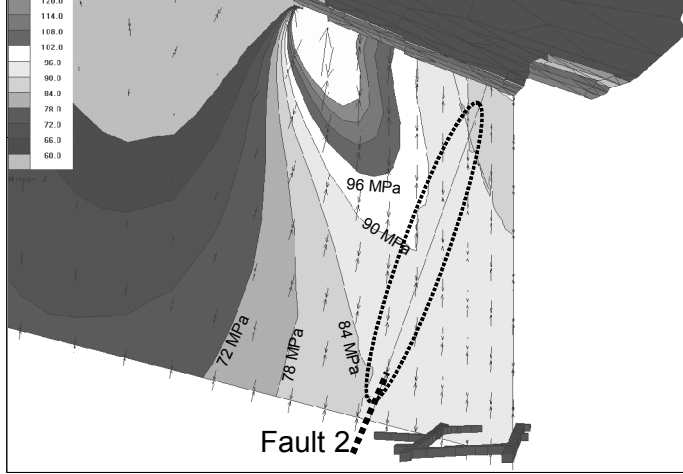


Figure 6a. View looking east onto the field points grid intersecting Fault 2 at the second seismic event. Contours and vectors of maximum in-plane stress are shown. The dotted ellipse delineates where the rock mass causes shear stress on the fault.

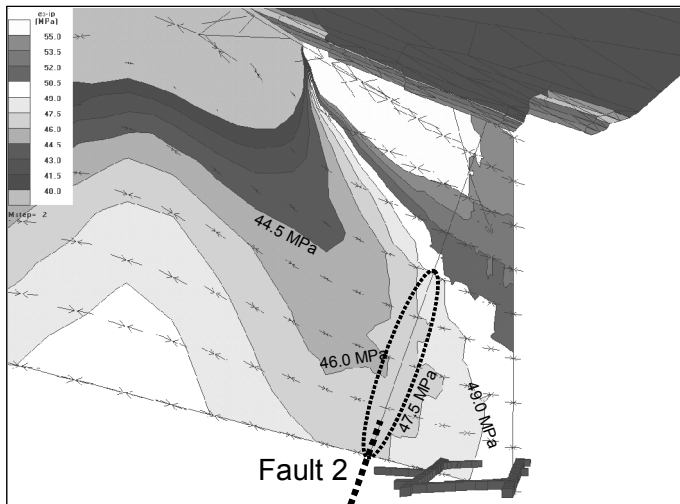


Figure 6b. Same view as above, with contours and vectors of minimum in-plane stress. The area of lowest clamping stress acting on the fault plane is delineated by the dotted ellipse.

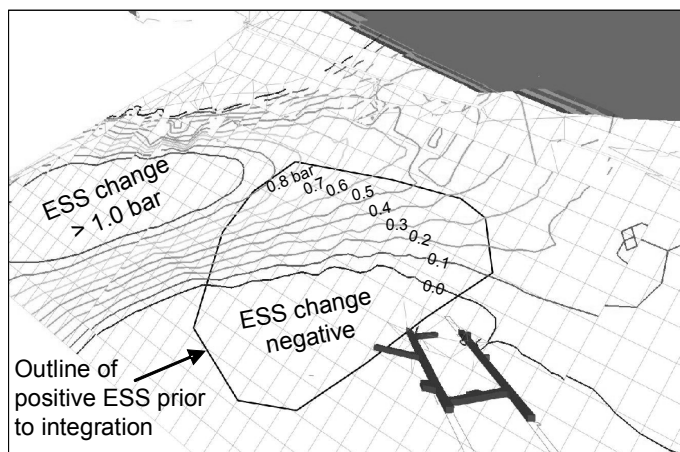


Figure 7. Contours of ESS change on Fault 2, as a result of integration of the seismic displacement on fault 1. The polygon indicates the positive ESS area prior to integration. Over this area, the shallower part experienced an increase in ESS due to integration, up to 0.8 bar. This static stress increase over a relatively large area on the fault is perceived to be the Coulomb Stress Trigger.

3 ESS FOR MINE SEISMIC HAZARD ASSESSMENT

The above analysis gives some confidence in the methodology and input information. The important information for this static elastic model is the in-situ stress state and structure friction coefficient estimates (static and dynamic). The model can hence be applied for assessing the seismic hazard of the structures whilst mining in the area.

For routine implementation, two parameters are derived from ESS to emphasize the effect mining causing an increasing trend, potentially leading to coulomb stress triggering. Firstly, average ESS is calculated considering only structure boundary elements for which ESS is positive. This effectively defines a spatial outline of a 'lobe' of potential co-seismic slip automatically. Care should however be taken with the input surface, since this may contain several lobes from different areas. A rough spatial filter may therefore be required beforehand to delineate areas of potential slip from visual inspection. Furthermore, a weighted average should be calculated, taking into account the actual surface area (m^2) of the individual boundary elements defining the structure. This parameter is named Average Weighted Positive ESS, denoted by *Ave_w_ESS+* (loosely referred to as Average ESS).

To quantify the potentially hazardous impact of mining steps on a structure, ESS increase is calculated only for boundary elements that experienced a positive change in ESS. As such it is named Positive ESS difference, denoted by *ESSdiff+* (loosely referred to as ESSdiff). It is sensitive to increases in ESS by mining, and therefore reflects the probability of triggering mine tremors.

The two criteria described above, can be viewed on the same graph in time. Average ESS indicates how close a structure is to failing, and on top of that, high ESSdiff values indicate a high probability to trigger a large event. The success will depend on, amongst more, accuracy of the in-situ stress state and the structure strength parameters, in particular friction coefficient. It is suggested here to use units of MPa for Average ESS, while using units of bar for ESSdiff, in correspondence with earthquake forecasting.

3.1 ESS analysis on Faults 1 and 2

The model setup used for the Coulomb stress triggering analysis was subsequently used to implement Average ESS and ESSdiff as described above, towards routine seismic hazard assessment in the current study area.

Section 2.2.2 discussed briefly how the friction coefficients were obtained. The peak friction coefficient determines the level of ESS, and hence the spatial size of the positive lobe. For this an elastic material property for the structure is set. Structure boundary elements can however also be modelled with a non-linear Mohr-Coulomb failure criterion (Jaeger and Cook, 1979), and from this seismic moment release can be calculated. It is determined by the peak friction coefficient, but to a large extent by the residual friction coefficient (i.e. the post-failure strength). This model parameter can thus be modified in trial and error fashion to give correlation between recorded Seismic Moment (a reasonably robust estimate from the seismic system) and modelled from the Mohr-Coulomb shear slip of structure boundary elements.

The numerical model, with parameter assumptions discussed in Section 2, was used to calculate Average ESS and ESSdiff are calculated per monthly step from January to May 2003. On the graphs, Average ESS is shown on the left-hand y-axis in units of MPa, and ESSdiff is shown on the right-hand y-axis in units of bar.

Figure 8 shows a picture of the area with some information annotated regarding the M2.4 event on Fault2, 26 May 2003. ESSdiff reaches a maximum value of 1.0 bar for the mining of May, when the M2.4 was triggered. Furthermore, Average ESS is at a significantly high level,

exceeding 6 MPa. Results suggest that the structure was at a critical stress state, being associated with the old remnant pillar to the north, and eventually triggered by the mining to the south thereof, even at approximately 100 m away.

Table 6 summarises the relevant data of this analysis, regarding both input parameters and results.

Table 6. Structure strength input parameters for Fault 1 and ESS results for the mining of May 2003, when the M2.4 event was triggered.

Recorded ESSdiff+	Modelled	Peak	Residual	Ave_w_ESS+	
Seismic Moment [Nm]	Seismic Moment [Nm]	Friction angle [deg]	Friction angle [deg]	[MPa]	[bar]
6.2E12	4.5E12	26.0	24.0	6.5	1.0

Figure 8 shows the picture and results for the M2.8 event on Fault 2, 26 May 2003. From March to May mining had a significant impact on Fault 2 (ESSdiff values of 1.7, 1.6 and 1.9 bar respectively), with the M2.8 eventually triggered on 26 May. Average ESS reached a level of 1.6 MPa at May. The last graph point is the impact of integration of the M2.4 event, and according to the methodology, ESSdiff is calculated as 0.2 bar. Although this is much lower than the impact of mining, it should be remembered that it occurred virtually instantaneously compared to the impact of a month's mining.

Table 7 again summarises the relevant data for this analysis.

Table 7. Structure strength input parameters for Fault 2 and ESS results for the mining of May 2003, when the M2.8 event was triggered.

Recorded ESSdiff+	Modelled	Peak	Residual	Ave_w_ESS+	
Seismic Moment [Nm]	Seismic Moment [Nm]	Friction angle [deg]	Friction angle [deg]	[MPa]	[bar]
2.5E13	4.2E13	20.0	14.5	1.6	1.9

3.2 ESS analysis on Dyke 1

This dyke was some distance ahead of the longwall at the time of the above seismic events, but was also used to test the stress triggering concept. The dyke would most likely not have slipped significantly historically, and hence the evolution of ESS leading up to the first shear slip events can be studied under the approaching longwall mining front. Two events of moment magnitudes 2.6 and 2.7 occurred on 25 November 2005 ahead of the face, most likely due to slip on the closer dyke contact.

Figure 9 shows the graph of Average ESS and ESSdiff, again with a picture of the area. Average ESS reached a level of 2.1, and ESSdiff is calculated at 27.3 bar, significantly higher than the previous cases.

Table 8 summarises the relevant data for this analysis.

Table 8. Structure strength input parameters for Dyke 1 and ESS results for the mining of November 2005, when the M2.6 and 2.7 events were triggered.

Recorded ESSdiff+	Modelled	Peak	Residual	Ave_w_ESS+	
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Seismic Moment [Nm]	Seismic Moment [Nm]	Friction angle [deg]	Friction angle [deg]	[MPa]	[bar]
2.7E13	7.0E12	22.0	18.0	2.1	27.3

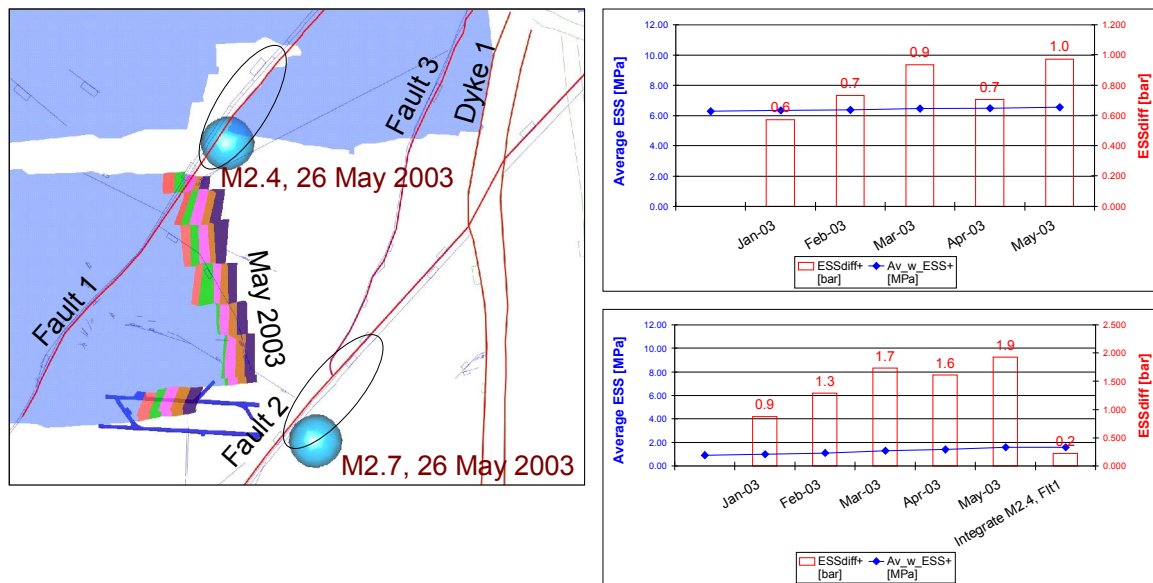


Figure 8. Average ESS and ESSdiff analysis for the two events considered. The top graph on the right gives the criteria leading up to the M2.4. The bottom graph gives the same prior to the M2.7, also showing the effect of integration of the triggering event.

3.3 Discussion

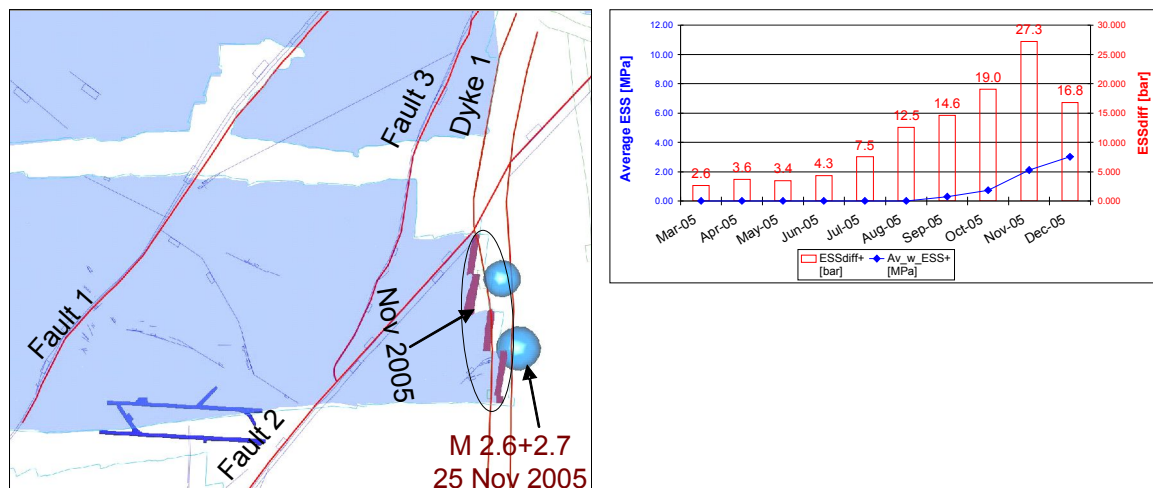


Figure 9. Average ESS and ESSdiff analysis for dyke ahead of the face, where two large tremors occurred on 25 November 2005.

It was shown how ESS analyses can be used routinely as a seismic hazard indicator. Parameters are derived from the elastic numerical model to quantify average levels of Excess Shear Stress

as well as increases thereof, due to advancing mining fronts. The emerging picture is however not as simple as considering a particular level of average ESS, with a particular additional increase, and that combination comprising a stress trigger. More work can be done towards this, but results presented here indicates that for an average ESS level of 1.6 MPa, calculated according to the methodology described, a large seismic event may be triggered. ESS increases comprising triggers by monthly mining were calculated as 1.0 bar and higher.

Another aspect that can be researched further is calibration of structure friction coefficients, which are naturally important parameters. Some calibration was done here to correlate recorded with modelled seismic moment, and although the values appear to be reasonable, absolute ESS level is not fixed. This may be possible by using estimates of seismic event Stress Drop and Apparent Stress, since these parameters relate to peak versus residual friction coefficients, and average shear stress on a structure.

4 CONCLUSIONS

The concept of Coulomb Failure Stress in earthquake seismology is identical to Excess Shear Stress in the underground mining environment, although different numerical techniques are used to model for normal and shear stress on fault planes.

Coulomb stress triggering can occur for increases as low as 1 bar for both natural earthquakes and underground mining tremors.

The case considered here, i.e. triggering of tremors in a tabular mining environment, provided a fairly clear picture of the source of tremors through the concept of Excess Shear Stress. An example was presented where it was almost certain that one tremor triggered another, in order to put stress triggering in perspective. Some light could be shed on the different nature of mine tremors experienced (stress level and source size). Elastic numerical modelling provided insight into this unexpected seismic event at a relatively large distance from the closest mining. It was concluded that the event, which caused significant damage to tunnels in the footwall, occurred due to unclamping (reduction in normal stress) over a relatively large area on the fault plane.

For this case study, the stress change due to an earlier seismic event was probably not the sole trigger. Excess Shear Stress increase due to advancing mining was at a significant rate of approximately 2 bar/month. However, the instantaneous static increase of up to 0.8 bar, together with dynamic loading due to the seismic waves comprised the trigger.

A limitation is that, although input parameters and results appear to be realistic, absolute ESS level is not attained due to the choice of friction coefficients, and more research can be done by taking into account recorded seismic source parameters. The procedures used here allow for estimation of average shear and normal stresses in a slip seismic source, with these average values used in seismic source quantification.

Although this paper discusses cases from a particular underground mining environment, it should be a useful reference case. The input information is known to a fair degree of accuracy, particularly in terms of the mining layout and in-situ stress state, and it is believed that the main features of the seismic event source mechanism are understood. Other similar analyses of Excess Shear Stress in the underground mining environment (not necessarily tabular) can be compared to the case study presented here, aiming to improve mine seismic hazard assessment.

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