4 May 2000

SIMRAC Gold & Platinum Sub-Committee
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Re: Draft Final Reports - Rock Engineering - GAP 114

... Attached please find a rock engineering draft final report GAP 114 for your consideration at the SIMGAP meeting to be held on 11 May 2000.

C. Gomes
Secretary
SIMRAC Gold & Platinum Sub-Committee

Approved
Safety in Mines Research Advisory Committee

Draft Final Project Report

Study of loading system stiffness in fault slip seismic events

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Research agency: University of Pretoria
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Executive summary

Many seismic events in mines are related to slip along geological structures such as faults. When a fault slips, the surrounding rock mass drives the slip movement. The surrounding rock mass may therefore be seen as the loading system. Because a fault loses strength once it starts to slip, the stiffness of the loading system has an important effect on how the slip movement occurs. If the loading system is soft, violent shear may occur, which could result in a large seismic event. Understanding the factors that affect the loading system stiffness will assist in designing mine layouts that improve the stiffness of the loading system.

The research presented in this report follows on a preliminary study carried out as project GAP003. The preliminary study made use of two-dimensional elastic models to assess the loading system stiffness. The objectives of this study were as follows:

- Determine whether three-dimensional models provide similar trends in loading system stiffness variations as two-dimensional models.
- Model three-dimensional situations to determine the effect of stabilizing pillars and the effect of mining towards a geological structure at different approach angles on loading system stiffness.
- Model three case studies using three-dimensional models to determine whether adverse seismicity was coincidental to changes in the loading system stiffness.
- Assess the effect of rock failure on loading system stiffness using two-dimensional models.

The studies showed that the loading system stiffness is closely related to the amount of slip that occurs along a fault plane. The results of the three-dimensional models confirmed the trends in loading system stiffness that were found from the preliminary two-dimensional analyses. It was further found that the presence of stabilising pillars resulted in a significant improvement in loading system stiffness, but increasing the width of the pillars resulted in little further improvement. Mining obliquely towards a fault was shown to be better than mining with the face parallel to the fault. Three case studies were unable to demonstrate a clear correlation between a reduction in the loading system stiffness and large seismic events. An assessment of the effect of rock failure around a stope on the loading system stiffness showed that rock failure has a detrimental effect on the loading system stiffness.

It is concluded that any measures to reduce the amount of slip along a fault will result in an improvement in the loading system stiffness. Strategies such as the reduction in the excess shear stress along a fault plane will therefore also result in improvements in the loading system stiffness.
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Glossary of symbols and abbreviations

Symbols

c : cohesion
k : Stiffness
L : Applied load
S : Shear displacement
T : Shear force

δ : Displacement
μ : Coefficient of friction
ϕ : Friction angle
σn : Normal stress
τ : Shear stress

Abbreviations

SS : Strain Softening
FLAC : Fast Lagrangian Analysis of Continua, a computer program
ESS : Excess Shear Stress
1 Introduction

1.1 Problem statement
Seismic events are the cause of a large proportion of the fatal and reportable accidents in deep gold mines. Methods of reducing the risk associated with seismic events have been the topic of SIMRAC research for many years. When designing mine layouts it is necessary to be able to optimize that layout so that seismicity will be reduced. Numerical models are widely used to simulate the proposed mining sequence and layout. The models are able to calculate equivalent stress levels around mine openings and it is possible to assess the effects of these stresses on the surrounding rock mass. Many techniques of assessing the potential for seismicity from numerical model results have been proposed in the past. The energy release rate (ERR) criterion has found wide acceptance but is limited in its scope (Salamon, 1993). The excess shear stress criterion (ESS) proposed by Ryder (1988) attempts to address the dominant mode of failure in mines, which is shearing along pre-existing geological structures. The ESS technique is widely used to assess the stability of known geological structures and to design bracketing pillars to limit the shear stress along the structures. More direct modelling of slip along planes of weakness have been undertaken using explicit modelling of the weakness planes in the rock mass. (Dennison & van Aswegen, 1993). The problems of defining the geometry of the planes and finding the correct initial state of such models precludes their use as every day design tools.

The evidence suggests that most mine related seismic events are shear failures, possibly stick-slip type slides along pre-existing geological discontinuities such as faults or dykes (Spittiswoode & Mc Garr 1975). Stiller et al (1983) recorded the similarity between many mine seismic events and natural earthquakes in terms of the seismic signatures associated with the various events. Rorke and Roering (1984) report first motion studies which suggest a source mechanism involving shear motion. The dominant role of shear slip in mine related seismicity requires that the shearing mechanism is well understood and accounted for in the design of mine layouts.

The ESS criterion uses the results of numerical stress analyses to provide an indication of areas along known geological structures where the dynamic shear strength of the structure may have been exceeded. The existence of excessive shear stresses does not necessarily imply that violent slip will occur. A geological structure may be driven to shear but the shear displacement may occur aseismically. Violent failure will only occur if the shear stiffness of the loading system is lower than the post peak shear resistance of the fault. A sudden drop in the shear resistance of a geological structure is likely to result in a sudden, violent failure. At present there are no readily available techniques for assessing the stiffness of the loading system that drives shear type seismic events. Other than a preliminary study of loading system stiffness reported in project GAP003 (1993), no further research into this aspect has been carried out.

1.2 Objectives
The focus of the research presented in this report is the stiffness of the loading system that drives a geological structure to shear. Knowledge of how the mining geometry may affect the loading system stiffness may assist in changing mine layouts to reduce the likelihood of violent seismic events. The research presented here is supplementary to the preliminary
work carried out under project GAP003. Since the work in GAP003 was only carried out using two dimensional elastic models, the focus of this work was to extend the work to three dimensional models, non-linear models and to conduct case studies. The specific objectives of this work were:

- Determine whether three-dimensional models provide similar trends in loading system stiffness variations as two dimensional models.
- Model three-dimensional situations to determine the effect of barrier pillars and the effect of mining towards a geological structure at different approach angles on loading system stiffness.
- Model three case studies using three-dimensional models to determine whether adverse seismicity was coincidental to changes in the loading system stiffness.
- Assess the effect of rock failure on loading system stiffness using two-dimensional models.

1.3 Scope of research

The research was commenced by a review of the literature to provide the necessary understanding of the concepts of loading system stiffness and to ensure that duplication of previous work did not occur.

Studies of idealised layout were carried out using the MINSIM-D stress analysis program of the Chamber of Mines of South Africa, (1985). It was necessary to develop a supplementary program to calculate the stiffness of the loading system from the results. The models evaluated were similar to those evaluated in two dimensions as part of project GAP0003. Additional models were set up to model situations that are not amenable to two-dimensional modelling.

Data for the case studies were collected by visiting three different mines, each representing a different mining district. Data on mining geometry, mining sequence, geological structures and seismic records were collected at each site. The evaluation of the case studies was carried out using the MINSIM-D program. Three cases were considered, two were longwall mining situations and the third was a remnant mining situation.

The non-linear models were carried out using the FLAC finite difference modelling program by Itasca (1995). The program has the ability to model geological structures explicitly and it is possible to study the shear displacements along these structures. The program has the ability to simulate the non-linear behaviour of the failed rock around the slope excavations. Stresses are re-distributed in response to the failure and this affects the geological structures too. A number of different models were set up to compare elastic and non-linear results for simplified layouts. The strain softening option of the FLAC model was used to simulate the failure of the brittle quartzite rocks. Extensive use was made of spreadsheet programs to evaluate the stiffness of the loading system from the FLAC results.
2 Loading system stiffness and shear failure

2.1 Loading system stiffness in compression

Instability in rock under load results from the constitutive behaviour of the rock material and may involve shearing, splitting or crushing of the intact rock. Loading intact rock is accompanied by deformation of the rock material. The resistance to load typically increases to a peak value, after which brittle rocks will shed load with continued deformation. The post peak failure behaviour of rock is strongly influenced by the stiffness of the loading system. A rock specimen can be made to fail gradually or in a violent manner, depending on the stiffness of the loading system. Stiffness $k$ may be expressed as:

$$k = \frac{L}{\delta}$$

where $L$ is the applied load and $\delta$ is the associated deformation. If the stiffness of the loading system is less than the post peak stiffness of the rock sample, the ability of the rock specimen to resist load decreases faster than the load applied to it by the loading system. The situation is unstable and results in violent failure as the excess energy is released in the form of kinetic energy. A similar process occurs when a discontinuity, such as a fault is loaded in shear. The post peak shear resistance of the fault and the shear stiffness of the loading system govern the post peak failure behaviour.

2.2 Fault shear and instability

When fault shearing takes place, the fault gouge may be seen as the specimen which provides resistance to shearing. The loading system is the surrounding rock, which attempts to drive the fault plane in shear.

![Image](image-url)

Figure 1 Typical shear resistance curve of a natural discontinuity
Changes in shear resistance with continuing displacements may be studied by direct shear tests on natural discontinuities in rock. The resulting shear force/shear displacement curve is typically as shown in Figure 1. As the shear displacement commences, the shear resistance rapidly increases to a peak value. Once the peak value is reached, a rapid reduction in resistance is observed. The reduction may be explained by the break down of cohesion along the shear surface, destruction of irregularities that provide interlocking and grinding of the material in the zone of displacement. The drop in shear resistance is dependent on the properties of the interface between the two sliding blocks as well as the magnitude of the normal stress across the shearing surface.

The shear stiffness of the failing surface may be determined by the slope of a tangent to the curve, as shown in Figure 1. The units of stiffness would be units of force per unit of displacement. It can be seen that the post peak stiffness of the plane varies as the displacement increases, decreasing to nearly constant residual values.

The effect of the loading system stiffness in shear is demonstrated by considering a simple spring and slider system, shown in Figure 2. The spring stiffness $K$ represents the shear stiffness of the surrounding rock mass, and the stress-displacement curve for the slider models the non-linear constitutive relation for the fault surface.

**Figure 2 Spring-slider system**

If the spring stiffness is greater than the slope of the post peak segment of the load-displacement curve of the fault, stable loading and displacement of the fault will occur, this is demonstrated in Figure 3 where the solid line represents a stiff spring. The dotted line represents a soft spring. In this case the system becomes unstable when the displacement exceeds the point indicated.

To determine the final equilibrium of the spring-slider system after unstable slip, it is necessary to consider the energy changes associated with the unstable motion. The area
between the load displacement curves for the spring and fault represents the energy released in the form of kinetic energy. In Figure 4, if the final state of equilibrium is indicated by position C. The energy released in block motion from A to B must be dissipated in various forms of damping such as frictional dissipation in the slider.

In the case of faults that are at a residual state of shear strength, the displacement weakening model is not sufficient to explain violent failure, and an alternative concept of unstable deformation must be considered. The velocity dependence of the coefficient of friction for sliding surfaces has been known for many years. The proposal that a coefficient of dynamic friction for a fault less than the static coefficient was the cause of earthquake instabilities was made by Brace and Byerlee (1966). It was proposed that the static shear strength of a fault surface is defined by:

\[ \tau_s = \mu_s \sigma_n \]  

Equation 2

where \( \mu_s \) is the coefficient of static friction. The dynamic resistance to slip is taken to be described by:

\[ \tau_d = \mu_d \sigma_n \]  

Equation 3

where \( \mu_d \) is the coefficient of dynamic friction. Evaluation of the two equations indicate a stress drop given by \((\tau_s - \tau_d)\), in the transition from static to dynamic conditions. Stress drops of 5-10% of the static shear strength have been observed in the laboratory. Ryder (1988) discusses variable fault shear strength in rockburst mechanics.

Figure 3 Loading through a stiff and soft spring
2.3 Determination of loading system stiffness

Two dimensional numerical models analyzed as part of the project GAP003 showed that the loading system stiffness is affected by the elastic properties of the rock mass, the geometry of the mining excavations, the orientation of the fault and the stress field. Several methods of calculating the loading system stiffness were compared as part of project GAP003. The method used in this research is the same as the method used in GAP003. The loading system stiffness was determined from numerical models in which the fault was explicitly modelled. The stiffness associated with a particular model set-up was determined by comparing the slip at different points along the fault with the corresponding shear stress across the fault. The procedure was repeated twice, varying the friction angle along the fault by a small amount so that two sets of results are obtained. By selecting a small increment in the friction angle, a line through the two points was assumed to represent a tangent to the shear stress-shear displacement curve. The following equation is used to calculate the stiffness at a point along a fault for a given friction angle $\alpha$:

$$k_\alpha = \frac{\tau_{\alpha+\delta} - \tau_{\alpha-\delta}}{S_{\alpha+\delta} - S_{\alpha-\delta}}$$

[Equation 4]

where $\tau$ is the shear stress and $S$ is the shear displacement at a point. The subscripts refer to the results at friction angles of $(\alpha + \delta)$ and $(\alpha - \delta)$ where $\delta$ is a small increment in friction angle, usually taken as one degree. This procedure was used in the three-dimensional MINSIM-D models as well as the two-dimensional non-linear FLAC models. This method of calculating the stiffness produces a stiffness result at numerous points (each element) along the fault structure. It also calculates a stiffness value even if the fault has not slipped in the conventional sense. If the fault is behaving elastically, a high positive stiffness will be calculated and if it has slipped, the stiffness will be negative.

![Shear displacement](image)

Figure 4 Final state of equilibrium
3 Three-dimensional analysis of loading system stiffness

The objective of the three dimensional analyses was first to verify that a three-dimensional model provides the same trends in results as the two dimensional models used in the GAP003 project. This was followed by modelling situations that are not amenable to two-dimensional modelling, such as changing the approach angle when mining to a fault and assessing the effect of stability pillars.

3.1 Method of analysis

The MINSIM-D stress analysis program was used in the analyses. Models were set up to replicate the two dimensional models used in project GAP003. A large mined out span was simulated approaching a fault. The fault was modelled explicitly as a discontinuity plane. The friction angle of the plane was varied so that two sets of shear stress and displacements results could be obtained, allowing a stiffness calculation to be made using Equation 4. The fault cohesion was set to zero in all the analyses to simulate the dynamic strength of the fault. A computer program was written which reads the output of the two MINSIM-D analyses and calculates the stiffness at each point in the plane of the fault. An example of the resulting stiffness values in a plane dipping at 80 degrees is shown in Figure 5. It can be seen that towards the edges of the area of slip the stiffness becomes more negative, i.e. the stiffness increases, while at the center of the slip area the stiffness is low. For the purpose of comparing stiffness results, the low point was taken as representative of the stiffness for a particular analysis. The reasoning was that if the fault fails in an unstable manner, it is most likely to commence at the point where the loading system stiffness is at a low value. Usually the low point coincides with the maximum value of the ESS.

For the three-dimensional analyses a base case similar to the two-dimensional analyses presented in project GAP003 was set up. The mining depth was 2000 m and a mined out span of 225m was modelled on one side of a fault. It was assumed that a 10m pillar of solid rock existed between the fault and the longwall face. The longwall face was parallel to the strike of the fault. The fault was modelled to extend 300m above and below the plane of the reef and was assumed to dip at 70 degrees. The properties of the rock mass and fault were as shown in Table 1.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Elastic modulus</td>
<td>70 GPa</td>
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<tr>
<td>Poisson's ratio</td>
<td>0.2</td>
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<tr>
<td>Rock density</td>
<td>2700 kg/m3</td>
</tr>
<tr>
<td>Horizontal to vertical stress ratio</td>
<td>0.5</td>
</tr>
<tr>
<td>Friction angle of fault</td>
<td>30°</td>
</tr>
</tbody>
</table>
3.2 Results
The results of the analyses, in which the effect of variations in the input parameters and geometry on loading system stiffness were varied, are presented below. All the analyses were based on the parameters and geometry described above. In the results that follow, only one parameter was modified at a time. Note that in the graphs that follow, stiffness values close to zero imply a lower stiffness and hence a greater likelihood of violent failure.
3.2.1 Effect of variation in elastic modulus of the rock mass.

The elastic modulus of the rock mass was varied between 30 GPa and 90 GPa. The variation in the minimum stiffness along the fault is shown in Figure 6. The results show that as the elastic modulus of the rock mass increases, the stiffness increases and flattens out when the modulus reaches a value of 70 GPa. The fact that the stiffness drops slightly when the modulus is increased to 90 GPa may be a model effect. These results confirm the general trend that the loading system stiffness increases with an increase in rock mass elastic modulus.

![Figure 6](image.png)

**Figure 6 Effect of variations in elastic modulus of rock mass on loading system stiffness**

3.2.2 Effect of mining depth

The effect of mining depth was evaluated by considering the reef plane at depths of 1000 m to 4000 m. The results showed that the loading system stiffness is insensitive to mining depth, although the amount of slip along the fault increased with increasing depth. The loading system stiffness varied by less than 2% for the different depths. These variations likely to be related to model accuracy.

3.2.3 Effect of friction angle of the fault

The friction angle of the fault was varied between 15 and 40 degrees. The results, shown in Figure 7 show that a lower friction angle results in lower loading system stiffness. This result may seem strange at first, since it may be argued that the “specimen” being loaded should not affect the loading system. However, the loading system is affected by the fault behaviour because the greater the length of fault slip the greater the dislocation between the two sides of the loading system. As the dislocation increases in length its stiffness decreases. This is similar to increasing the mined out span when considering the loading system in pillar stability analyses.
3.2.4 Effect of fault dip angle

The fault dip angle was varied between 30 and 90 degrees. The resulting variation in stiffness of the loading system is shown in Figure 8. It can be seen that shallower dipping faults are more favourable in terms of stiffness than steeper faults.
3.2.5 Effect of distance of mining face to fault

As a longwall face approaches a fault the changes in the geometry affects the loading system stiffness. The results of simulations in which the longwall face was modelled to be distances between 20m and 5m from the fault are presented in Figure 9. The results show an almost linear decrease in the loading system stiffness as the longwall face approaches the fault.

![Graph showing the relationship between loading system stiffness and distance of longwall face to fault.](image)

**Figure 9** Effect of the distance of the longwall face to the fault on loading system stiffness.

3.2.6 Effect of stability pillars

Stabilizing pillars will have the effect of clamping a fault and reducing the potential area of slip. In these analyses a series of stabilizing pillars were modelled which were perpendicular to the strike of the fault, i.e. the pillars were abutting against the fault. The center spacing of the pillars was 240m and the pillar width was varied between 20m and 60m. Figure 10 shows the results of the analyses. The loading system stiffness is seen to increase with increasing pillar width. The changes are small relative to the increase in pillar width, for example trebling the pillar width from 20 m to 60 m only increases the stiffness by about 7 percent.
3.2.7 Effect of angle between longwall face and fault

When mining towards a fault it is common practice to change the angle at which the longwall approaches the fault. If the longwall approaches the fault so that the face is parallel to the fault, the reasoning is that a larger proportion of the fault will be affected simultaneously, which could result in large seismic events. Two models were set up to evaluate the effect of approaching a fault at 45 degrees and at 30 degrees. The models were set up so that the final step would be identical to the base case in which the longwall face is parallel to the fault. The results are presented in Figure 11, where it can be seen that a small advantage is gained in the loading system stiffness if the approach angle is 45 degrees rather than 30 degrees.
3.3 Discussion of three-dimensional analyses

The three dimensional analyses confirmed the general trends found in the two-dimensional analyses which were conducted as part of project GAP003. The three dimensional models were in addition used to assess the effect of introducing stability pillars and the effect of mining at different angles between the fault and the longwall face. The results showed that stability pillars have a beneficial effect on the loading system stiffness, although increasing the pillar width did not have a significant benefit in terms of the loading system stiffness. Mining towards the fault at an angle of 45 degrees rather than 30 degrees was shown to have a limited benefit in terms of loading system stiffness.

Since the loading system stiffness is affected by the size of the area that has slipped, it can be said that minimizing the potential area of slip along a fault surface will increase the loading system stiffness. This allows the conclusion in the GAP003 report to be repeated here: "...any action taken to reduce the length of fault slip will also reduce the potential for violent slip".
4 Case studies

4.1 Method of analysis

The MINSIM-D stress analysis program was used to conduct the analyses for the case studies. Data on mine seismicity, mining geometry and mining sequence were obtained from the mines in question. Where possible local field stress data and other rock related data were collected. The sites selected for analysis were all associated with large, violent seismic events that were thought to be associated with one or more major geological structures.

4.2 Case study – Far West Rand longwall mining

This case study evaluates longwall mining in a deep mine on the Far West rand. The longwall in question was mining towards a number of large geological structures illustrated in Figure 12. During September 1992 a large seismic event occurred which was thought to have been associated with the acid dyke. The mining up to and beyond September 1992 was modelled in nine increments. The loading system stiffness was determined for the Acid dyke at each mining step.

The loading system stiffness results for the nine mining steps and the actual seismicity for the corresponding period are shown in Figure 13. The results show that the model "predicts" a sudden decrease in stiffness during November 1992. A large seismic event occurred during September 1992. Although the model does not show accurate time correlation, for planning purposes the indication that a violent event could occur would have been useful and may have resulted in an evaluation of alternative strategies.
Figure 12 Far West Rand case study

Figure 13 Variation in stiffness and cumulative seismic moment for Far-West Rand case study
4.3 Case study - Remnant mining in the Welkom Area

The general layout and location of geological structures relative to the mining faces are shown in Figure 14. The mining took place at a depth of about 2600 m in the proximity of a large fault with a displacement of approximately 200m. Seismicity in the vicinity was monitored. This study was carried out to evaluate the effect of the mining on the 200m fault. The loading system stiffness along the fault for the different stages of mining and the actual seismicity for the corresponding period are shown in Figure 15. The results show that the loading system stiffness was soft at step 7 and was followed by an increase in seismicity during step 8.

Figure 14 Plan showing layout of Welkom case study
Figure 15 Variation in stiffness and cumulative seismic moment for Welkom case study
4.4 Case study – East Rand longwall mining

The mining evaluated as part of this case study took place at a depth of about 3000m at a mine in the East Rand. The general layout and location of geological structures relative to the mining faces and the direction of mining are shown in Figure 16. The loading system stiffness was calculated for dyke 4 and for dykes 2 and 3 with dip angles of 80 and 35 degrees respectively. A major seismic event took place during the mining of step 5, shown in Figure 16. It is not clear which one of the two geological structures was responsible for the event.

Figure 16 Plan showing mining layout and geological structures for East Rand case study
The results of the loading system stiffness of the 80 degree fault are shown in Figure 17. The loading system stiffness of the 80 degree fault tends to increase as the mining progresses and hence the possibility of a violent seismic event on this specific structure decreases. The loading system stiffness of the 35 degree fault remains constant at a value of -0.2 GPa/m from step 1 through to step 5.

From the stiffness results it was not evident which of the two faults was responsible for the seismic event in step 5. The stiffness combined with other parameters could be used to indicate increased risk of violent seismicity.

4.5 Discussion of case studies

The case studies show that a tentative correlation appears to exist between a decrease in loading system stiffness and the occurrence of large seismic events. Many more case studies would have to be evaluated to determine whether a firm relationship exists. The combination of loading system stiffness with other model parameters may provide a more reliable method of predicting the likelihood of large seismic events.
5 Non-linear two-dimensional analyses

5.1 Objectives

The two-dimensional model analyses had the objective to determine how the non-linear behaviour of the rock mass surrounding a deep mine excavation would affect the stiffness of the loading system. The analyses were therefore carried out using a stress analysis program that is able to simulate the non-linear behaviour of the failed rock and the resulting stress re-distribution.

5.2 Method of analysis

The two-dimensional stress analysis program FLAC (Itasca, 1995) was used in the analyses. The program was used to set up a model of a deep level stope and a fault, similar to the models used in the elastic analyses. The model layout and dimensions are shown in Figure 18. The stiffness was determined in a similar way to that used in the elastic models. Each model was run twice, varying the friction angle of the fault by a small amount so that two sets of shear stress – shear displacement data were obtained. Most of the models were analysed for both elastic and non-linear rock mass parameters.

For the non-linear analyses the rock mass was assigned strain softening behaviour. Strain softening was achieved by cohesion softening only, the friction angle of the rock mass was assumed to remain constant. The dilation angle was assumed to reduce linearly from a value of 12° to zero as the non-linear strain increased form zero to a value of 0.016. The properties of the rock mass and the fault interface are summarised in Table 2. Appendix 1 is an example data file of one of the FLAC models. An example of the results obtained from one of the models is presented in Figure 19.
K-RATIO = 0.5
ROCK - QUARTZITE

FAULT:
COH = 0
FRIC = 29° / 31°
$K_N = 10E9$
$K_S = 10E9$

Figure 18 Layout of two-dimensional model
Figure 19 Example of two-dimensional model output

Table 2 Properties used in two-dimensional models

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk modulus</td>
<td>39 GPa</td>
</tr>
<tr>
<td>Shear modulus</td>
<td>29 GPa</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>0.5 MPa</td>
</tr>
<tr>
<td>Cohesion</td>
<td>30 MPa</td>
</tr>
<tr>
<td>Residual cohesion</td>
<td>0.5 MPa after 0.016 strain</td>
</tr>
<tr>
<td>Friction angle</td>
<td>30° constant</td>
</tr>
<tr>
<td>Dilation angle</td>
<td>12° reducing to 0° after 0.016 strain</td>
</tr>
<tr>
<td>Fault normal stiffness prior to slip</td>
<td>10 GPa/m</td>
</tr>
<tr>
<td>Fault shear stiffness prior to slip</td>
<td>10 GPa/m</td>
</tr>
</tbody>
</table>
The loading system stiffness associated with each model was calculated using a spreadsheet program. Input to the spreadsheet was obtained by saving the shear stresses within the fault plane and the shear displacements of both sides of the fault from the FLAC analysis. This was repeated for two runs, each using a different friction angle. The two sets of results were then used to calculate the loading system stiffness.

### 5.3 Results

The effect of rock mass failure on the shear behaviour of a vertical fault is illustrated in Figure 20, where the slip displacement along the fault is plotted for an elastic analysis and a non-linear strain softening analysis. The slope face was 10 m from the fault plane. The results show that if rock failure is allowed to occur the slip movements increase, this would reduce the stiffness of the loading system.

![Figure 20 Slip along a fault for elastic and strain softening models](image)

**Figure 20 Slip along a fault for elastic and strain softening models**

Figure 21 illustrates the changes in the shear stress along the fault for an elastic analysis and a non-linear strain softening run. The shear stresses along the fault are shown to increase in magnitude. From a point of view of magnitude of potential seismic event, the increased slip and increased stresses indicate the potential for larger seismic events to occur.
The stiffness results for a fault in a strain softening model is shown in Figure 22 that combines the slip and stiffness results. The two slip graphs, for 29 and 30 degree friction angles, are shown together with the resulting stiffness graph. The resulting stiffness is negative where the fault has exceeded its elastic limits and has broken the bond between the two sides of the interface, i.e. the fault has sheared. When the fault is behaving elastically, the stiffness is positive, because an increase in shear stress results in an increase in shear resistance. Once the fault has sheared, the stiffness is negative, because the shear stress decreases across the fault while the slip is increasing. The positive stiffness values are very high and plot off the graph.

A comparison between the stiffness of the fault for elastic and non-linear, strain softening cases is illustrated in Figure 23. The graph shows the stiffness results in both the elastic and sheared portions of the fault. It can be seen that the strain softening model results in a lower value of system stiffness when the fault has sheared. This would imply a greater tendency to cause violent failure. However, the two graphs are similar in shape and the rock failure does not change the overall trend in stiffness behaviour.

5.4 Discussion of results
The two dimensional non-linear model results have shown that rock failure around a stope excavation has a detrimental effect on the loading system stiffness. The slip displacements are increased and the result is a reduction in the loading system stiffness. The overall behaviour of the loading system is not affected.
Figure 22 Change in slip along fault and resulting stiffness

Figure 23 Difference in loading system stiffness for elastic and strain softening models
6 Conclusions
The study of the loading system stiffness in fault slip seismic events has shown that:

- Three-dimensional models confirm the overall behaviour of the loading system shown in two-dimensional analyses that were carried out as part of project GAP003.
- The loading system stiffness is shown to be closely related to the area of slip along a fault plane. The larger the area of slip, the lower and more hazardous the loading system stiffness becomes. This is doubly hazardous, since the magnitude of a seismic event is also related to the extent of slip.
- Case studies did not reveal a clear relationship between the loading system stiffness and the occurrence of large seismic events.
- Non-linear model analyses have shown that rock failure around a stope excavation results in lowering the loading system stiffness, hence increasing the potential for violent failure.
- The conclusion made in GAP003, that any changes made to reduce the potential amount of slip along a fault will also reduce the likelihood of violent failure of the fault, is confirmed. This implies that, for example, strategies to reduce the ESS will automatically improve the stiffness of the loading system.
7 References


Appendix 1: Data file for FLAC analysis
new
3
SS - mined to dyke
grid 80 80
set large
set grav=10
mo ss
*BOTTOM PART
gen 0,0 0,150 100,150 100,0 i=1,11 j=1,17 rat=0.83,0.83
gen 100,0 100,150 300,150 300,0 i=11,71 j=1,17 rat=1,0.83
gen 300,0 300,150 375,150 375,0 i=71,81 j=1,17 rat=1.2,0.83
*MIDDLE PART
gen 0,150 0,230 100,230 100,150 i=1,11 j=17,58 rat=0.83,1
gen 100,150 100,230 300,230 300,150 i=11,71 j=17,58 rat=1,1
gen 300,150 300,230 375,230 375,150 i=71,81 j=17,58 rat=1.2,1
*TOP PART
gen 0,230 0,800 100,800 100,230 i=1,11 j=58,81 rat=0.83,1.2
gen 100,230 100,800 300,800 300,230 i=11,71 j=58,81 rat=1,1.2
gen 300,230 300,800 375,800 375,230 i=71,81 j=58,81 rat=1.2,1.2
win 80 320 100 240
* PROPERTIES
* vg rock quartzites
prop bu=39e9 sh=29e9 den=2700 tens=0.5e6 ctab=1 ftab=2 dtab=3
table 1 0.30e6 0.016,0.5e6
table 2 0.30
table 3 0.12 0.016 0
*DO MINING
mo null i=40 j=1.80
*RE-GENERATE
gen 100,0 100,150 200,150 200,0 i=11,40 j=1,17 rat=1,0.83
gen 200,0 200,150 300,150 300,0 i=41,71 j=1,17 rat=1,0.83
*MIDDLE PART
gen 100,150 100,230 200,230 200,150 i=11,40 j=17,58 rat=1,1
gen 200,150 200,230 300,230 300,150 i=41,71 j=17,58 rat=1,1
*TOP PART
gen 100,230 100,800 200,800 200,230 i=11,40 j=58,81 rat=1,1.2
gen 200,230 200,800 300,800 300,230 i=41,71 j=58,81 rat=1,1.2
int 1 aside fr 40,1 to 40,30 bside fr 41,1 to 41,80 kn=10e9 ks=10e9
int 1 coh=0 fric=31
* STRESSES
ini syy=-60e6 var 0 21.6e6
ini sxx=-36e6 var 0 12.96e6
ini szz=-20e6 var 0 7.1e6
fix x i=1
fix x i=81
fix x y j=1
fix y j=81
step 1
mo null i=19,38 j=30
*HISTORIES
his unbal
his ydis i=40 j=31
his ydis i=41 j=31
his ydis i=40 j=35
his ydis i=41 j=35
step 2000
sav vf3831b.sav
set log r3831.log
set log on
pr ydisp i=40
pr ydisp i=41
pr if 1
set log off