SAFETY IN MINES RESEARCH ADVISORY COMMITTEE

# SIMRAC

# Final Project Report

Title : PRELIMINARY STUDY OF THE EFFECTS OF FAULT PROPERTIES AND MINING GEOMETRY ON THE STIFFNESS OF THE LOADING SYSTEM IN FAULT SLIP SEISMIC EVENTS AS A BASIS FOR IDENTIFYING SITUATIONS PRONE TO SEISMIC ACTIVITY

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## SUMMARY

The mechanism of most seismic events is shear displacement along geological faults. Seismicity occurs if the slip takes place violently and kinetic energy is released into the surrounding rock. The rock surrounding the fault plane may be seen as a loading system which drives the slippage along the fault. The stiffness of the rock surrounding a fault plane will determine whether slips takes place violently or not. The project was aimed at determining how the relative geometry of a fault and a tabular excavation affects the shear stiffness of the surrounding strata. If the shear stiffness is high, a fault will be less prone to slip.

Two-dimensional numerical model analyses were carried out in which a tabular excavation and a fault plane were simulated. The fault was allowed to slip by varying the shear resistance of the fault. The magnitude of slip between the sides of the fault and the shear resistance of the fault were used to determine the stiffness of the loading system. A number of analyses were carried out in which the relative geometry of the fault and excavation were varied to assess the effects on the loading system stiffness.

It was found that the length of fault which is subject to slip has the most significant effect on the stiffness of the loading system. As the length of fault which has slipped increases, the shear stiffness of the surrounding rock decreases, this is similar to the situation in coal mines where the normal stiffness of the surrounding strata is reduced as the mining span increases. Therefore, any remedial action to reduce the length of slip along a fault will also reduce the potential for violent failure.

Cost of project: The budget for the project was R11 800 exclusive of value added tax.

CONTENTS

# PRELIMINARY STUDY OF THE EFFECT OF FAULT PROPERTIES AND MINING GEOMETRY ON THE STIFFNESS OF THE LOADING SYSTEM IN FAULT SLIP SEISMIC EVENTS AS A BASIS FOR IDENTIFYING SITUATIONS PRONE TO SEISMIC ACTIVITY

**PROJECT GAP003**

## 1.0 INTRODUCTION

### 1.1 Background

The mechanism of most large seismic events in mines is known to be shear displacement (slip) along geological faults[1]. Seismicity occurs if the slip takes place violently and kinetic energy is released into the surrounding rock in the form of seismic shock waves. Under certain conditions non-violent slip may occur without releasing any kinetic energy. One of the factors which determines the amount of kinetic energy released during fault slip is the shear stiffness of the surrounding strata. The surrounding strata is seen as a loading system which drives a fault to failure. If the shear stiffness of the loading system is high, faults are less likely to slip in a violent manner[2].

### 1.2 Stable and unstable slip along a fault

During fault slip the shear stress on the fault decreases whilst the slip displacement increases. The shear stiffness of the surrounding strata at any point along a fault ($K_s$) is the ratio between the drop in shear stress and the resulting slip displacement.

$$K_s = \frac{\Delta \tau}{\Delta s} \qquad (1)$$

Since the shear stress decreases with an increase in slip the resultant stiffness will be negative.

Similarly, the stiffness of the fault ($K_f$) is defined as the ratio between the slip displacement and the shear resistance between the two surfaces of the fault. The fault strength and stiffness may be divided into three components of behaviour: elastic, slip weakening and residual, shown in figure 1. Before slip takes place the fault behaves elastically and has a positive stiffness. This behaviour continues until its peak strength is reached. Once the peak strength is exceeded the fault starts to slip and the resistance to slip decreases, resulting in negative stiffness. After a certain amount of slip, the fault reaches its residual strength

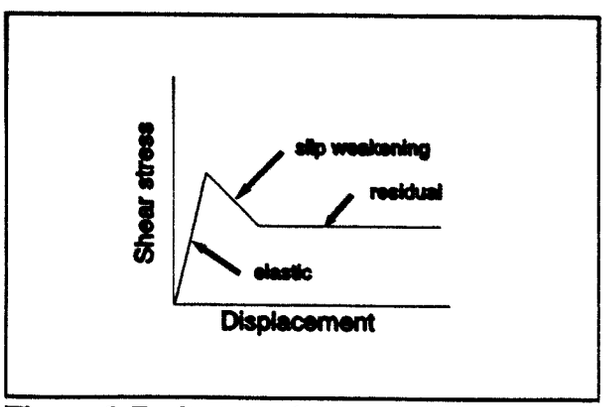

**Figure 1** Fault strength

and the stiffness becomes zero.

The drop in strength along the fault, from peak to residual values, has an effect on the mode of slip, whether it will be controlled or uncontrolled. If the loading system stiffness is less (steeper negative slope, see figure 2a) than the post peak stiffness of the fault, slip will occur in a controlled manner. However, if the loading system stiffness is greater (flatter negative slope, see figure 2b) then uncontrolled slip will occur.

The stiffness of the loading system can therefore determine whether a fault will slip in a controlled or uncontrolled manner. Two similar faults will therefore not necessarily slip in a similar manner if the loading system stiffness is not the same. The geometry of the fault and mining excavations will determine the rate at which the loading system unloads during slip and whether slip will be violent or not.

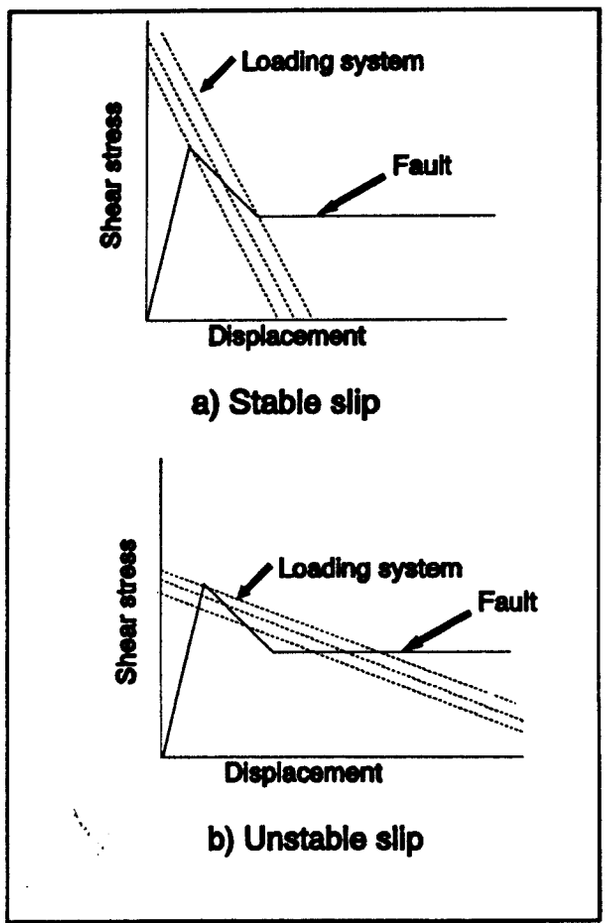


**Figure 2** Stable and unstable slip conditions

### 1.3 Objective

The objective of this investigation was to determine how the relative geometry of a fault and a tabular excavation affects the stiffness of the loading system so that situations which are prone to seimic activity can be identified.

### 1.4 Scope of study

The study was limited to typical gold mining situations in which a tabular excavation is mined towards a planar fault. A simple two dimensional numerical model was used to simulate a fault and a tabular excavation. Only quasi-static conditions were considered. The amount of slip along the fault was compared to the shear stress on the fault to determine the stiffness of the surrounding strata. Initial analyses were carried out to determine a method for calculating system stiffness and to assess the sensitivity of the model to the input parameters. Analyses were then carried out to evaluate the effect of the following on loading system stiffness :

a) mined out span;
b) depth below surface;
c) distance from fault to excavation;
d) fault inclination;
e) the presence of backfill.

## 2.0 METHOD OF ANALYSIS

The BESOL P5002 stress analysis program[3] was used to simulate a fault and tabular mining excavations. The program is a two dimensional boundary element stress analysis package which is makes use of displacement discontinuity elements[4] to simulate excavations with large aspect ratios. The displacement discontinuity elements are also used to simulate the behaviour of faults by assigning initial stiffnesses to the elements and forcing them to comply to the Mohr-Coulomb criterion to simulate slip. The program is not able to model the dynamic behaviour of a fault during slip, but rather solves for the equilibrium condition after slip has taken place.

### 2.1 Model geometry

The layout of a typical problem geometry used in this study is shown in figure 3. The inclination of the fault, excavation span, depth below surface and distance between the excavation and the fault were varied in the analyses. Details are presented with the results of each case as it is discussed.

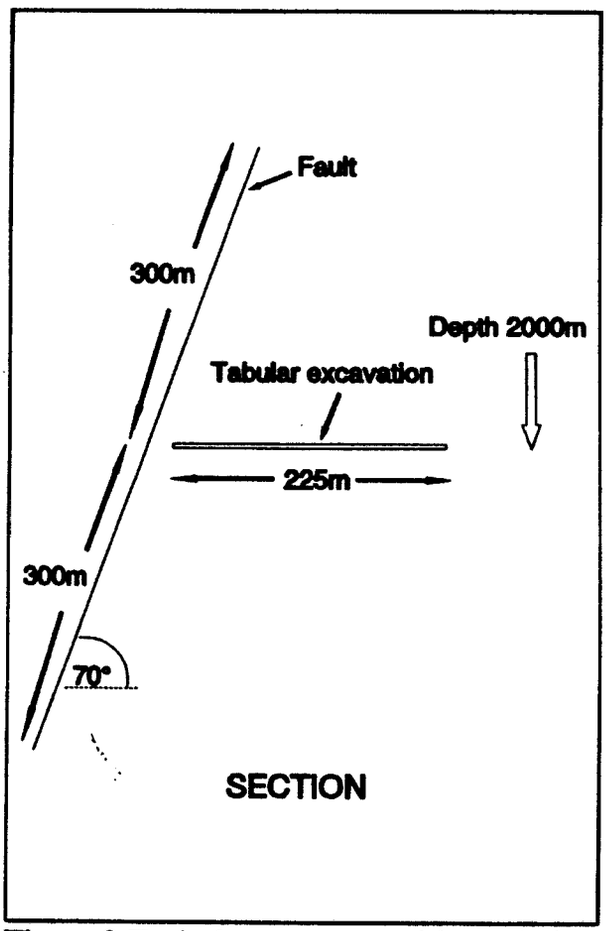


**Figure 3** Typical geometry used in analysis

### 2.2 Model parameters

The elastic properties of the surrounding rock in the analyses were as follows:

Elastic modulus = 70,0 GPa
Poisson's ratio = 0,2

The fault was assumed to be 0,01 m wide with elastic stiffness as follows:

Normal stiffness = 350,0 GPa/m
Shear stiffness = 145,8 GPa/m

The strength of the fault was assumed to remain constant during slip, unlike the true behaviour where the strength reduces with slip. The model allows slip to continue until a state of equilibrium is achieved. The results obtained from the model therefore indicate the equilibrium situation after slip. Intermediate conditions during slip cannot be assessed using the model.

### 2.3 Method of evaluating system stiffness

Initially a number of analyses were carried out to determine a suitable method of assessing the system stiffness. The stiffness at a single point along a fault was first determined by modelling a fault and an excavation. The strength of the fault was reduced by reducing the friction angle in steps. For each friction angle the shear resistance changes and a different

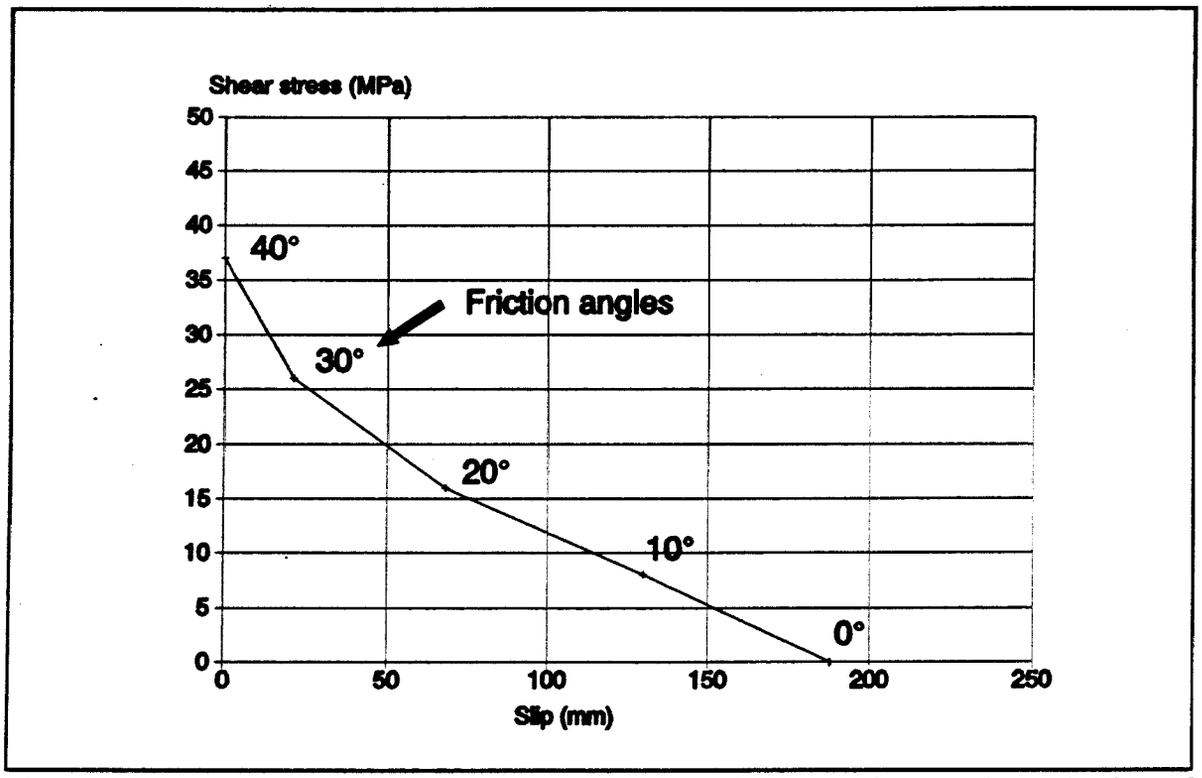


**Figure 4** Stress-slip curve for a single point along a fault. Slip induced by reduction of friction angle.

amount of slip resulted at the point of interest. The results are shown in figure 4. The stiffness is the slope of the line. It can be seen that as the amount of slip increases the stiffness becomes less negative. One of the reasons for the change in stiffness is that the length of slip along the fault changes as the slip increases. The behaviour of the fault therefore influences the stiffness of the loading system.

There are a number of methods which may be used to obtain the obtain the stiffness over the entire length of the fault. All the methods involve changing the stress condition in the fault and noting the response of the surrounding rock. The stiffness may then be calculated using equation 1. The stresses can be changed at a single point along the fault, along the entire fault or only where slip has occurred. The reaction of the surrounding rock depends on the length of fault activated. Different stiffness results will therefore be obtained by different methods of fault activation. Four different methods of fault activation are described below, followed by a summary of the results.

*a) Stress changed at a point - frictionless fault*

The first method that was investigated was modelling the fault as a slit with zero cohesion and friction. The stiffness at a point along the fault was determined by imposing an external shear stress and noting the resulting slip at that point. A model was set up to simulate a horizontal excavation with a span of 225m and a vertical fault at a depth of 2000m. There was a 10 m pillar between the fault and the one end of the excavation. The base case was obtained by running the model without any stresses along the fault, this provided the slip along the fault for zero stress. A shear stress of 5 MPa was imposed on the fault at a point

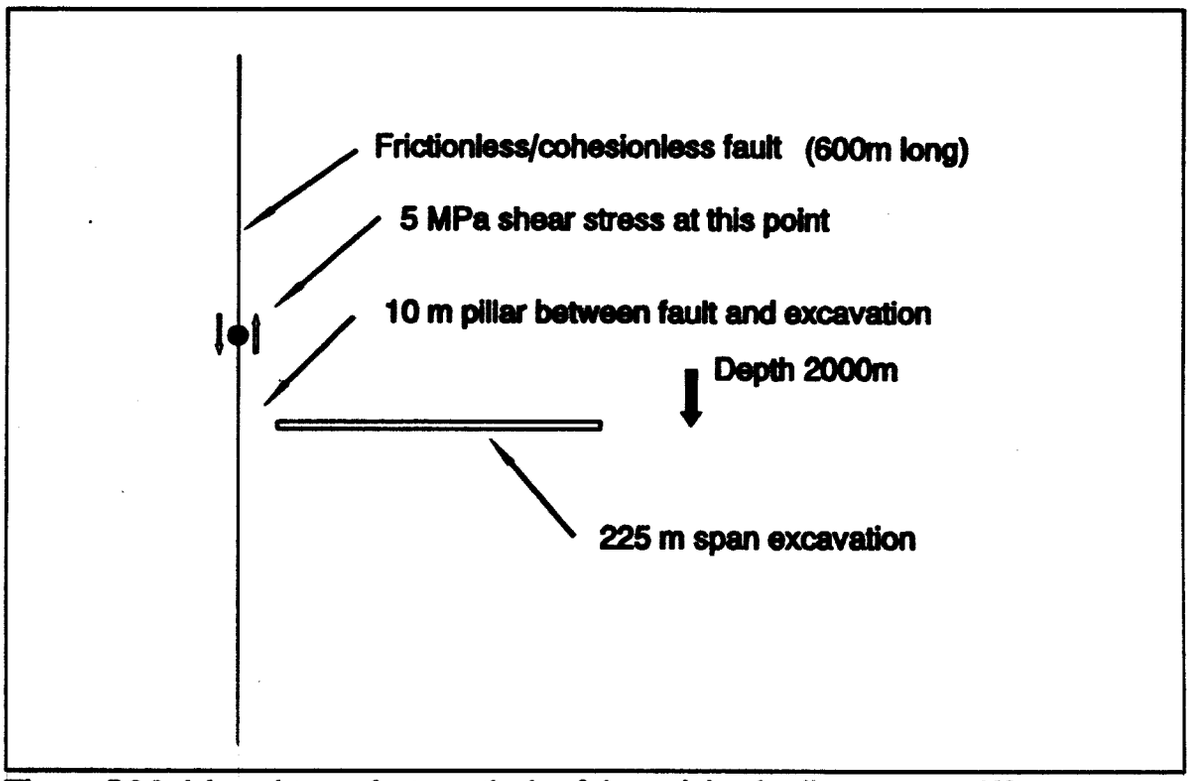


**Figure 5** Model used to evaluate methods of determining loading system stiffness

45m above the excavation, as shown in figure 5 and the slip at the point recorded.

*b) Stress changed along the entire frictionless fault*

A second run was carried out using the above model, but the fault was activated by imposing a constant stress of 5 MPa along its entire length. The slip at the point 45m above the excavation was again recorded.

*c) Stress changed at a point - realistic fault properties*

The third method was aimed at obtaining the system behaviour with more realistic fault properties. An analysis was carried out in which the fault was assumed to have a friction angle of 30° with zero cohesion, it was allowed to slip and come to equilibrium. The fault element 45 m above the excavation was then changed into an element where a shear stress of 5 MPa could be imposed. The resulting slip was recorded at the element.

*d) Stress change obtained by varying fault friction*

In reality stress changes occur over a specific portion of a fault, depending on its strength. The length of fault activated in this manner will affect the stiffness of the loading system. It was therefore decided to allow the model to impose its own stress changes along the unstable portion of the fault by slightly modifying the friction angle so that different amounts of shear resistance and slip would result. The model was run with friction angles of 29° and 31°. The cohesion was set to zero. The differences in shear resistance and slip between the two runs was used to calculate the system stiffness as follows:

$$K_{s30} = \frac{\tau_{31} - \tau_{29}}{S_{31} - S_{29}} \qquad (2)$$

where $\tau$ is the shear resistance at a point and S is the slip.
The resulting stiffnesses of the four methods are presented in table 1.

**Table 1 System stiffness at a point along a fault determined by four methods**

| | Method | System stiffness (GPa/m) |
|---|---|---|
| a) | Activate a single point along a frictionless/cohesionless fault | -0,883 |
| b) | Activate the entire frictionless cohesionless fault | -0,058 |
| c) | Activate a single point along a fault with a friction angle of 30° | -1,111 |
| d) | Activate the slipped portion of a fault with a friction angle of 30° by modifying the friction angle | -0,153 |

The above table clearly shows that the length of the fault activated has a significant effect on the system stiffness. If the entire length of fault is activated the system has a low stiffness (least negative), however, in reality only a portion of the fault is activated when slip occurs and the "clamped" part of the fault has the effect of increasing the system stiffness. Since the length of fault activated will depend on its strength, the stress field and the geometry, it was decided to use the last method (method (d)) for determining the stiffness of the system. This method ensured that only the portions of the fault that slips at a realistic friction angle of 30° are activated. A problem with this approach is that some points may be elastic in the one run and may have slipped in the other run. The stiffness calculated for such points will be incorrect because it will be an average of the stiffness of two different types of behaviour. However, it is fairly easy to identify such points from the results because they plot at the ends of the slipped portion of the fault.

An example of results is shown in figure 6, where the different types of fault behaviour and resulting system stiffnesses are shown. It can be seen that at approximately the middle of a slipped portion the loading system stiffness is the least negative (it will have the flattest slope in a stress-slip plot). At this location the loading system will therefore be most likely to cause unstable slip along the fault. This minimum stiffness value was used to characterize the fault behaviour.

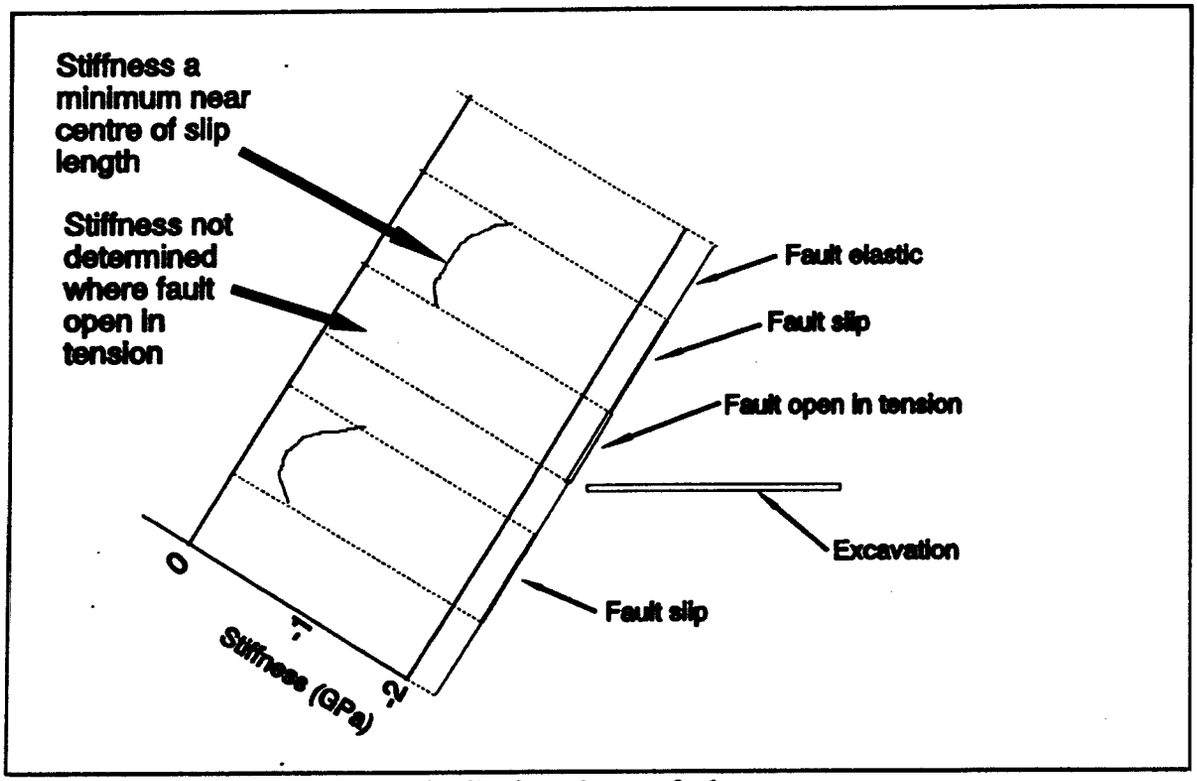


**Figure 6** Example of stiffness distribution along a fault

## 3.0 RESULTS

All the stiffnesses were determined by allowing the fault to slip and varying the friction angle slightly to activate the slipped portion only. The minimum system stiffness (least negative) in the portions of the fault that slipped were used as an indicator of stiffness in all the following results.

### 3.1 Sensitivity to material properties

The sensitivity of the system stiffness to changes in the elastic properties of the surrounding strata was first assessed. A standard model was set up as in figure 3 with a 10m pillar between the end of the excavation and the fault. The sensitivity for Poisson's ratio is shown in figure 7, where it can be seen that the system stiffness could vary by about 20% for realistic variations of the Poisson's ratio.

The effect of variations in the elastic modulus is shown in figure 8, where it can be seen that there is a linear relationship between the elastic modulus and the system stiffness. This means that rock with a low elastic modulus will be more prone to violent slip than rock with a high elastic modulus.

### 3.2 Sensitivity to field stresses

The model in figure 3 was analyzed with horizontal to vertical field stress ratios of 0,25, 0,3, 0,4 and 0,5. The effect of the field stress ratio on stiffness is shown in figure 9. A reduction

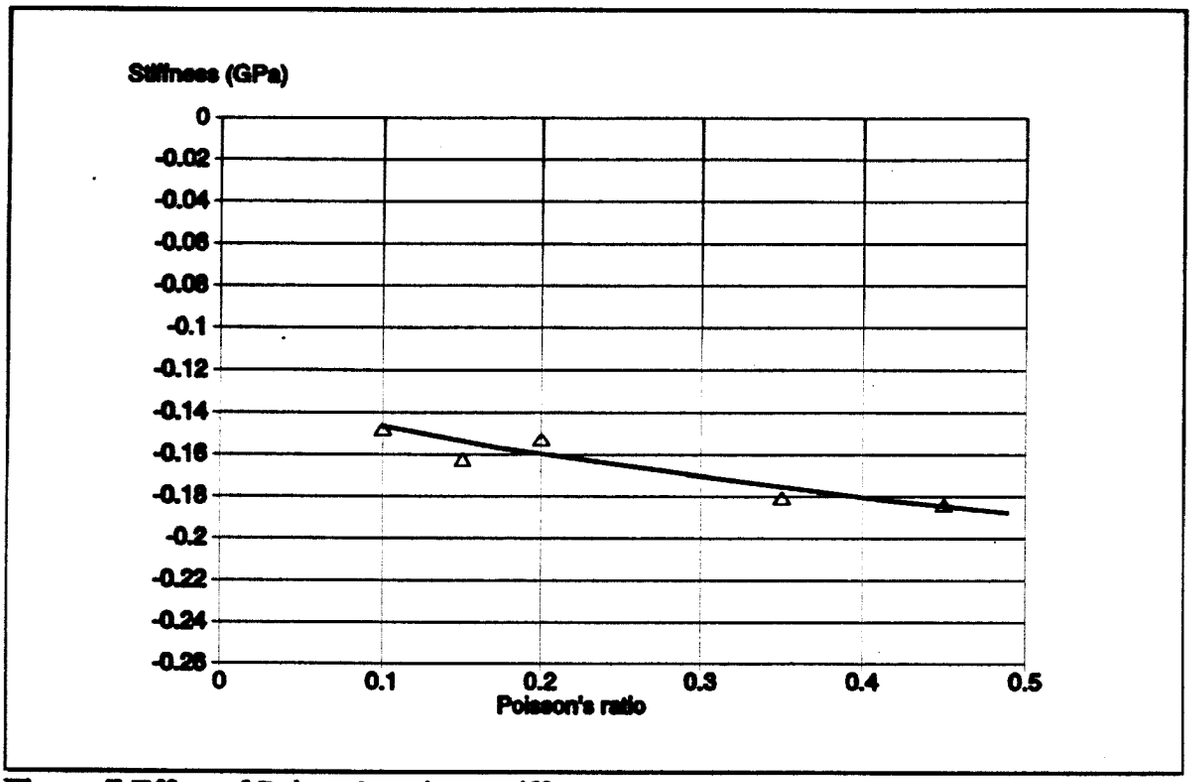


**Figure 7** Effect of Poisson's ratio on stiffness

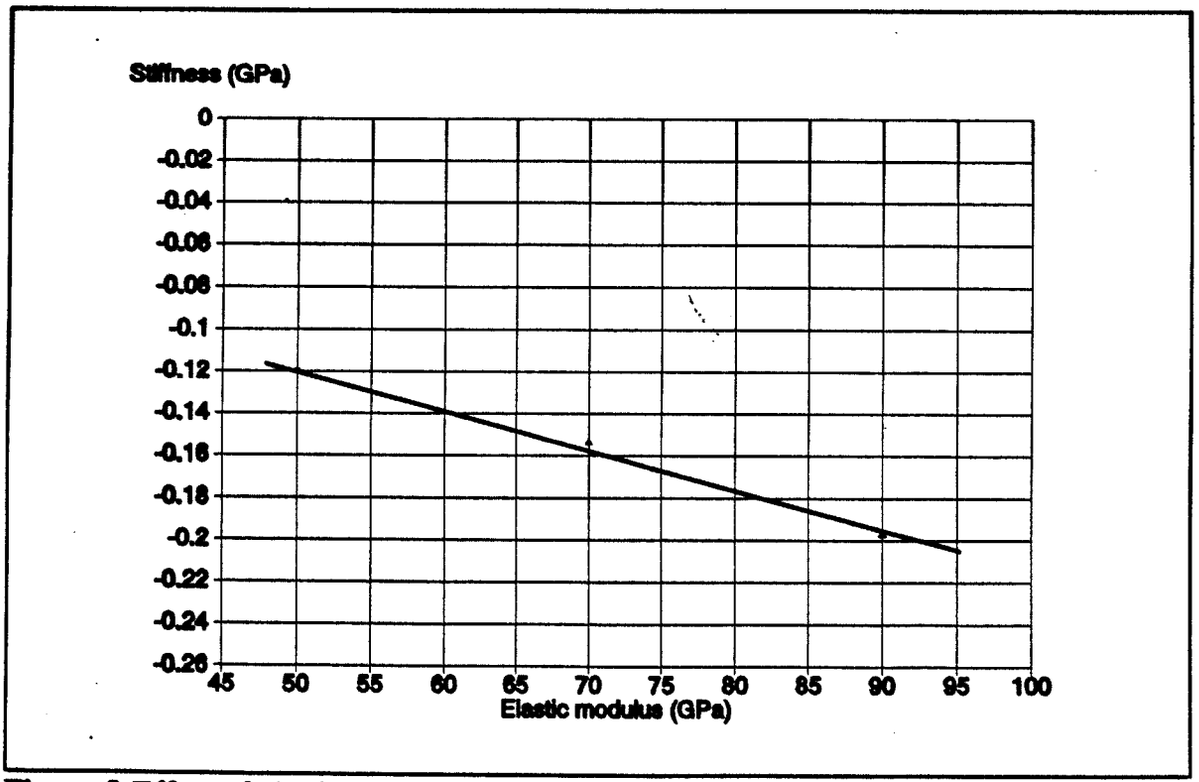


**Figure 8** Effect of elastic modulus on system stiffness

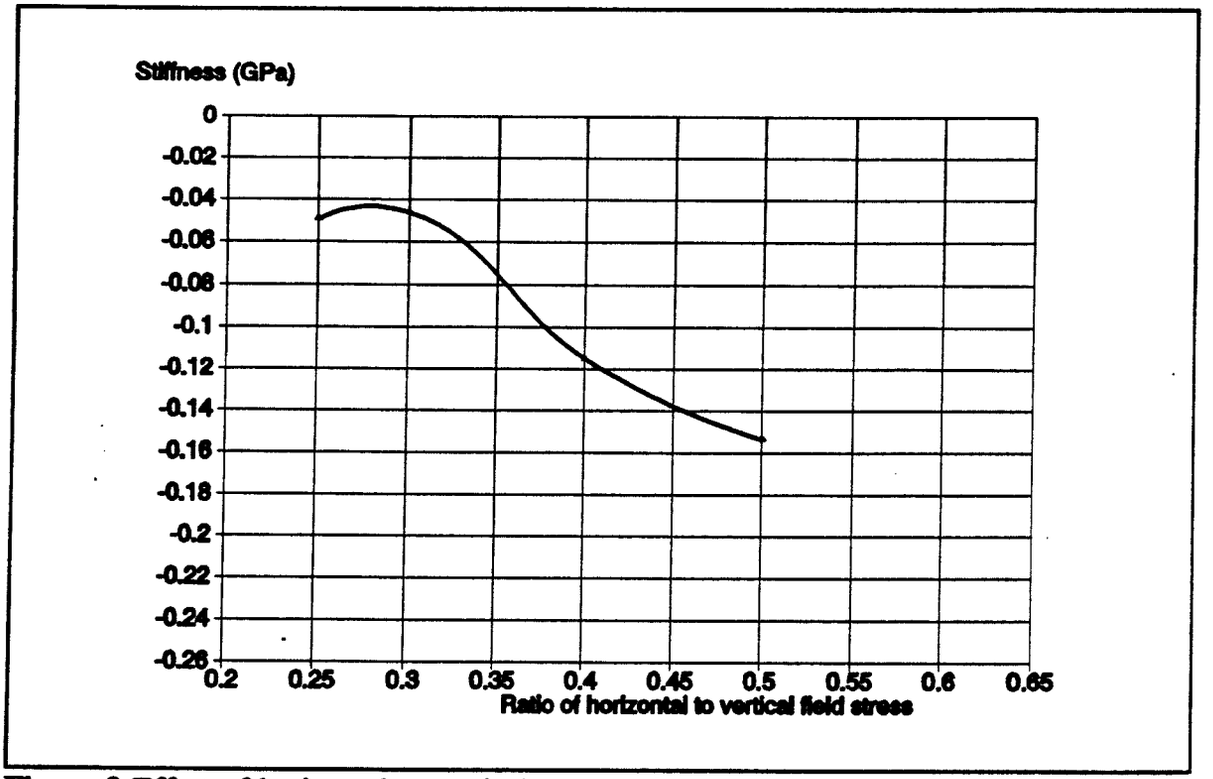


**Figure 9** Effect of horizontal to vertical stress ratio

in the ratio causes a considerable reduction in the stiffness of the loading system. The reason is that as the horizontal stress decreases, the length of fault that slips increases, and hence the stiffness decreases. The change in slope of the stiffness curve at the lower stress ratios is caused by the fact that the entire 600m length of the fault slips and the ends of the fault limit the magnitude of slip. The change in slope of the graph is therefore a model effect.

### 3.3 Sensitivity to fault properties

Since the system stiffness for a particular geometry is greatly influenced by the length of fault that has slipped, any parameter which causes an increased length of fault to slip will have a major effect on the loading system stiffness. Figure 10 shows how the stiffness reduces if the fault friction angle is reduced. A flattening of the curve, at low friction angles, occurs because the entire 600m length has slipped and a further reduction in stiffness is inhibited by the finite length of the fault.

### 3.4 Effect of distance from excavation to fault

The effect of the distance between the stope excavation and the fault was assessed by modelling the excavation as if it had mined right into the fault, and at increments of 10 m away from the fault up to a maximum of 60 m from the fault. The geometry of the fault and excavation was that shown in figure 3. The stope span was kept at 225 m in all the runs. The minimum stiffness of the loading system in the slipped portion of the fault was again used as an indicator of stiffness. The results are shown in figure 11. When the stope is far from the fault the stiffness is high because only a small length of the fault slips. As the distance

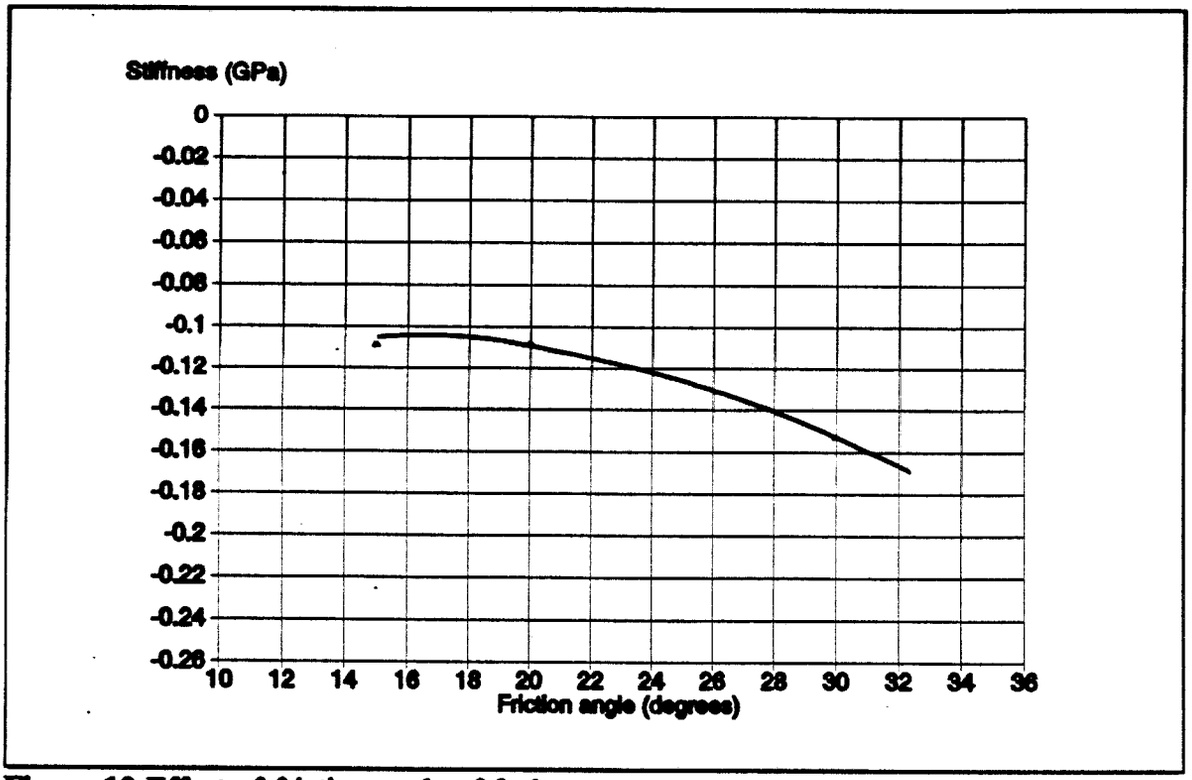


**Figure 10** Effect of friction angle of fault

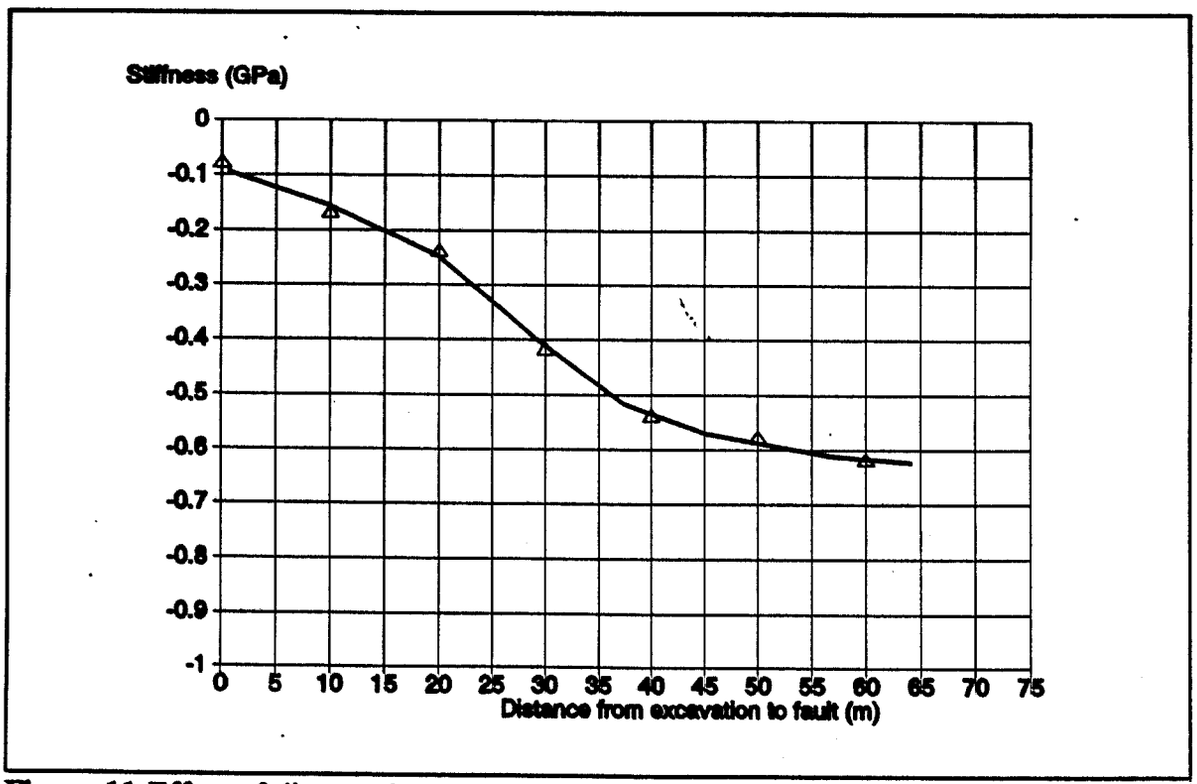


**Figure 11** Effect of distance between excavation and fault on stiffness

is reduced, a greater length of fault slips and the stiffness is reduced. The length of slip together with the proximity of the excavation causes the reduction in the stiffness of the loading system.

### 3.5 Effect of excavation span

As the excavation span is increased it has a greater disturbing effect on the fault resulting in increased slip and decreased stiffness. The results of a number of runs to assess the effect of the stope span on the stiffness of the loading system are shown in figure 12. The excavation was modelled as if it had mined up to the fault. It can be seen that if the span

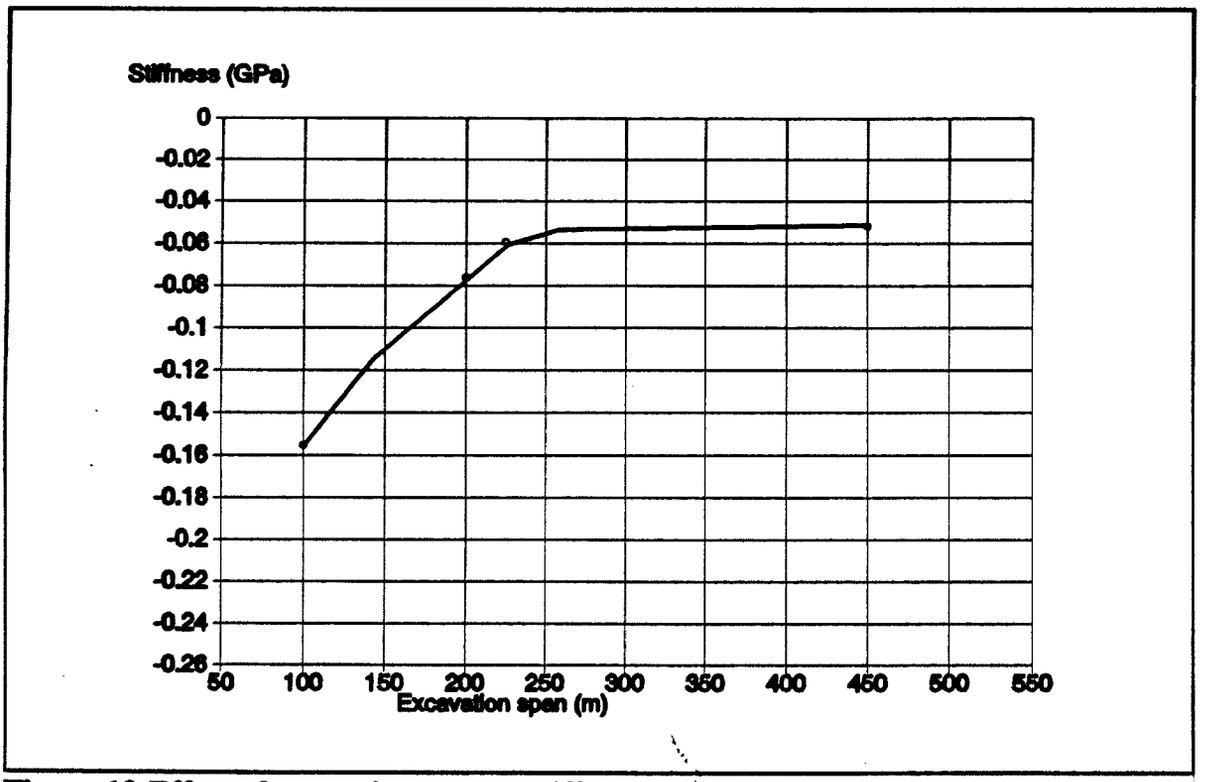


**Figure 12** Effect of excavation span on stiffness

exceeds 250 m the loading system is not sensitive to the span. When the span is less than this amount, the stiffness becomes less negative, and is more sensitive to the span. The span at which the curve flattens is related to the critical half span of the excavation. It appears that when the span exceeds the critical halfspan there is very little change in the system stiffness.

### 3.6 Effect of fault dip

The effect of the dip of a fault on the stiffness of the loading system was determined by modelling an excavation which has mined up to the fault. The stiffness for different fault inclinations is shown in figure 13. The results for the portions of the fault below and above the plane of the excavation are shown separately. The results show that steeply dipping faults will be more prone to violent failure than shallow dipping faults. The lower part of the fault does not slip when the dip is 40° or less and the system stiffness was not determined. The upper part of the fault continues to slip when the fault dips at 30°, however, at such a

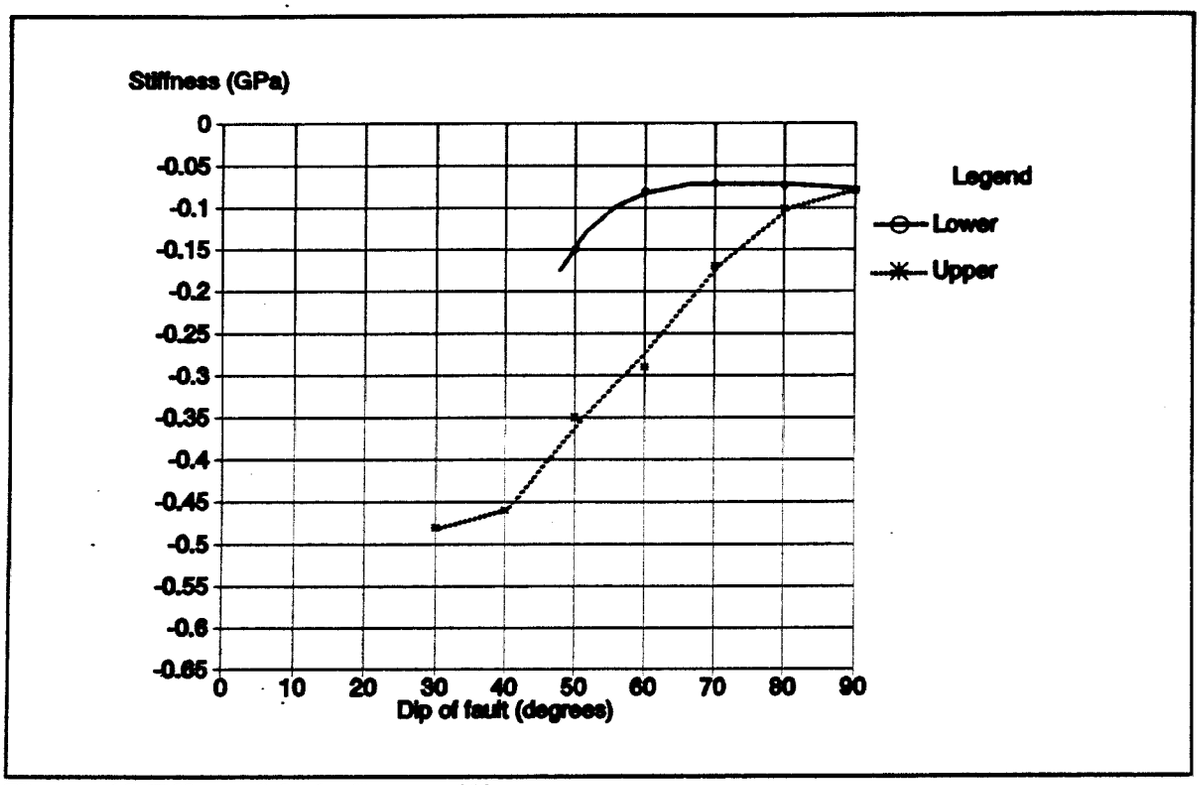


**Figure 13** Effect of fault dip on stiffness

shallow inclination the larger proportion of the fault is open in tension and only a small part of it is subject to slip.

### 3.7 Effect of depth

A model in which the depth was set to 1000, 2000 and 3000m was analyzed. The excavation span was set to 100m, half the critical span and equal to the critical span at each depth. The results are shown in figure 14. It can be seen that there is a slight improvement in the loading system stiffness as the depth below surface increases. If the mined out span is kept constant at 100m the loading system stiffness is almost unaffected by the depth.

### 3.8 Effect of backfill in stope

A number of analyses were carried out in which the excavation was assumed to be filled with typical classified tailings backfill used in the gold mines. The mined out span was 225 m in all the runs, the fault dip was 70° and the excavation was modelled right up to the fault. The change in system stiffness with and without fill for different depths is shown in figure 15. The backfill can be seen to have a significant effect on the loading system stiffness above the plane of the excavation. The stiffness of the loading system below the plane of the excavation was hardly affected by the presence of the backfill.

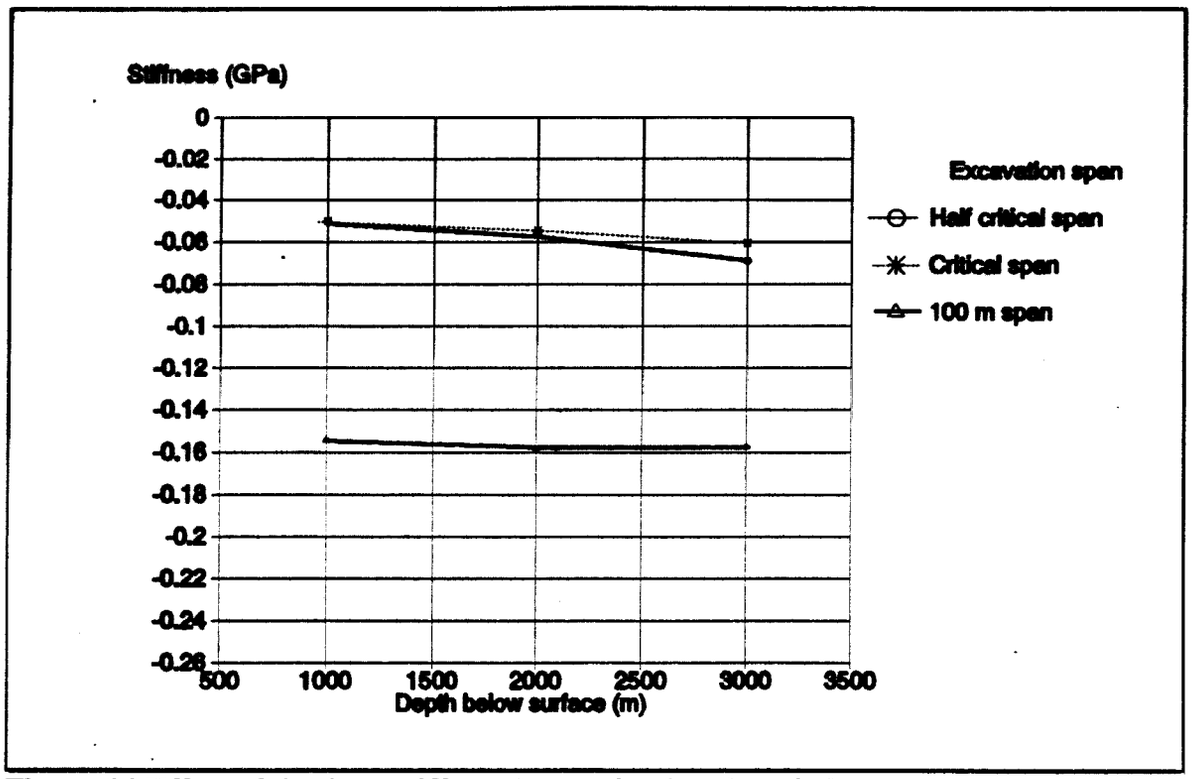


**Figure 14** Effect of depth on stiffness (excavation length varied)

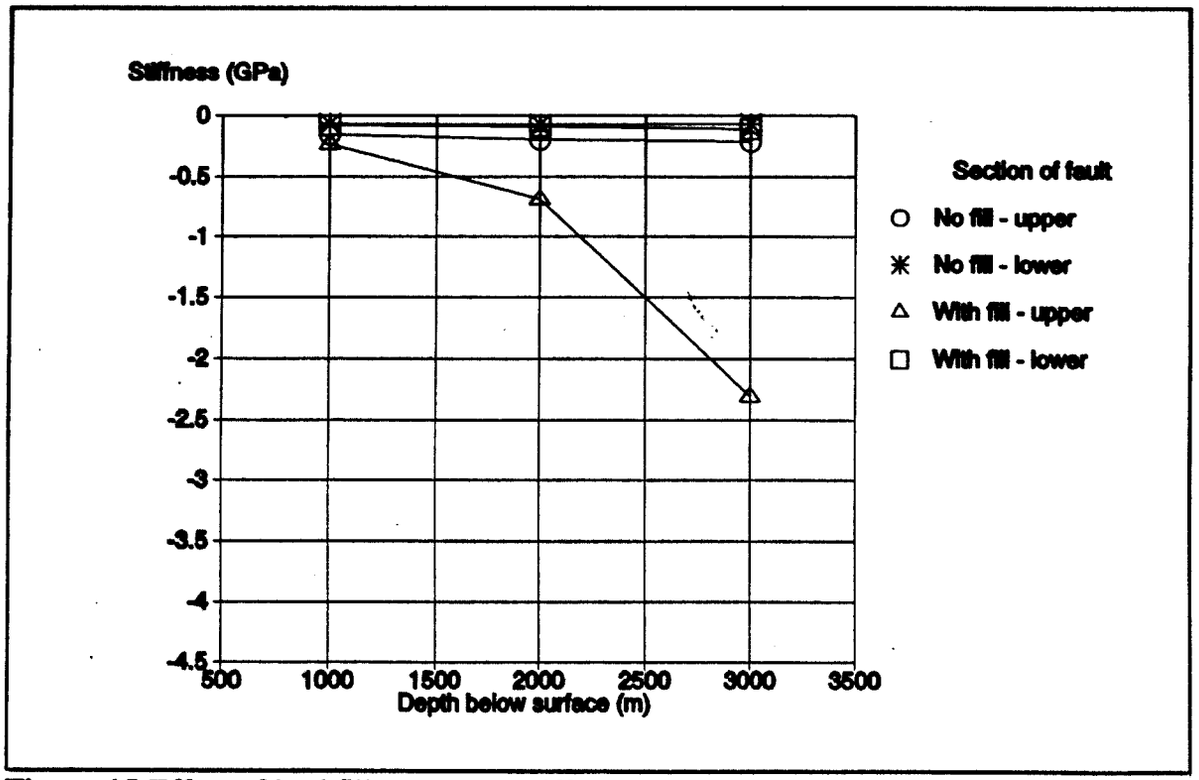


**Figure 15** Effect of backfill on system stiffness (upper and lower part of fault)

## 4.0 CONCLUSIONS

The study has shown that the length of fault subject to slip has the most significant effect on loading system stiffness. Any changes to the system which will result in a reduced length of potential slip will therefore also reduce the likelihood of uncontrolled failure. Factors like the ratio of horizontal to vertical stresses, fault strength, fault dip, excavation span and support in the excavation will all affect the system stiffness by affecting the length of potential fault slip. In general it can be said that any action taken to reduce the length of fault slip will also reduce the potential for violent slip.

Some of the specific results discussed below:

a) The potential for uncontrolled slip is decreased by decreasing the excavation span. However, a significant improvement is only achieved by reducing the excavation span to less than the critical half span.

b) The depth below surface has only a minor effect on the loading system stiffness. This means that the potential for violent slip does not change with depth.

c) Backfill may improve the stiffness of the loading system considerably if there is sufficient closure to load the fill. For example, at a depth of 1000m with mining spans of 200 m the backfill will have a minor effect, but at 3000 m depth with similar spans there will be a significant effect on the system stiffness.

d) Backfill appears to improve the stiffness of the loading system only along that portion of the fault which dips towards the mining excavation.

The above conclusions and comments are based on the study of two-dimensional models of faults and excavations in quasi-static conditions. It was possible to study the fundamental behaviour of the loading system using this approach, but further analyses are required. It is suggested that :

a) Three dimensional numerical models as well as dynamic models be used to determine whether the differences in system stiffness will be significant in realistic situations.

b) Verification of these results by the analysis of actual seismic events along faults.

c) Post peak stiffness of faults be evaluated to determine the significance of changes in system stiffness.

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## 5.0 REFERENCES

1 Ryder JA, Excess shear stress assessment of geologically hazardous situations. J S Afr Inst Mining & Metall, vol 88, 1988 pp 27-39.

2 Rice JR, Shear instability in relation to the constituitive description of fault slip, Proc 1st Int Congr Rockbursts & seismicity in mine, ed. Gay & Wainwright, SAIMM, Johannesburg, 1983 pp 57-62.

3. Geologic Research Inc, BESOL user's guide, 1985

4. Crouch SL, Analysis of stresses around underground excavations: an applicatin of the displacement discontinuitty method, Dept Civil Eng, Univ Minnesota report, 1976.

## APPENDIX 1

## PROJECT OUTPUTS

| Enabling output No. | Description | Outcome |
|---|---|---|
| 1. | Method of assessing system stiffness | A number of different methods were evaluated for determining the shear stiffness of the strata adjacent to a fault plane. The method finally used required that two analyses be conducted in which the fault shear resistance was modified marginally so that two slip magnitudes were obtained along the fault. This allowed the shear stiffness to be determined at each fault element in the model by dividing the change in slip by the change in shear resistance at each point. The minimum value of shear stiffness along a fault was used to compare results of different analyses. |
| 2. | Results of evaluation of different fault - mining combinations | The results of different fault orientations, stress field, rock properties and mining spans, mining depths were tabulated and compared. The detailed results are presented in the main body of the report. The results allowed certain conclusions to be drawn about the factors which influence the potential for violent slip along a fault. |

## APPENDIX 2

## REPORTS AND PUBLICATIONS

| No | Description | Date |
|---|---|---|
| 1 | Progress report to GAPREAG | July 1993 |
| 2 | Final report - not in SIMRAC format | October 1993 |
| 3 | Final report - this report | January 1994 |