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The application of excess shear stress to the design of mine layouts*

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SYNOPSIS

The application of excess shear stress as an aid to the design of mine layout is reviewed, and the critical parameters required to describe slip on a plane of weakness are noted. A design procedure that is required to model the cyclic build-up of excess shear stress is described. A number of simple examples of mine layouts on two reef planes intersecting a fault plane are then considered to illustrate the application of the design concept and to highlight some of the pitfalls that may be encountered.

SAMEVATTING

Die aanwending van oormaatskuifspanning as 'n hulpmiddel by die ontwerp van mynuitlegte word in oënskou geneem en die kritieke parameters wat nodig is om 'n glyverskuiwing op 'n swak vlak te beskryf, word aangegee. Daar word 'n ontwerpprosedure wat nodig is om die sikliese opbouing van oormaatskuifspanning te modelleer, beskryf. Daarna word daar eenvoudige voorbeelde van mynuitlegte op twee rifvlakke wat op 'n verskuiwingsvlak kruis, gegee om die toepassing van die ontwerpkonsep te illustreer en sommige van die slaggate wat 'n mens kan teëkom, na vore te bring.

Introduction

Seismic activity usually accompanies large-scale deep-mining operations, but only the seismic events of large magnitude that occur infrequently are of particular concern in the design of underground excavations. In this regard, it is important that the sequence of extraction should be such that the released potential energy of the rockmass due to mining is dissipated in a regular manner. Conversely, mining sequences that lead to metastable conditions, which are followed by sudden and extensive rock movements, must if possible be identified and avoided.

The sudden failure of rock under either excessive compression or shear can cause seismic events. It is often true that, in earthquake and rock mechanics situations, the initial seismic source is generated by slippage on pre-existing faults or by the shearing of intact rock[1,2]. However, where faults intersect extensively mined areas, large stope closures may also arise.

The stresses arising from tabular excavations, as well as slip movements on fault planes, can be modelled by numerical methods[3-5]. The possible hazard on a given fault plane can be interpreted by means of excess shear stress. This paper describes the application of this measure to some layout design problems in the vicinity of weak structures, and points out some of the difficulties in the application of the concept.

Excess Sheer Stress as a Design Criterion

The analysis of sliding on a plane of weakness can be discussed in elementary terms by means of the Coulomb criterion for shear failure[1].

Suppose that τ is the absolute shear stress existing on the plane and let σ denote the absolute normal stress on the plane. If the normal stress is compressive, sliding is assumed to be possible if the following condition is true at any point on the slip plane:

$$\tau \geqslant \mu_s \sigma + S_o, \qquad (1)$$

where μ_s = Static coefficient of friction prior to sliding
S_o = Inherent shear strength (cohesion) of the slip plane (MPa).

For this condition to be used in the solution of mine layout problems, the possible difference between states of static and dynamic friction[6] must be considered. Assumptions made about these two conditions are fundamental to the conclusions that are drawn, and are at present only tenuously supported by field observations. This is discussed in greater detail by Ryder[7]. In the present paper, the specific assumption is made that, once sliding commences, the static friction coefficient, μ_s, drops to a dynamic value, μ, and the shear strength of the slip plane, S_o, falls to zero. Therefore, after the onset of failure, an out-of-balance driving stress exists and is initially equal to $\tau - \mu\sigma$. This difference is denoted by τ_e, the excess shear stress. Then,

$$\tau_e = \tau - \mu\sigma. \qquad (2)$$

It is convenient to distinguish the static excess shear stress, τ_s, which is defined as follows:

$$\tau_s = \tau - \mu_s\sigma - S_o. \qquad (3)$$

The Coulomb failure criterion, expressed by equation (1), is then equivalent to τ_s being zero or positive at any point of the fault plane. Strictly speaking, τ_s should by

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hypothesis never be greater than zero at any point on the fault plane, and should everywhere be negative under equilibrium conditions.

In the computation of the state of stress and stability that will be associated with a particular mining layout in the vicinity of a plane of weakness, each step in the mining sequence leading to the current configuration must be evaluated. The detailed procedure might be as follows.

(a) Advance the mining positions for the current increment and reset the static coefficient of friction, μ_s, and strength parameter, S_o, on all planes of weakness.
(b) Solve the current mining increment.
(c) Determine the static excess shear stress, τ_s, at critical points on the planes of weakness.
(d) If τ_s is everywhere negative, return to step (a).
(e) If τ_s is zero or positive, re-solve the layout allowing the planes of weakness to slip with friction coefficient set to the dynamic value, μ, and shear strength, S_o, set to zero.
(f) Return to step (a) unless mining has been completed.

In the above procedure, care must be taken to ensure that no mining increment is so extensive that large positive values of the static excess shear stress, τ_s, are generated. In addition, it can be appreciated that the difference between the static and the dynamic friction coefficients, μ_s and μ, and the magnitude of the shear strength, S_o, will control the upper bound that the excess shear stress, τ_e, can attain, and hence the extent of slip.

The design problem is to sequence the extraction in such a way that, when this bound is exceeded, the smallest possible area on the planes of weakness will be mobilized. Measures of the severity of the seismic event are the seismic moment, M_o, and the magnitude, M, given by the following formulae[2,7].

Moment, $M_o = GA\bar{\eta}$ *MN-m* .... (4)

Magnitude, $M = [\log_{10}M_o - 3,1]/1,5$ .... (5)

where
G = Modulus of rigidity ($E/2(1+\nu)$ MPa)
A = Area of movement (m^2)
$\bar{\eta}$ = Average ride in area of movement (m).

The ride is defined as the difference in tangential displacement between the hangingwall and the footwall sides of the fault plane, and is a quantitative measure of the fault slip. Rides in the direction of the fault strike are assumed to be small and are neglected here.

Patterns of Excess Shear Stress

The stress patterns surrounding real mine layouts are complex and must be modelled individually. So that progress can be made towards some general conclusions, an ideal layout in the vicinity of a normal fault loss is used here as an illustration. The characteristics of the layout are shown in Fig. 1. In this layout two reef horizons, denoted UPPR and LOWR, are displaced a distance of 100 m vertically by a fault plane dipping at 60 degrees and at a nominal depth of 3000 m. (The elastic constants used are Young's modulus = 70 000 MPa and Poisson's ratio = 0,2.) For convenience, the dip of the reef plane is assumed to be zero. Mining is assumed to advance symmetrically away from a central raise in each stope. The distance extracted is denoted by L in Fig. 1. In the cases described below, the angles of static and dynamic friction are assumed to be the same and equal to 30 degrees ($\mu_s = \mu = 0,58$). The excess shear stress, defined as τ_e in equation (2), is denoted by the mnemonic ESS.

Fig. 2 shows the profiles of excess shear stress developed along the centre line of the fault when the strike mining distance L is 100 m and when it is infinitely long. No mining takes place on the lower reef. It can be seen that, even in the case of limited strike extraction, excess shear peaks of up to 10 MPa are present. If this value of ESS exceeds the shear strength of the fault plane, slip will occur. If ESS values are everywhere negative, no slip is possible whatever the strength of the fault plane. The ESS arising when the upper plane is mined to an infinite extent along strike is seen to exceed 40 MPa close to the fault–reef intersection. Since this probably exceeds the intact shear strength of the rock, it is unlikely that this state is attainable in a single mining step. Slip will occur at a prior extent of extraction, and the cumulative movements should be determined in a series of mining increments.

The ESS profiles that arise when both the upper and the lower reef planes are progressively and simultaneously extracted along the strike direction are shown in Fig. 3. (In this diagram the x-axis corresponds to the centre line of the fault plane. The intersections of the upper and lower reef planes with the fault plane are shown as inclined broken lines.) Clearly, the level of ESS increases as the extent of mining is increased. It is also interesting to note that ESS peaks occur in both the hangingwall and the footwall areas, and in the central region of the fault. The level of ESS in the central region becomes more dominant as mining proceeds.

At this stage, a possible design criterion would be to limit the degree of extraction and so ensure that the shear strength of all the fault planes is never exceeded. This could be accomplished if the ground adjacent to all the stope–fault intersections were left unmined to form protective barriers, termed bracket pillars. Consider the 'worst' case of infinite mining in the strike direction and a stope AB located on the upper reef plane as illustrated in Fig. 4. For a given fault, dipping at angled, the maximum excess shear stress arising on the fault will increase as the stope span is increased. If point A of the stope is fixed, Fig. 4 shows the variation of the maximum ESS (based on a friction angle of 30 degrees) as a function of stope span for several fault dip angles. The fault is rotated about a fixed central point, P, 50 m below the stope, as indicated in Fig. 4.

For example, if the ESS is to be bounded to 10 MPa, the stope span cannot exceed 290 m if the fault dips at 45 degrees. In this case, the size of the bracket pillar between the stope and the fault would need to be 160 m.

Fig. 5 illustrates the variation of the maximum ESS for the same set of fault angles but with a second stope A'B' located on the lower reef plane. The stope span is the same in AB and A'B', and points A and A' are assumed to be fixed. Some combinations of the fault dip and the required stope spans and pillar sizes to limit ESS to 10 MPa are reported in Table I.

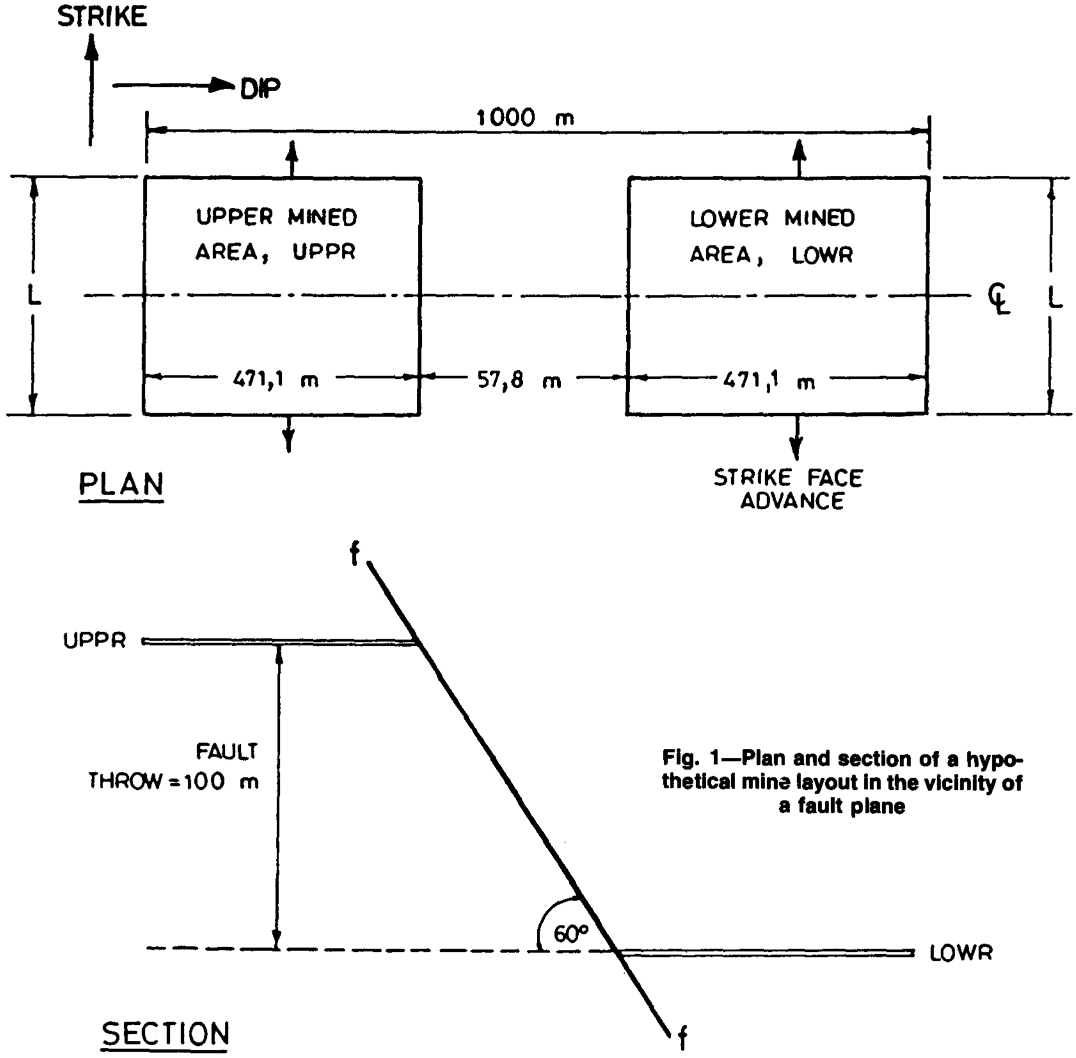

Fig. 1—Plan and section of a hypothetical mine layout in the vicinity of a fault plane

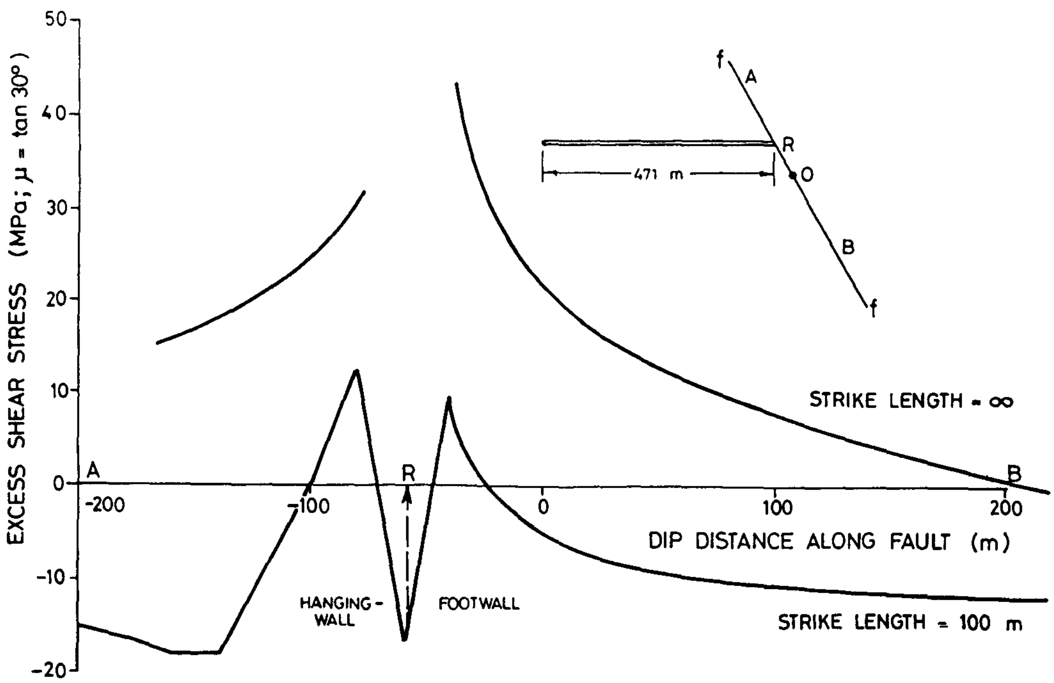

Fig. 2—Profiles of excess shear stress for single finite and 'infinite' strike excavations adjacent to a fault (fault dip = 60 degrees)

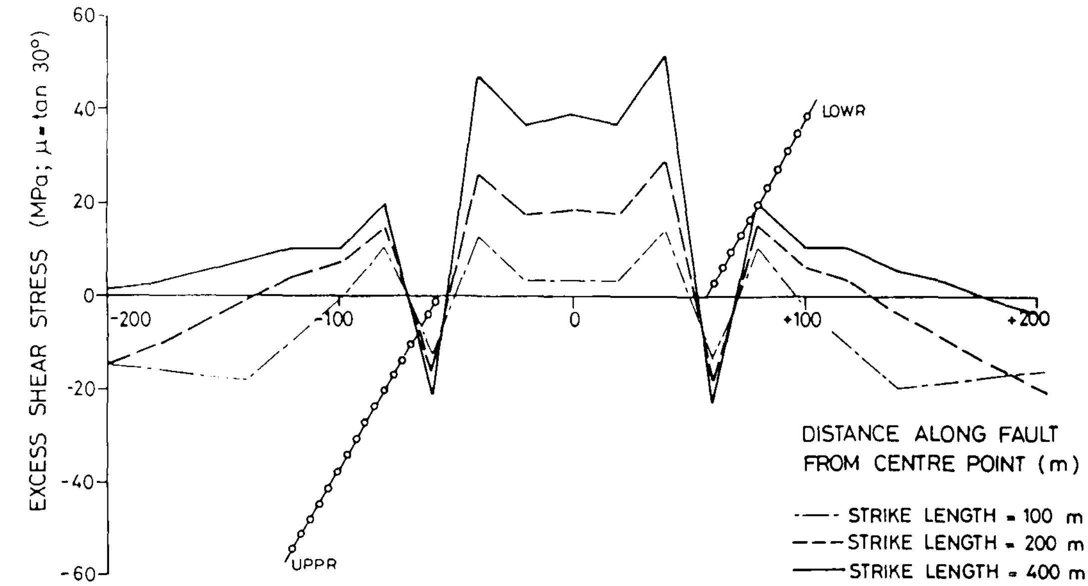

Fig. 3—Excess shear stress along a fault plane for different extents of mining parallel to the fault strike

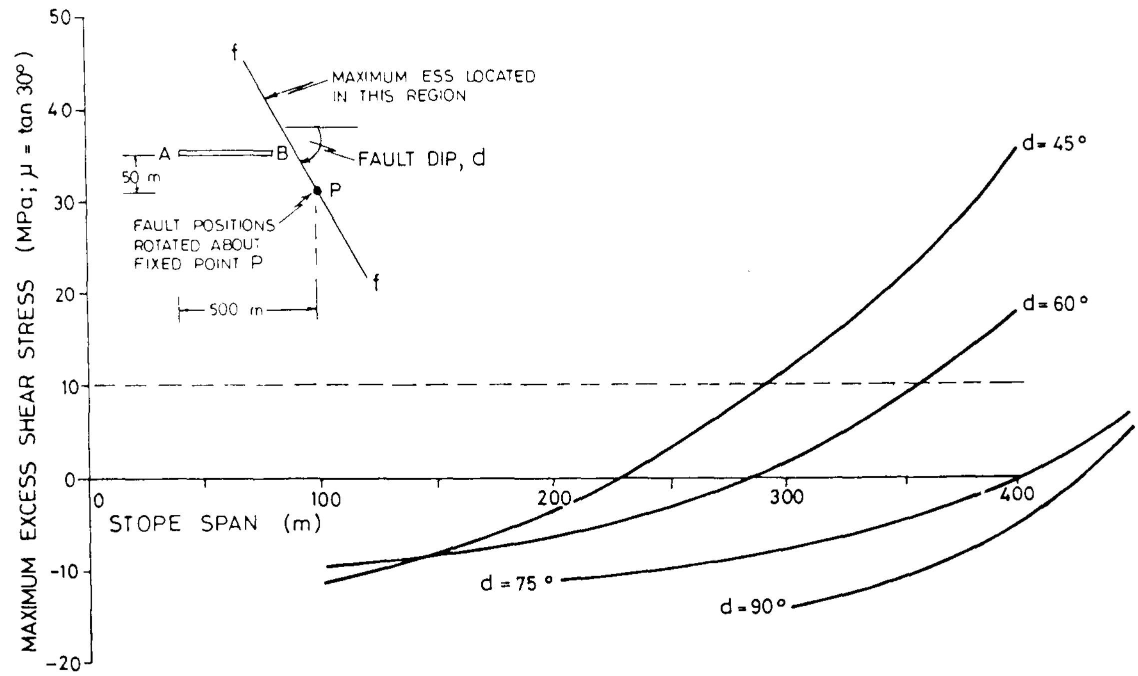

Fig. 4—Maximum excess shear stress on faults with different angles of dip—single reef plane extensively mined in the direction of strike

It is apparent from Table I that, in most cases, very large bracket pillars are required to limit the ESS to 10 MPa. Clearly, a lyout design demanding that the ESS should never exceed a prescribed limit can lead to very conservative pillar sizes. It should also be emphasized that the layouts illustrated in Figs. 4 and 5 can expose an extensive area of the fault plane to a sudden slip movement if the shear strength of the fault plane happens to be exceeded.

Three ESS patterns that are generated when the extent of mining along strike is limited to a distance of 400 m are shown in Fig. 6. These correspond to the omission of bracket pillars, the installation of one bracket pillar on the upper reef plane, and the installation of two bracket pillars, respectively. It is seen that each bracket pillar has a strong local effect on the ESS magnitude in the fault loss area between the intersections of the two reef planes but that, in the external hangingwall and footwall areas, the ESS peaks are not reduced. It can be anticipated that fault movements in the hangingwall and footwall areas are not inhibited by bracket pillars, although movement within the fault loss area is reduced considerably. This is an important consideration if a haulage is to be located near the fault plane in the fault loss region as opposed to the location of the haulage in the footwall area below the lower reef plane.

Fig. 7 compares the effects of backfill ribs of 'good' quality fill material, in place of the bracket pillars. In this particular case it is interesting that the fill ribs have little effect on the ESS within the fault loss zone but apparently reduce the ESS in the hangingwall and footwall locations.

The effect of persistent movement on the fault plant

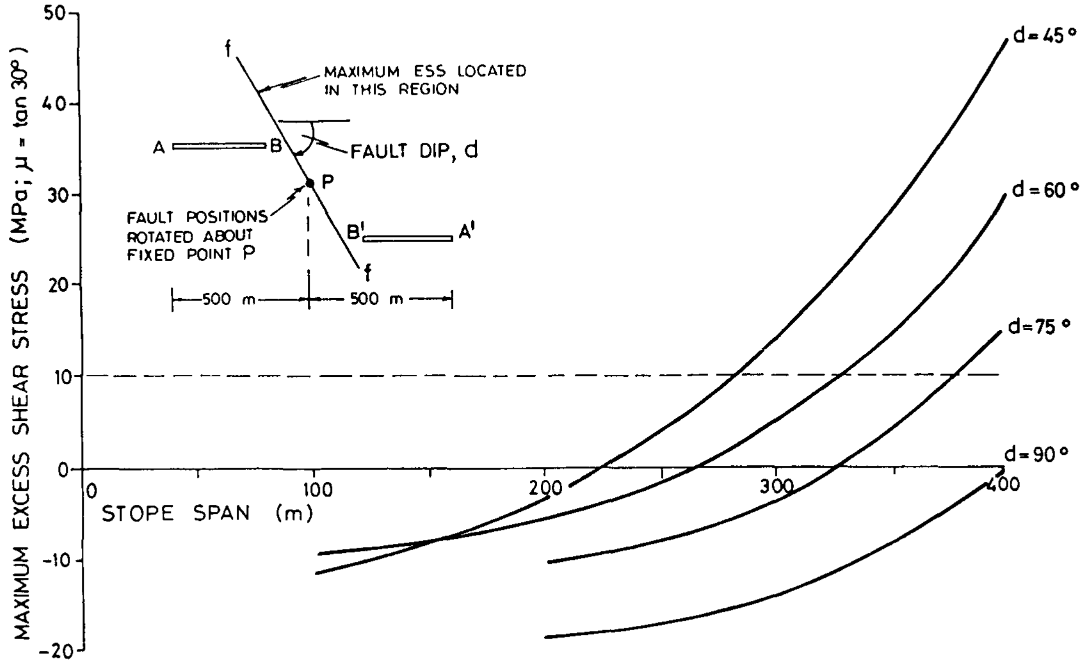

Fig. 5—Maximum excess shear stress on faults with different angles of dip—two reef planes extensively mined in the direction of strike

TABLE I
STOPE SPAN AND SIZES OF BRACKET PILLARS REQUIRED TO LIMIT ESS TO 10 MPa FOR PARTICULAR MINE LAYOUTS ADJACENT TO A FAULT

	Single stope		Two stopes	
Fault dip degree	Stope span m	Pillar size m	Stope span m	Pillar size m
45	290	160	280	170
60	355	116	325	146
75	460	17	375	111

can be shown by a series of mining-step runs in which the strike extraction is increased incrementally and the expected magnitude of periodic slip motions is evaluated.

Fault Slip Motions

From the previous considerations, it appears that the levels of excess shear stress can probably not be bounded unless the extraction ratio is unacceptably conservative. A more useful design criterion could then be a limitation of the maximum slip movement occurring on planes of weakness. The degree of movement can be measured by the seismic moment, M_o, which is proportional to both the area that moves and the average ride. With this in mind, it is interesting to contrast the excess shear stress patterns prior to movement with the actual areas that are mobilized for four particular layouts. In each case, the strike mining distance is assumed to be 400 m and two reef planes are mined adjacent to a 60-degree fault as depicted in Fig. 1. The individual characteristics of each case are as follows.

(a) Mining is carried out up to the fault plane on each reef horizon.

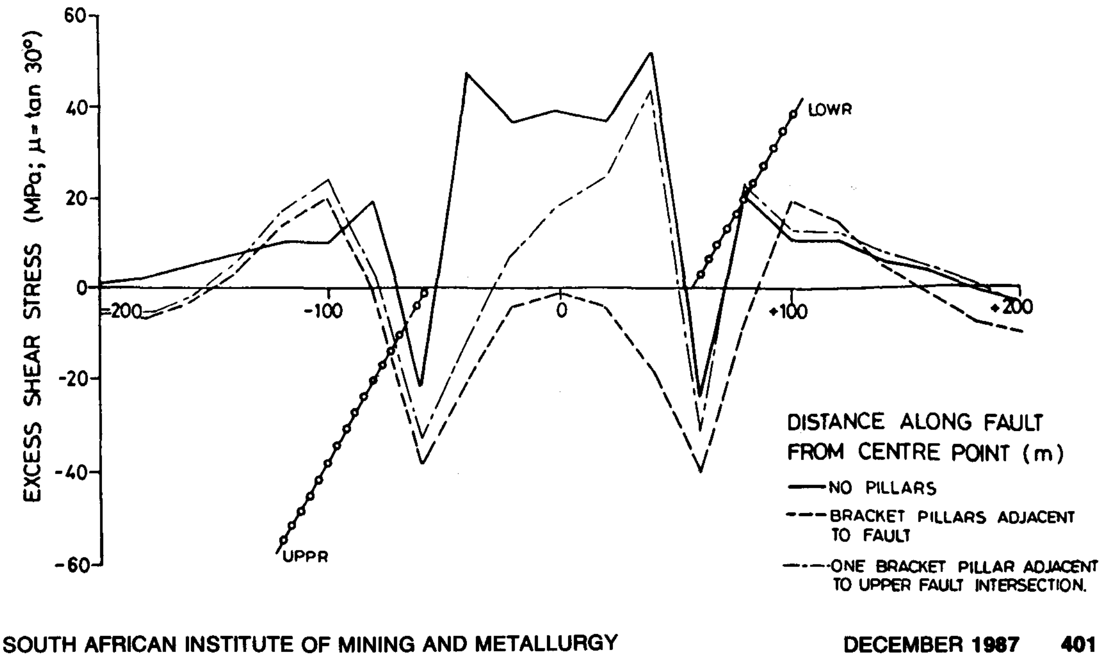

Fig. 6—Excess shear stress along a fault plane with various pillar configurations—stopes mined 400 m in the direction of strike

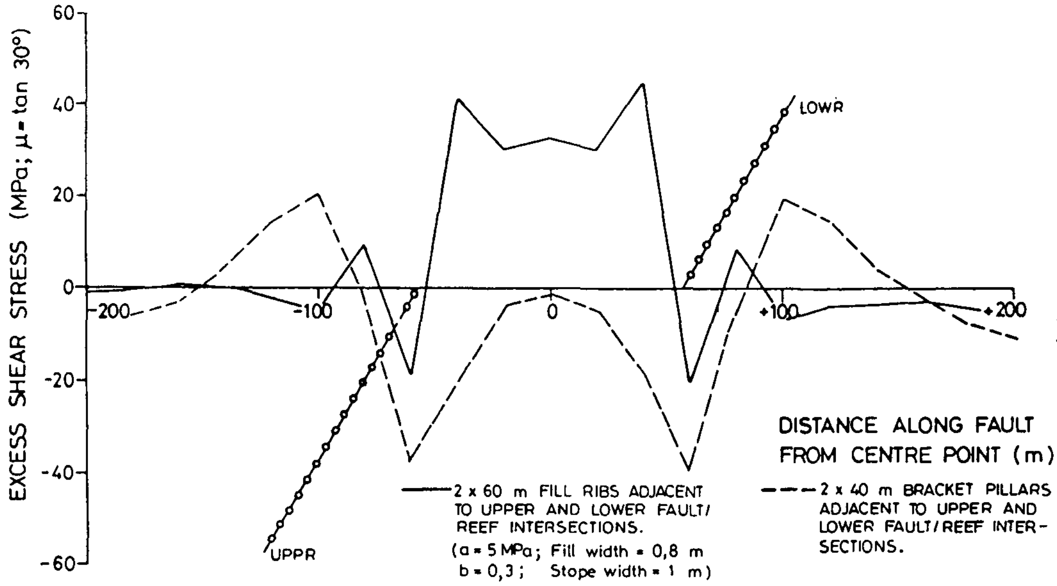

Fig. 7—Comparison of excess shear stress on a fault plane for pillar and backfill alternatives —stopes mined 400 m in the direction of strike

(b) Mining is the same as in case (a) but both stopes are filled with a 'good'-quality backfill material having a characteristic stress parameter a = 5 MPa and an ultimate strain b = 0,3. The fill width is assumed to be 1 m in a stope width of 1,3 m.
(c) Mining is carried out up to the fault plane but a dip pillar 30 m wide is left at the centre of each stope.
(d) Two bracket pillars 30 m wide are left adjacent to the fault plane on the upper and lower reef planes.

The excess shear stress that arises in each of these cases, on the assumption that no movement occurs on the fault plane, is shown in Fig. 8. In this diagram the zero contour outlines the areas in which the ESS is positive, and the contour marked + 10 bounds those areas where the ESS exceeds 10 MPa. It is apparent from Fig. 8 that the ESS is positive over the largest area in case (a), where mining has continued up to the fault plane. The highest ESS occurs in the fault loss area in this case. If backfill material is placed in the stope, case (b), the zones of positive ESS are diminished outside the fault loss area but are persistently large between the reef planes and below the lower plane intersection.

Fig. 8(c) clearly shows that the effect of leaving a dip pillar in each stope is to cause separate maxima for excess shear stress, which appear on adjacent sides of the pillar and between the reef-plane intersections. It is also important to observe that, in this case, the zone of positive ESS 'bridges' the two areas adjacent to the central pillars. These zones can be completely separated if sufficiently wide pillars are left, the size of the required pillars also being dependent on the magnitude of the fault throw.

In case (d), where bracket pillars are left, the area of positive ESS between the upper and the lower reef intersections is considerably smaller than in any other case. However, two zones of positive ESS appear in the hangingwall and footwall areas of the upper and lower reef planes respectively. Significant slip movements can be expected to be associated with these zones.

Each case considered above was assumed to be the starting condition for the initiation of slip movement on the fault plane. The complete movements on the fault plane were solved on the assumption of a dynamic friction angle of 30 degrees and a dynamic shear strength of zero. The resulting ride movements in millimetres are plotted for each case in Fig. 9. The signs of the contours indicate whether the slip is in the normal sense. (A positive sign indicates that the fault 'hangingwall' moves downwards relative to the fault 'footwall'.)

Fig. 9 confirms that the largest movements are associated with case (a), in which no pillars are left and no fill material is used. In this case, the positive slip area spans the central zone between the reef-plane intersections and extends into the footwall area below the lower reef plane. It is interesting to note that reverse slippage can occur in the hangingwall above the upper reef plane. A similar pattern of movement occurs in case (b), although the reverse slip area is severely curtailed. The slip volume (area multiplied by average fault ride) in case (b) is only marginally smaller than in case (a). (See also Table II.)

Fig. 9(c) shows that, with dip pillars in place, the slip movements are reduced to less than half the magnitude without pillars. However, movement is pervasive in the

TABLE II

SEISMIC MOMENT AND MAGNITUDES CORRESPONDING TO SLIP EVENTS OCCURRING IN HYPOTHETICAL LAYOUTS

Case number	Average ride mm	Slip area m^2	Moment, M_0 (*MN-m*)	Magnitude, *M*
(a) Open stoping	57,4	66 400	11,1 × 10^7	3,30
(b) Stopes back-filled	53,9	60 800	9,57 × 10^7	3,25
(c) 30 m dip pillars	23,7	58 400	4,03 × 10^7	3,00
(d) 30 m bracket pillars (upper region)	15,1	36 800	1,62 × 10^7	2,74
Bracket and dip pillars (upper region)	5,7	20 000	0,33 × 10^7	2,28

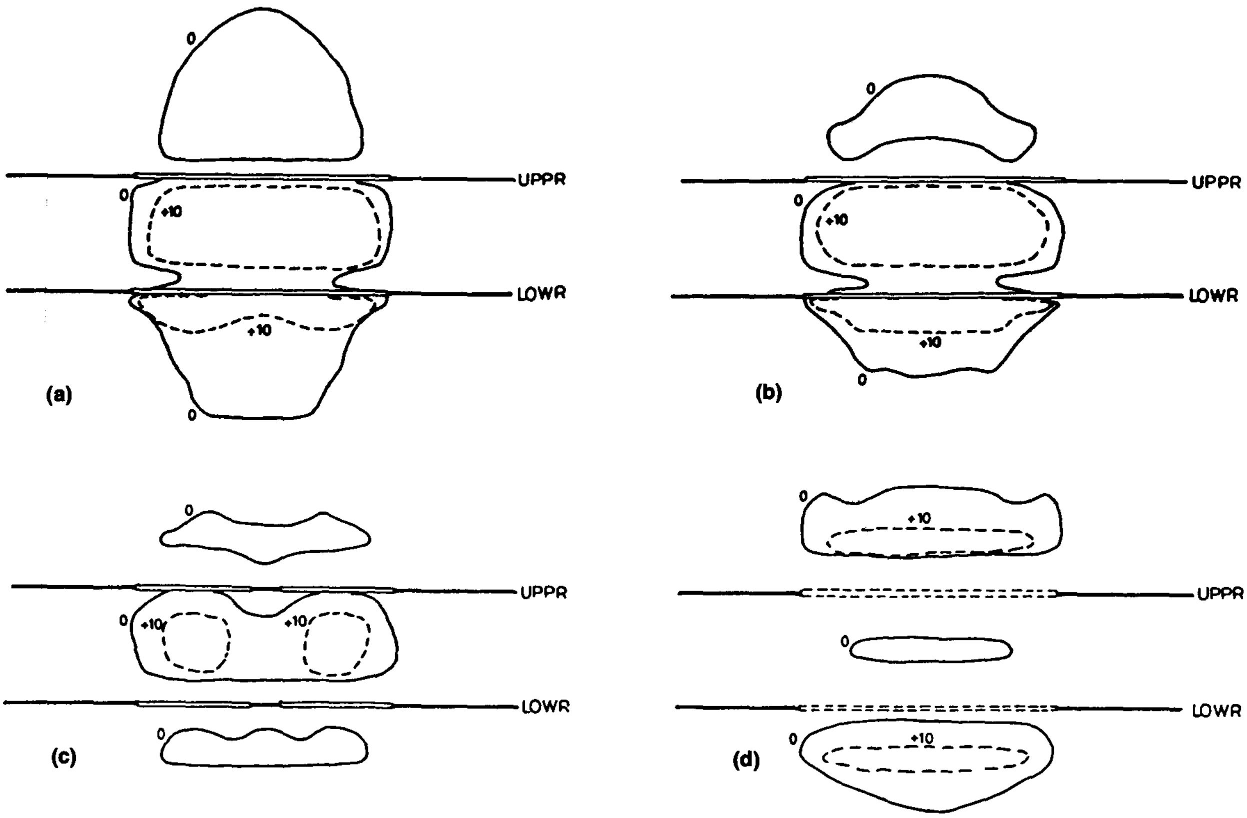

Fig. 8—Patterns of excess shear stress associated with four possible layouts adjacent to a fault plane
(a) Mining up to the fault plane in upper and lower stopes
(b) Stopes backfilled
(Hyperbolic material, *a* = 5 MPa, *b* = 0,3, *Fw* = 1 m, *Sw* = 1,3 m)
(c) Central 30 m dip pillars in upper and lower stopes
(d) Two 30 m bracket pillars adjacent to upper and lower fault intersections

area between the reef-plane intersections and continues without interruption into the footwall region. The installation of bracket pillars, case (d), succeeds in confining the slip movements to localized zones in the hangingwall and footwall, but does not prevent a small amount of movement in the zone between the reef-plane intersections. The sense of slip movement associated with bracket pillars is always positive. The seismic moments and magnitudes associated with each positive slip area depicted in Fig. 9 are summarized in Table II. This implicitly assumes that slip occurred as a single event following the previous excess shear levels shown in Fig. 8, which may be somewhat unrealistic in cases (a) and (b).

Slip can be eliminated entirely on the fault zone between the upper and the lower reef-plane intersections if a combination of dip and bracket pillars is left. This is shown as a final example in Fig. 10, in which both a 30 m dip pillar and a 30 m bracket pillar are left on each reef plane. Fig. 10(b) shows that, in this case, slip movement occurs only in the hangingwall and footwall regions and is reduced to a maximum magnitude of 13 mm. It is, in fact, interesting to note that none of the layout alternatives summarized in Table II can eliminate movement in these zones, and a design decision must be based on the maximum movement and seismic moment that can be tolerated. The values corresponding to this last case are entered in the final line of Table II. Fig. 10(a) shows the ESS levels that remain after slip has taken place, based on a friction angle of 30 degrees. The vulnerability of the layout to subsequent slip movement cannot be inferred from Fig. 10(a). Further mining increments must be modelled with the friction coefficient and shear strength of the fault plane reset to static values until the ESS again reaches the assumed critical level.

Conclusions

The concept of excess shear stress can in principle be used in the design of mine layouts and in the assessment of potential seismic events in the vicinity of fault planes. Fault slip should, in general, be modelled with incremental mining steps, and critical assumptions are required to be made about the static and dynamic friction parameters controlling slip. It appears that the complete elimination of potential slip movements in fault-loss situations may be unpractical, and a viable design criterion must be set that bounds the magnitude of mining-induced seismic events (measured, for example, by the seismic moment) to a prescribed level. It might be desirable to design the mining sequence to permit a regular controlled sequence of small events and to avoid layouts that can trigger sudden and extensive slip movements as may occur, for example, if mining approaches a fault plane on breast.

Bracket pillars appear to be effective in limiting movements of fault planes in the zone between the intersection of two reef planes and a fault, but will not restrict the movement of a fault in the hangingwall and footwall

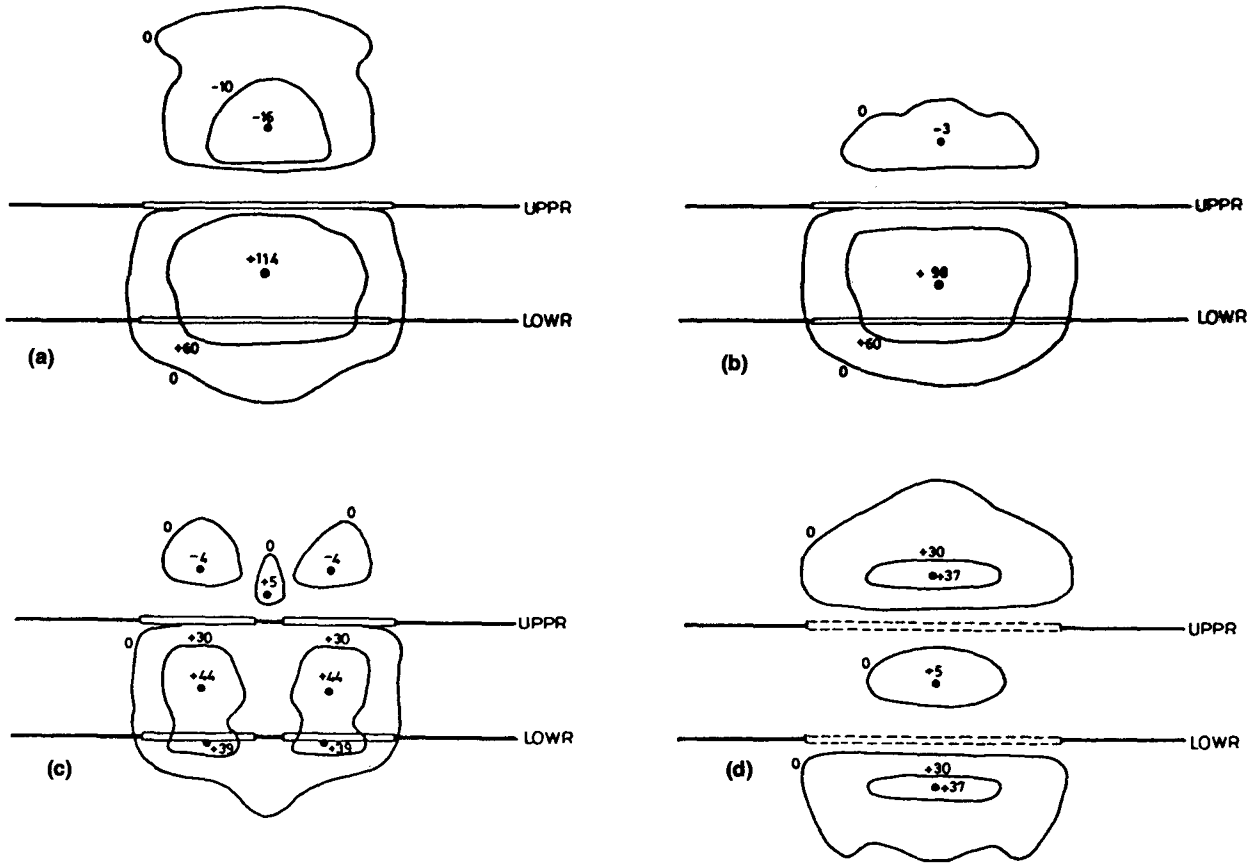

Fig. 9—Fault ride movements generated by the patterns of excess shear stress shown in Fig. 8
(a) Mining up to the fault plane in upper and lower stopes
(b) Stopes backfilled
(Hyperbolic material, a = 5 MPa, b = 0,3, Fw = 1 m, Sw = 1,3 m)
(c) Central 30 m dip pillars in upper and lower stopes
(d) Two 30 m bracket pillars adjacent to upper and lower fault intersections

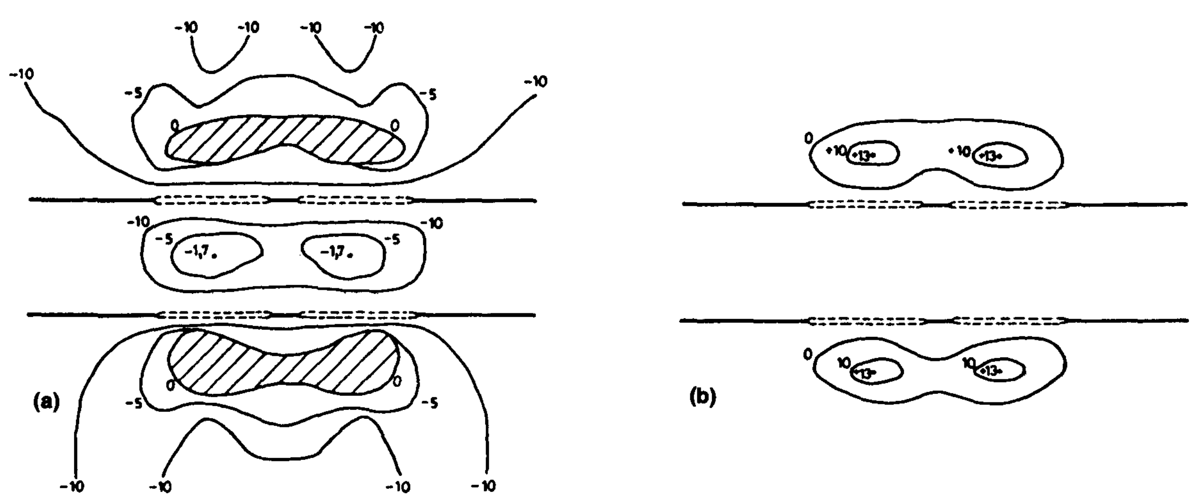

Fig. 10—Excess shear stress and fault ride after slip has taken place in a layout having both bracket and dip pillars
(a) Contours of excess shear stress (MPa) after slip movement
(b) Contours of slip movement (mm)

regions unless they are very wide (wider than 100 m). Periodic dip pillars can potentially segment the regions on the fault plane where slip movements occur. Dip and bracket pillars used in combination can reduce fault movements to moderate levels, allowing haulages to be sited in fault-loss areas. Finally, it is interesting to note that, if backfill ribs are used in place of bracket pillars, slip movement in the hangingwall and footwall areas is reduced, although the motion on the fault between two reef-plane intersections is not inhibited.

It is clear that further layout studies need to be carried out on the effect of such factors as reef dip, fault dip, fault throw, and the virgin stress field. More refined numerical modelling of the dynamic nature of slip motions should also be undertaken. However, the main thrust of development of the excess shear concept as a design aid should centre on the back-analysis of field events to obtain a quantitative understanding of the controlling friction and virgin-stress parameters in order to be able to set a meaningful design level on the size of the seismic events that can be tolerated.

Acknowledgement

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Corrigendum

The levels in Table II on page 276 of the September 1987 issue ('An evaluation of the electrochemical oxygen probes used in steelmaking' by M.J.U.T. van Wijngaarden, R.J. Dippenaar, and P.M. van den Heever) are incorrect. The table should read as follows.

TABLE II
SUCCESS RATE OF OXYGEN MEASUREMENTS UNDER PLANT CONDITIONS

No. of measurements	Success rate			
	Processing unit	e.m.f. response curve		
		Excellent	Acceptable	Unacceptable
100	92	45	35	20

Applied measurements

The 1st IFAC Workshop on Applied Measurements in Mineral and Metallurgical Processing is to be held in Sabi-Sabi Game Park, Transvaal, South Africa, from 11th to 14th October, 1988.

The scope of the Workshop will be as follows:

- Presentation and discussion of the theory and application of measurement techniques and instruments suitable for the mineral- and metal-processing industry
- Case studies and *in situ* evaluations of new measurement techniques specifically developed for on-line analysis and quality control in the mineral- and metal-processing industry
- Contributions based on estimation techniques resulting in applied on-line measurements.

Attendance will be limited to 60 participants, and preference will be given to those who have submitted contributions.

- The closing date for receipt of applications to attend is 31st March, 1988. Invitations will be sent out within 2 weeks of that date.
- Two copies of each abstract should be sent in by 15th February, 1988. The length should be approximately 300 words. Notification of acceptance will be made by 1st April, 1988.
- The final copy of each accepted paper should reach the organizers not later than 15th August, 1988.
- Papers must be prepared according to the *Instructions to Authors* sent together with the notification of acceptance of the papers.

The venue is one of the world's largest private game reserves, and lies adjacent to the famous Kruger National Park. It is situated on 70 000 ha of lowveld bushveld, 500 kilometres northeast of Johannesburg.

Technical tours to the industrial centres near Johannesburg can be arranged on request, and will depend on demand. A scenic tour covering the Garden Route and Cape Town will be arranged on request.

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Automation of hard-rock mining

The 1st IFAC Workshop on Advances in Automation of Underground Hard Rock Mining will be held in Montreal, Canada, from 12th to 14th September, 1988.

The objectives of the Workshop are

- To favour the transfer of technology from novel fields of automation to underground hard-rock mining
- To establish the current status of automation and its application to underground hard-rock mining
- To advance towards fully automated mining systems in underground hard-rock mining. The main topic will be the automation of machines used for direct ore mining in underground hard-rock mines. More specifically the following themes will be emphasized:
  - Automation of drilling, blasting, loading, transportation, and ground control
  - Vehicle guidance, vision systems, and robotic application
  - Artificial intelligence applications to underground hard-rock mining
  - Geological controls over mine planning and extraction processes.

Attendance will be limited to 50 participants, and preference will be given to those who have submitted contributions. The closing date for receipt of applications to attend is 1st April, 1988. Invitations will be sent out within 2 weeks of that date.

Contributors should send 2 copies of their abstracts to reach the organizers by 1st February, 1988. The length should be about 500 words. Notification of acceptance will be made by 15th March, 1988.

The final copy of each accepted paper should reach the organizers no later than 15th June, 1988. Papers must be prepared according to the 'Instructions for Authors', which will be sent together with the notification of acceptance of papers. The organizers will provide each registered workshop participant with copies of the workshop papers received.

Communications should be addressed to

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