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Hangingwall behaviour in tabular stopes subjected to seismic events

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SYNOPSIS

This paper describes simple calculations to evaluate the stability of hangingwall and footwall strata at the working face and in backfilled areas. It shows that the benefits of support provided by backfill can best be realized when the fill is placed as close to the face as possible. The main beneficial effects of fill are that it reduces the stope span, at the same time providing a damping effect on vibrations, and prevents the fall-out of blocks in filled areas, thus maintaining the competence of the strata.

SAMEVATTING

Hierdie referaat beskryf eenvoudige berekenings om die stabiliteit van dak- en voetlae by die werkfront en in teruggevulde gebiede te evalueer. Dit toon dat die voordele van die steun wat terugvulling verskaf, die beste verwesenlik kan word deur die opvulling so na as moontlik aan die front te plaas. Die vernaamste voordele van opvulling is dat dit die afbouspanwydte verminder en terselfdertyd 'n dempende uitwerking op vibrasies het en voorkom dat blokke in opgevulde gebiede uitval, en daardeur die bevoegdheid van die lae handhaaf.

Introduction

Throughout the South African gold-mining industry there is much informal evidence regarding the effective performance of backfill under seismic loading conditions. There are also specific cases in the literature referring to the beneficial effects of backfill[1,2]. In all instances, the opinions appear to be unanimous that backfilled stopes are much less prone to seismically-induced damage than conventionally-supported stopes. However, little analytical work has been carried out to substantiate this observation.

The object of this paper is to identify various ways in which seismicity could cause damage in stopes, and to present some simple calculations (Addendum), together with the results of some field measurements, to illustrate the basic principles involved. The source and mechanism of the seismic events are not dealt with, and are not relevant to the considerations. However, it is assumed that the events result in the rock adjacent to a stope moving with some particle velocity. A conservatively high peak velocity of 10 m/s is referred to in the calculations.

Effect of Seismic Waves

The manner in which a seismic wave affects a stope depends on whether the stope is filled or not. The various ways in which backfill reduces the influence of seismic loading can be summarized as follows.

(a) Filled areas:
- Reduction in volumetric closure and therefore seismicity
- Partial transmission of seismic waves, and hence a reduction in the 'throw-off' potential of reversed seismic waves
- Development of reactive support to ejected blocks and fragments of rock
- Damping of seismically induced vibrations of the detached stratum

(b) Working areas:
- Development of reactive shears on the ends of the detached hangingwall stratum overlying the working place
- Development of reactive mid- and endspan moments in the detached stratum
- Reduction of the slenderness ratio of the detached stratum, with a resulting increase in its buckling stability
- Increase in the natural frequency of vibration of the detached stratum, and hence a reduction in the potential for resonant oscillations.

The effect of backfill in reducing volumetric closure has long been amenable to calculation by means of the MINSIM type of computer programs[3] and is not dealt with in this paper. Simple calculations are presented in respect of the other aspects referred to above, except for the last in each category, for which the results of relevant field observations are discussed.

Seismic Disturbances in Backfilled Areas

The direct effects of backfill on a stope under seismic loading are described in this section. The indirect effects on the adjoining unfilled areas of the stope are discussed in the next section of this paper.

Partial Transmission of Seismic Waves across Fill

An incident compressive shock wave is reflected as a tensile wave at a free surface. In a stope, this has the effect of ejecting blocks of rock into the adjoining open area. If the stope contains backfill, part of the incident energy will be transmitted by refraction instead of being

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reflected. The magnitude of the reflected tensile wave and its 'throw-off' effect will accordingly be reduced.

Ergin[4] presented expressions defining the proportions of the reflected, c^2, and the refracted, e^2, energy. For the case of a compressive wave propagating in a direction normal to the hangingwall–fill interface, these expressions assume the following form:

$$c = (V_1\rho_1 - V_2\rho_2)/(V_1\rho_1 + V_2\rho_2)$$
$$e = 2(V_1\rho_1 V_2\rho_2)^{0,5}/(V_1\rho_1 + V_2\rho_2),$$

where V and ρ denote wave velocity and density respectively, and subscripts 1 and 2 the adjoining media, in this case the hangingwall and backfill respectively.

The following are typical values for these parameters:

V_1 = 5500 m/s
V_2 = 400 to 1200 m/s
ρ_1 = 2,7 T/m^3
ρ_2 = 1,6 to 1,9 T/m^3.

The ranges of values given for the backfill correspond to its state shortly after placement, and to that far away from the face in the back area. The corresponding values for the proportions of the reflected and transmitted energies are therefore 0,83 to 0,59 and 0,17 to 0,41. Close to the face the fill will transmit a relatively small proportion, 17 per cent, of the energy incident upon the rock–fill interface and in the back area a substantial proportion, 41 per cent.

The transmission of seismic energy by the backfill in the back area can be interpreted as a stabilizing criterion. The considerable magnitude of the transmitted energy is compatible with the expected behaviour of a consolidated backfill far from the face. However, close to the face the transmission of seismic energy by the backfill is far too small to explain the beneficial effects that compressible fills have been observed to show.

Development of Fill Resistance to Keyblock Ejection

A typical deslimed tailings backfill (single-stage cycloned Vaal Reefs tailings, no flocculant) has a stress–strain relationship for a uniaxial strain path, which can be expressed as

$$\text{Stress} = 3916\ (\text{strain} - 0{,}01)^3\ \text{MPa}.$$

The ejection velocity of a potentially loose block resulting from reflection of the shock wave is double the peak particle velocity[5], which may project the block into the fill as shown in Fig. 1. On the basis of this phenomenon, the above stress–strain law, and Newton's laws of motion, the relationship between the peak particle velocity, v, and the distance, d, through which a block of thickness t is projected before being arrested by the reaction in the fill is given approximately by the expression

$$v^2 = [0{,}72\ d\ (d - 0{,}01)^3\ 10^6/t - 5\ d]. \quad \text{..........} \quad (1)$$

This relationship is shown plotted in Fig. 2 for the typical ranges of values for the parameters. It is evident that potentially loose blocks would neither be displaced excessively nor by amounts exceeding their own thickness. For example, a block 3,2 m thick would be displaced by only 150 mm subject to a peak particle velocity of 10 m/s before being arrested by the reaction developed in the fill. The restraint of the blocks to displacements less than their own thickness illustrates one of the support functions of the fill.

It should be observed that equation (1) is based on the assumption that the hangingwall touches the fill but exerts no load on it at the time of being accelerated by the seismic wave. In other words, the fill is in its most compressible state at the start of the ejective motion. The ejective displacements will be far less at a stage when the hangingwall has already subjected the fill to some consolidation settlement.

Damping of Seismically-induced Vibrations

The transmission of seismic energy across an unfilled stope has been investigated by means of direct measurement as described by Spottiswoode and Churcher[6]. No information in this regard has yet been obtained for filled stopes. It can, however, be assumed with reasonable certainty that backfill will act as an effective damper to vibrations and oscillations of the adjoining rock strata. The fact that the hanging- and footwall strata have been observed by Spottiswoode and Churcher to move relative to one another almost certainly means that the backfill will cause the movement of one stratum to interact with that of another. For certain phases of such relative movement, the backfill will be additive to the mass of the moving stratum and thereby change its natural frequency of vibration.

Indirect Stabilizing Effects of Backfill in Working Areas

The detached hangingwall stratum lying over the working area is subjected to its own weight and to an ejective loading caused by seismic shockwaves or associated vibrations. These loads give rise to maximum shearing stresses at the ends of the unsupported stratum, and to maximum bending moments at the middle and the ends. The resistance of the stratum to ejection under these conditions, its buckling stability, and its resonant oscillating behaviour are discussed below. However, it is first necessary to outline the criteria used in these considerations.

Rockburst Damage in Terms of Peak Particle Velocity

A relationship has been established[7] between the peak ground velocity caused by a seismic event, the magnitude of the event, and the distance from the source of the event. This is presented in graphical form by Wagner[8], who has also tabulated a summary of information on rockburst damage, including estimated peak particle velocities. In the data, the estimated peak particle velocities are compared with observed damage, from which it is concluded that velocities in excess of 2 m/s are particularly dangerous. Complete stope closure would be expected for velocities in excess of 3,5 m/s. The relationship has been derived from measurements made in the far field and, as indicated by Spottiswoode[9], under-estimates the likely peak particle velocity in the near field.

For the purposes of estimating the upper bound effect of seismic events on the stability of the fractured material surrounding a stope, it is necessary to know the frequency distribution of the magnitudes of seismic events at various locations and distances from the stopes in the South African context. As an alternative to this theoretical approach, for which all the required data are not

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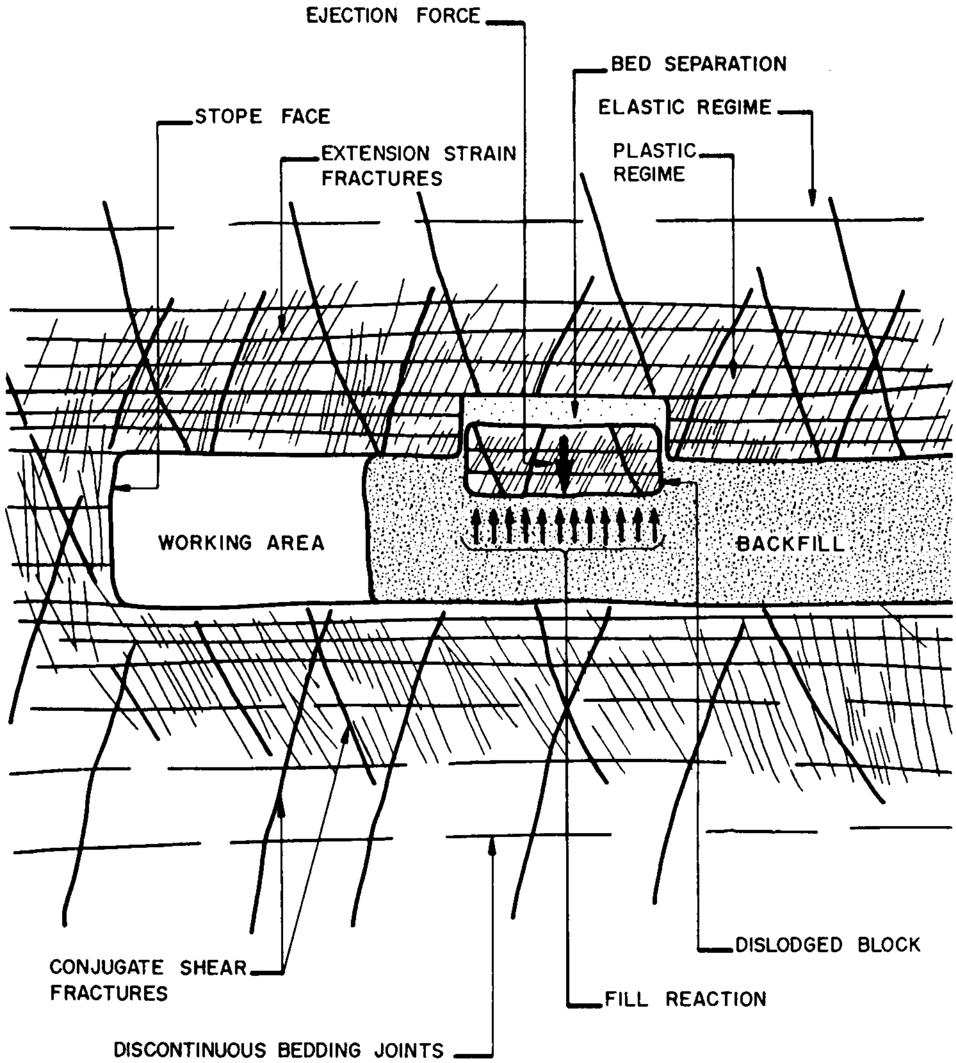

Fig. 1—A loose block ejected into backfill

available, the maximum peak particle velocities to which a stope may ever be subjected during a burst can be estimated from the empirically established behaviour of rapid-yielding hydraulic props. In terms of the manufacturer's design specification, their maximum rate of yield is believed to be between 2 and 3 m/s, above which they would split. Props split only rarely, which by implication indicates that closure velocities seldom exceed 3 m/s; otherwise, the design specification would have been changed. For the purposes of the calculations presented in this paper, an upper value of 10 m/s was assumed for peak particle velocity, which is well above the velocities normally encountered.

Some physical appreciation is lent to the magnitude of the peak particle velocity, when one considers that, using the relationship of McGarr *et al.*[7], a value of 10 m/s could result at a distance of 10 m from the source of an event of 3,6 Richter magnitude or, alternatively, at a distance of 60 m from the source of an event with a Richter magnitude of 5,0.

Rockfall Hazard in Terms of Displacement and Closure

In addition to the maximum peak particle velocity to which a stope may ever be subjected, it is necessary to establish the closure beyond which conditions in the working place will be catastrophic. It is suggested that this bound corresponds to dynamic closures or deflections of either the hangingwall or the footwall in the working area of 300 mm. Sudden displacements of the detached hangingwall or footwall strata in excess of 300 mm would generally be considered to be associated with very hazardous circumstances. Loose rock would have fallen from the hangingwall, and the stick or prop support would either have collapsed or punctured into the surrounding rock.

Shear Resistance of Unsupported Detached Stratum

The ejective action to which the detached stratum is subjected and the resisting shears that are mobilized on its ends are illustrated in Fig. 3. Based on the principle that the ejection velocity is double the peak particle velocity, Newton's laws of motion, and the Mohr–Coulomb law for the relationship between the shearing and normal, p, stresses on the ends of the stratum, the span of the working area, w, should not exceed that given in the following equation:

$$w = 0{,}000\,368\ pd/(v^2 + 5\ d) \qquad (2)$$

The relationship is shown plotted in Fig. 4 for typical

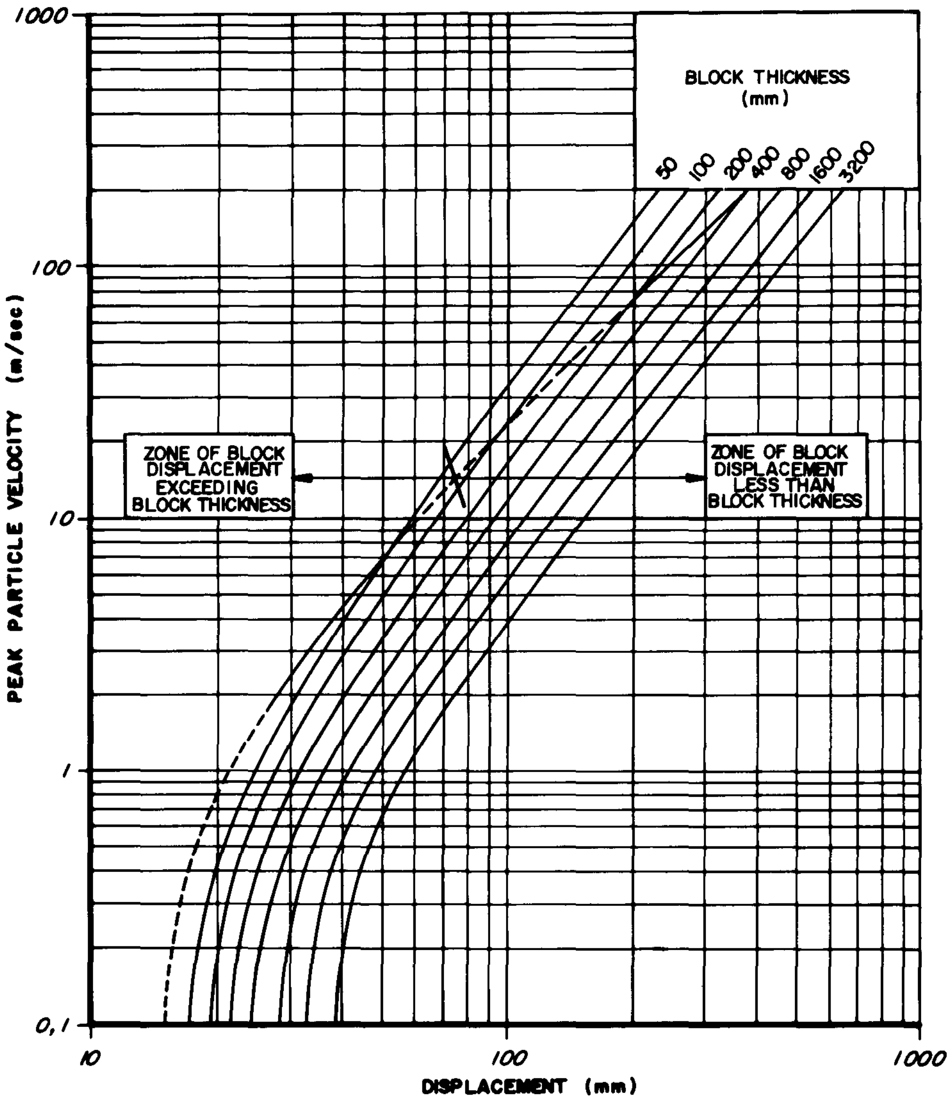

Fig. 2—Peak particle velocity versus displacement for a block supported by fill reaction

ranges of values. The horizontal normal stress in the detached stratum is assumed to be 4,0 MPa, which has been determined to be realistic from finite element analyses. The span over the working area should be limited so that, when it is subjected to peak particle velocities in excess of 2 m/s, the stratum is limited by the end shears to a maximum deflection of 300 mm. It is evident from Fig. 4 that, for an upper-bound peak particle velocity of 10 m/s and for a maximum displacement of 300 mm, the fill-to-face lag should not exceed 4,4 m for the detached stratum to remain stable.

The limiting peak particle velocities and displacements that the detached hangingwall can withstand under end shearing are sensitive to the unsupported span and the horizontal clamping stresses. As a result, it is clear that, while the above analysis may be very simple, the unsupported span of the detached stratum should be kept to the absolute practicable minimum. The uncertainties surrounding the reduction in initial closure and the avoidance of shrinkage in the fill further confirm this conclusion.

Bending Resistance of Unsupported Detached Stratum

The ejective actions to which the detached hangingwall stratum is subjected under bending conditions are illustrated in Fig. 5. In terms of the concepts referred to previously and the compatibility of the plastic hinges that form at points of maximum moment, it is shown in the Addendum that the peak particle velocity should not exceed a critical value given by the following expression if the detached stratum is not to be ejected:

$$v^2 = 12\,250\, d(t - h)(t + 2h)/w^2t - 2{,}5\, d,$$

where $h = 0{,}5\,t - \{w^2 - [w^4 - 4(2\,t + d)w^2d]^{0,5}\}/8(2\,t + d)$.

The relationship for a block with a thickness of 800 mm is shown plotted in Fig. 6 for typical ranges of values. The unconfined compressive strength of the rock in the detached stratum was assumed to be 100 MPa.

Based on the same criteria as for the end shears, it is evident that, for a peak particle velocity of 10 m/s and for a maximum midspan deflection of 300 mm, the unsupported span over the working area should not exceed 5,5 m if the stratum is not to be ejected. It can also be seen from Fig. 6 that the limiting peak particle velocities and displacements that the detached stratum can resist under bending are very sensitive to its span and thickness. Irrespective of the simplicity of the calculations referred to, the clear span of the unsupported detached stratum should therefore be kept to the absolute practicable mini-

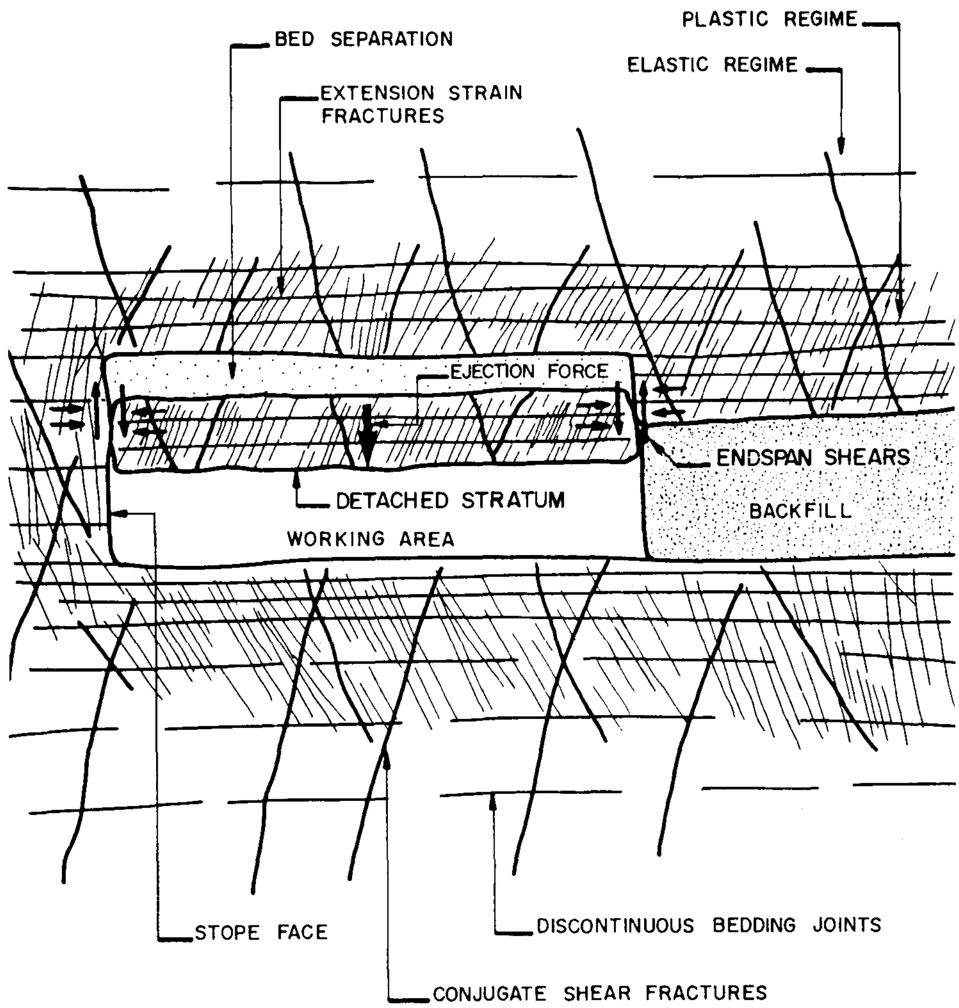

Fig. 3—A detached stratum stabilized by endspan shears

mum, especially in view of the difficulties of reducing the initial closure of the stope and avoiding the shrinkage of the fill.

Buckling Resistance of Unsupported Detached Stratum

The buckling stability of the detached stratum immediately behind the face is a function of its slenderness ratio and the in-plane horizontal stresses clamping it. The stratum may for the purposes of buckling stability be taken to represent a strut of length w that is hinged at both ends. The critical magnitude of the horizontal stress, s, in excess of which the stratum would buckle in terms of classical Euler theory is given by the expression

$$s = 3\,E_t\,(11\,t/21\,w)^2,$$

where E_t represents the tangent modulus for the rock at failure, which can be taken to be half of that at zero stress, 65 GPa.

An upper bound value for the horizontal stress in the detached stratum close to the face has been shown by Kirsten[10] from finite element analyses to amount to 60 MPa. The span of the unsupported hangingwall stratum, w, over the working place should therefore not exceed the value given by the following expression in terms of its thickness, t, if it is not to buckle:

$$w = 21{,}11\,t.$$

The thickness of individual slabs in the hangingwall ranges typically from 0,2 to 0,3 m, for which the corresponding values for w from the expression given vary from 4,2 to 6,3 m. The fill-face lag should therefore not exceed this range of values if individual slabs are not to buckle. It is evident from the expression given that the fill-face lag will be even less for slabs of lesser thickness. Although it is hardly practicable to mine at fill-face lags of less than 4,2 to 6,3 m, the indications from the analysis, however simple it may be, are that the fill-face lag should at all times be kept to an absolute minimum.

In terms of classic column-buckling theory, the stability of the detached hangingwall stratum is reduced by the transverse shearing effects induced by an incident seismic wave. Although such effects cannot yet be quantified, it confirms the requirement that the fill-face lag should be kept as small as possible.

Suppression of Resonant Oscillations of Detached Stratum

Besides the ejecting effects described above, the passage of seismic waves can induce vibrations in the rock mass that may lead to resonance effects in the hanging- and

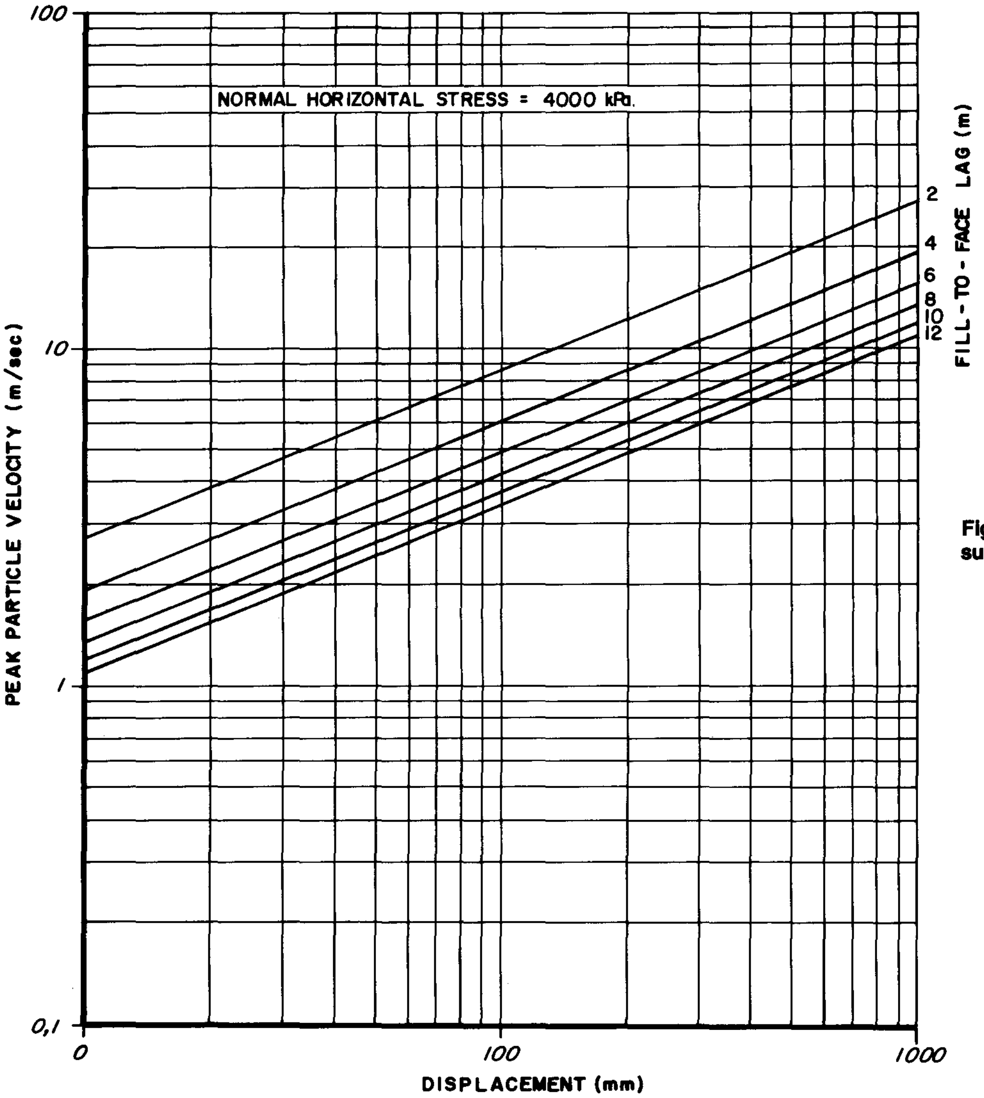

Fig. 4—Peak particle velocity versus displacement for a block supported by endspan shears

footwalls. Spottiswoode and Churcher[6] have described the data observed from a number of geophones placed specifically in the immediate hanging- and footwalls of an unfilled longwall at West Driefontein to study the transmission of seismic energy across the stope and to assess how backfill may affect the situation. Their findings can be summarized as follows.

- The amplitudes of ground motion are larger close to the stope than remote from it.
- The frequencies of vibration in the fractured regimes adjoining the stope are significantly less at 70 Hz, than those of 200 Hz in the remote elastic regime. Also, the natural frequencies of vibration in the fractured regimes are neither dependent on the magnitude of the source events nor on the distance from them.
- The stope damps the amplitudes of vibration of the waves crossing it.
- The detached strata in the hanging- and footwalls move to a greater extent relative to one another than they do in unison either up or down.
- The peak particle velocities in the fractured regimes adjoining the stope are 2,5 times larger than those remote from rock boundaries.

Spottiswoode and Churcher concluded from these findings that the nether hanging- and footwall strata are detached from the adjoining elastic rock and that they behave independently of each other. Furthermore, the vibrational characteristics observed confirmed that specific sections of the detached strata, which are separate structual components affecting the stability of the stope in the working area, may be subject to potential oscillations, are of limited extent.

According to Spottiswoode and Churcher, backfill will reduce the spans of the detached strata and thereby increase their resonant frequencies from 70 Hz to, say, 140 Hz. The radiated seismic energy at 140 Hz is one quarter of that at 70 Hz, and therefore there would be far less excitement and shake-out of the potentially loose material at the higher frequency. The reduced energy at the higher frequencies of vibration will also be more rapidly attenuated in the fractured ground. The backfill itself will act as a more effective damper through the dissipation of interparticle frictional energy than will conventional stope support.

Conclusions

The simple considerations presented in this paper concerning the stability of a stope under dynamic loading