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DEPARTMENT OF MINERALS AND ENERGY

SIMRAC

FINAL PROJECT REPORT - Survey of Horizontal Stresses in Coal Mines from Available Measurements and Mapping (SIMRAC Project COL802)

SEPTEMBER 2002

REPORT NO : 01-001-SMR/1

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REPORT ON :   FINAL PROJECT REPORT - Survey of Horizontal
Stresses in Coal Mines from Available Measurements
and Mapping (SIMRAC Project COL802)

REPORT NO :   01-001-SMR/1

REFERENCE :   Our MOA dated 11/6/2001 for Project COL 802

PREPARED BY :   R. Frith

DATE :   27th September 2002

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Principal

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EXECUTIVE SUMMARY (SIMRAC Project COL 802)

A detailed review of the role of horizontal stress in coal mine roadway roof stability and control within both the Witbank and Highveld Coalfields has been undertaken by Strata Engineering (Australia) Pty Ltd.

The review contains the following essential elements:

(i)   Inspections and mapping of a representative sample of mining conditions within the two coalfields, with particular emphasis on both the manifestation of horizontal stress and examples of actual roadway roof instability.

(ii)   An assessment of the *in-situ* stress measurements that were available from both coalfields.

(iii)   A summary of regional horizontal stress trends and variations thereof.

(iv)   A proposed conceptual model for the origin of horizontal stress in the coal measures.

(v)   The provision of a technical link between horizontal stress in the ground and roof stability/instability in mine roadways.

(vi)   Consideration of the operational significance of horizontal stress in terms of both the mining processes and ground support methods in use.

(vii)   Guidelines for the future use of horizontal stress mapping for operational strata management.

(viii) Suggestions as to how any deleterious effects of horizontal stress could be further mitigated within the practicalities of the mining methods in use.

Based on the work undertaken, the following project findings have been arrived at:

(a)   Horizontal stresses are clearly evident within both coalfields with magnitudes that are often higher than the vertical stresses, as given by the weight of overburden alone.

(b)   Having considered the various properties of the horizontal stresses that are known to exist, it is almost certain that they are "tectonic" in origin, this meaning that they are a result of far-field horizontal movements. However, this does not then necessarily imply that they are directly related to tectonic plate boundaries.

(c)   A conceptual model for the origin of horizontal stress within coal measures strata has been postulated, this relating to the transfer of stresses (or strains) from the underlying Pre-Karoo basement.

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(d)   Whilst general directional trends are clearly evident within the measured horizontal stresses, significant variations are apparent as a function of:

- The stiffness of the host rock type.

- Proximity to the edge of the coal basin (ie Pre-Karoo outcrops).

- The structural geology of the coal measures.

Essentially, whilst general trends in horizontal stress are evident, significant local variations undoubtedly exist. In fact, a fifty-fold variation in horizontal stress magnitude is contained within the measurement data reviewed by the project.

(e)   As a result of (d), extreme caution needs to be used when applying known horizontal stresses from an existing area to new mining areas. Similarly, it also suggests that horizontal stress needs to be considered as a significant variable rather than well-defined input parameter when undertaking any form of roadway roof stability modelling.

(f)   In an general sense, the available evidence leads to the assessment that the operational significance of horizontal stress is low, due to:

- The almost routine use of unsupported cut-outs of typically >12 m in roadways of 6 to 6.5 m width. This leads to the conclusion that static roof conditions pre-dominate during roadway development. In contrast, mines with significant levels of horizontal stress whereby buckling of the roof occurs are unable to achieve such roadway development outcomes.

- The low propensity for major falls of ground outbye the development face, despite the use of relatively low primary bolting densities.

- The strong link between major outbye falls of ground and localised structural anomalies (ie faults, dykes etc.).

The one area whereby the impact of horizontal stress is clear-cut is the stability of the skin of the roof between the installed primary roof bolts. Guttering and associated instability at this low level is rarely a production constraint, but in thick seam workings, even relatively small pieces of roof skin falling can present a significant safety hazard.

(g)   In terms of improving skin stability, the concept of roof slotting has been suggested as a possible control, as opposed to such methods as the application of roof mesh etc. which do not fit well with the mining systems in use.

(h)   Current stress mapping techniques in use in South African coal mines are more than adequate for operational purposes. Consequently, there is no obvious benefit in attempting to develop and utilise more detailed methods. This is especially relevant when it is considered that a two pass development method (as is commonly used) will

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almost certainly influence the location and form of stress-driven guttering that occurs in the immediate roof and so reduce the reliability of stress direction determinations from stress mapping of such guttering.

In an overall sense, the general findings in terms of mine roadway roof behaviour and stability and in particular, the role of horizontal stress are entirely consistent with the models developed and used within the Australian coal industry by Strata Engineering. However, the key differences are in such areas as the nature of the geotechnical environments being mined and the mining methods and practices in use, rather than any particular fundamental difference in the relevant laws of geomechanics or ground support.

1.0   INTRODUCTION

This report contains the findings and outcomes relating to SIMRAC Project COL802 entitled "*Survey of Horizontal Stresses in Coal Mines from Available Measurements and Mapping*".

The scope of work for the project was outlined in the proposal submitted to SIMRAC in mid-2000 and is summarised as follows:

(i)   to undertake a peer review of available *in-situ* stress measurements relating to the Witbank and Highveld coalfields in South Africa;

(ii)   to undertake inspections and mapping of roadway roof and related geotechnical conditions at a number of coal mines within both coalfields in order to consider the influence of horizontal stress (and variations thereof) on actual mining outcomes;

(iii)   to provide a technical explanation of the link between horizontal stress in the roof and the occurrence of falls of roof in mine roadways;

(iv)   to summarise regional and local trends in horizontal stresses and consider their practical significance using the outcomes of (iii) in relation to roadway roof stability and ground support;

(v)   to comment on the use and limitations of stress mapping for practical mine management purposes.

It is noted that it has not been possible or practical to visit all underground mine sites within the Witbank and Highveld coalfields or even all sections within those mines that were visited. Use has been made of the experience of local rock engineering practitioners in order to be exposed to what may be termed as a "representative sample" of roadway roof conditions within the two coalfields as the fundamental basis for the project. In this regard, the following elements have been integrated into the site visits:

(a)   collaboration with several (but not all) of the major coal mining companies (ie Anglo Coal, Ingwe, Sasol and Eyesizwe);

(b)   visits to as many different mine sites as possible (a total of 12 mine visits were made – see later) to give a reasonable spatial coverage of the project area;

(c)   visits to each of the primary seams being mined (ie the 2, 4 and 5 Seams);

(d)   inspection of both typical or normal areas as well as problem or atypical areas at each mine/seam in order to gain a reasonable perspective as to the range of roof conditions;

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(e)   a focus on first workings bord and pillar development rather than secondary extraction (e.g. longwall, shortwall or stooping).

Based on the stated variations, it is intended that the project outcomes will be sufficiently broad-based to have general application, but accepted that they will almost certainly not be fully comprehensive in their range.

In terms of the criteria for the various project outcomes that were stated in the proposal, it is worth summarising them as follows as these form the basis as to whether the project has achieved its overall objectives or not:

- they must be readily understandable by operational personnel, mine site strata control engineers, geologists and mine planners;

- they must be practical and able to be implemented by both operational and geotechnical professionals;

- they must be backed by historical data from both South Africa and overseas;

- they must be of use in reducing the safety risk posed by roadway roof instability in underground coal mines;

- they must assist in improving the efficiency by which adequate roadway roof stability is engineered;

- they must be of use in optimising the mine planning process.

Each of these criteria have been applied as part of the project and the outcomes have been based upon meeting them accordingly.

As a final introductory comment, it is stated that the project outcomes are really no more than a series of observations and informed opinions that have their technical foundation within the experience base of roadway roof conditions and support practices of the Australian coal industry. They are intended to supplement rather than supersede those principles already in use in South Africa. In addition, it needs to be realised there are a number of fundamental differences between the South African and Australian coal mining industries in terms of both the geotechnical setting of the coal seams and the mining methods in use. In particular, the pre-dominance of bord and pillar mining in South Africa as compared to largely longwall mining within Australia, which is a significant difference when considering the impact of the geotechnical environment on mining operations.

Nonetheless, when the geotechnical and mining method differences have been accounted for, it is apparent that there is little if any technical conflict between the two industries and that the same basic roadway roof control principles can be applied to both, albeit at varying scales. This will be covered in detail within the report as it is probably the primary outcome of the project, albeit one that was not envisaged when the proposal was first submitted.

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A detailed description of the project outcomes will now be given.

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2.0 DESCRIPTION OF STRATA ENGINEERING'S ROADWAY ROOF BEHAVIOUR, STABILITY AND SUPPORT MODEL

As stated in the project proposal, Strata Engineering have brought a working model for roadway roof behaviour and support into the project and it forms the fundamental basis for many of the project outcomes. As such, the relevant sections of it need to be described in sufficient detail as a pre-cursor to the project findings as the reader needs to be familiar with the basics of the model in order to put the findings into their full and correct context.

The model in question is essentially based in structural engineering rather than classical rock mechanics and a clear distinction between these two approaches needs to be made as they do lead to differences in outcome in a number of key areas, including failure mechanisms, geotechnical factors of significance and support practices. Certainly within the Australian coal industry, the two approaches are quite distinct from one another with Strata Engineering being the major proponent of the structural engineering approach, largely due to the fact that almost all of the technical principles involved have been developed by the current principal engineers at Strata Engineering.

A detailed discussion on the specific advantages and disadvantages of the various technical approaches to strata control in mining will not be given herein. However, the various technical aspects of the structural engineering approach will be presented with the end user being required to decide for him/herself as to which approach is most appropriate for their own application.

The structural engineering model used by Strata Engineering for roadway roof control contains the following basic elements :

(i)   modes of roof behaviour;

(ii)   roof falls and their causes;

(iii)   implications to support practices;

(iv)   practical application of the model.

The first two elements are of most relevance to this project and will therefore form the basis of the discussion herein.

It is noted that the model has been developed from extensive roof displacement monitoring through detailed sonic probe extensometry (ie thousands of installations at many mines within the Australian coal industry in both research and operational applications) and the assessment of many major roadway roof falls to identify both primary (ie local) and secondary (ie regional) factors involved. As such, the model has its fundamental grounding in what actually occurs in practice, rather than rock mechanics theory.

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It will also become apparent during the report that there are significant differences in scale between many of the measured roof behaviour outcomes from the Australian coal industry, whereby several metres of roof material can be actively mobile in a general sense across a wide area, as compared to the more localised mass movements of roof material that seem to occur within many of the South African coal mines visited. Nonetheless, as will be demonstrated, once the scale differences are accounted for, it is evident that the same basic technical principles can still be applied in a credible manner.

The relevant aspects of the model will now be discussed in detail.

2.1   Modes of Roof Behaviour

The most fundamental issue to consider in roadway roof control is the mode of roof behaviour occurring as the roadway is being formed and/or during subsequent mining activities. This can have a wide ranging effect (varying from none to highly significant) on such issues as bolting requirements, timing of support installation and ultimately the potential for roof instability to occur (see **Section 2.2**)

There are two primary or common modes of roof behaviour which have been identified and proven through extensive monitoring studies at a large number of Australian underground coal mines. Both can lead to stable roof conditions, but both also have one or several associated failure modes which can potentially lead to a roof fall situation if not adequately controlled.

The two basic modes of roof behaviour are now described.

2.1.1 Static Roof (Figure 2.1)

Static roof involves roof conditions whereby the level of stress acting within the roof is insufficient to cause bedding plane separation (i.e. through the action of vertical tension or bedding plane shear), which thus prevents the roof measures breaking down into thinner discrete units. Essentially, the roof measures "absorb" any stress changes due to roadway formation without undergoing any change in state apart from primarily elastic movement. The lower the stress acting, the more likely that static roof will persist (all other factors being equal). Similarly in general terms, increases in bedding thickness as well as the vertical tensile and shear strengths of bedding planes (ie bedding cohesion and friction) will also increase the likelihood of static roof conditions being maintained.

In terms of extremes, a highly stressed roadway roof environment (e.g. 30 MPa horizontal stress and higher) can still exhibit static behaviour (e.g. current workings at a Southern Coalfield mine in New South Wales at 500 m depth of cover) if high horizontal stress occurs in combination with thickly bedded or massive roof measures. Similarly, quite low horizontal stresses (ie < 10 MPa) can cause significant buckling of the roof (see **Section 2.1.2**) in a thinly and/or weakly bedded roof environment.

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Horizontal
Stress
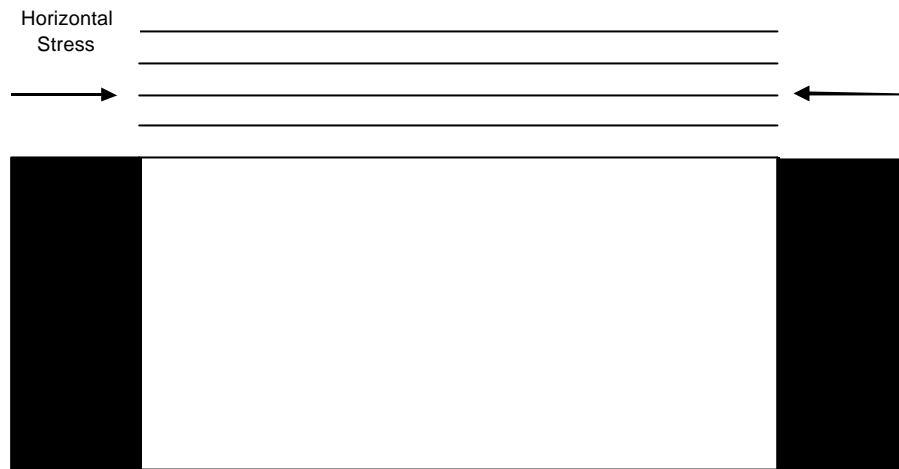
* bedding planes remain intact
* roof measures behave as one thick unit
* static roof environment - low displacements
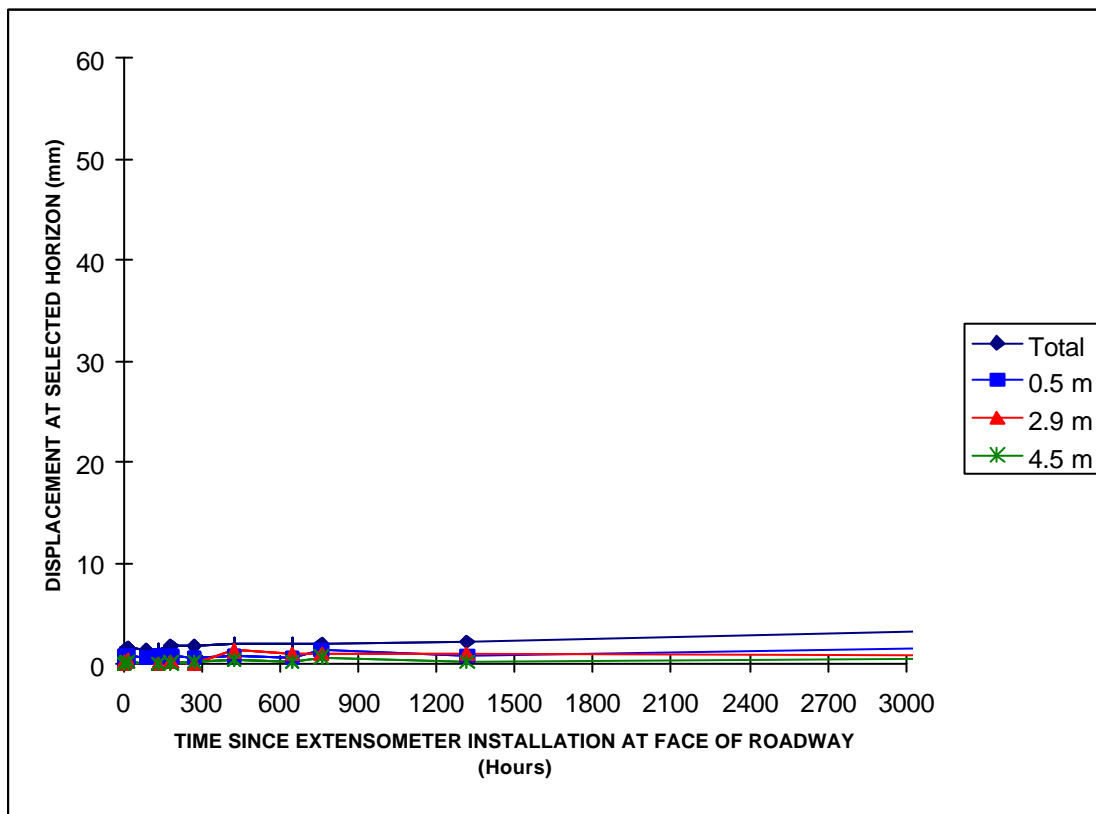
FIGURE 2.1. Schematic Illustration of Static Roof and Typical Time Dependent Displacement Trends

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This all leads to the inevitable conclusion that both the stresses and the nature of the roof must be considered in combination when assessing the likely mode of roadway roof behaviour for a given roadway geometry.

Typically, a static roof environment will undergo < 5 mm of roof movement as a result of roadway formation and in some instances, no discernible roof movement can be detected by roof extensometry. **Figure 2.1** illustrates a static roof schematically and gives an example of associated extensometry data from Strata Engineering's database.

It is noted that in terms of roof stability across the entire roadway width, roof movements referred to in this report are always taken from a point at least 0.5 m up into the roof, whereby skin effects between roof bolts are unlikely to influence overall displacement trends. Experience has shown that the immediate roof skin can behave in a manner which is inconsistent with that of the overlying main roof and a distinct difference between the behaviour of the skin (usually taken as being up to 0.3 m into the roof) and that across the entire roadway width needs to be made. The importance of this distinction is no more apparent than in the context of the findings of this project, as will be detailed.

2.1.2 Buckling Roof (Figure 2.2)

Buckling roof behaviour occurs once a portion of the roof measures undergo tensile and/or shear bedding plane failure, resulting in the formation of a number of thin discrete units that can buckle under the action of horizontal stress, whereas one thick static unit existed previously. The onset of roof buckling should not be considered as "roof failure" though, as despite the obvious occurrence of bedding plane failure within the roof, a buckling beam has a structural strength in its own right and can still lead in many instances to full equilibrium and stability being re-established in the roof.

The basic geometry of the buckling of thin beams under end loading (ie horizontal stress in this instance) can be simply reproduced and demonstrated through the end loading of a 300 mm plastic ruler and whilst it is not being suggested that the roof of a roadway behaves exactly as per a plastic ruler, the same basic mechanistic principles can be shown to apply.

Figure 2.2 illustrates the occurrence of a buckling roof schematically and presents typical time-dependent displacement trends in the roof leading to an equilibrium condition being attained. Note the stark contrast in behaviour with the static roof in **Figure 2.1** as well as the fact that full equilibrium is only established some 900 hours (5.4 weeks) after initial roadway drivage.

It is also worth noting that throughout the entire section of buckling roof, the primary behaviour mechanism measured is for the opening up of bedding planes (this has been confirmed on many occasions with borescope observations - see **Figure 2.3**) rather than block roof movement. This is strong evidence in support of an end-loaded buckling, rather than a self-loaded bending roof behaviour model, although the latter can occur as will be discussed later, but usually only under extreme rock mass conditions.

In order to further explain the basic mechanics of buckling, use can be made of the principles of Euler Buckling as will now be detailed.
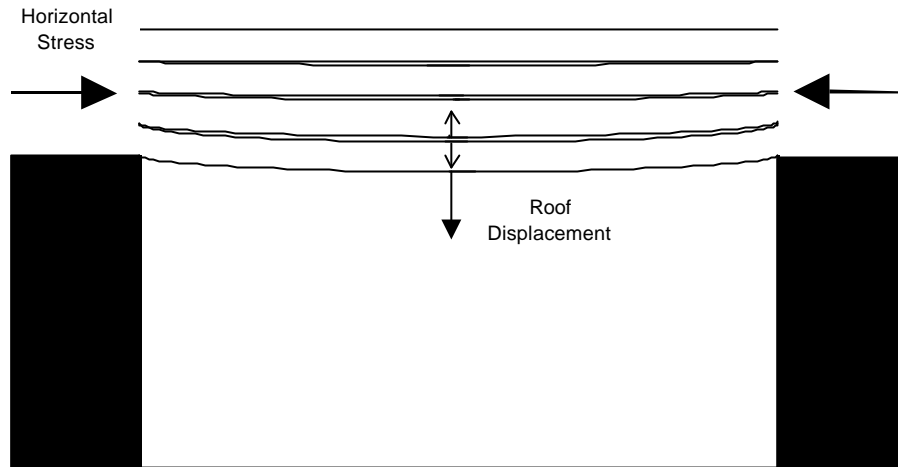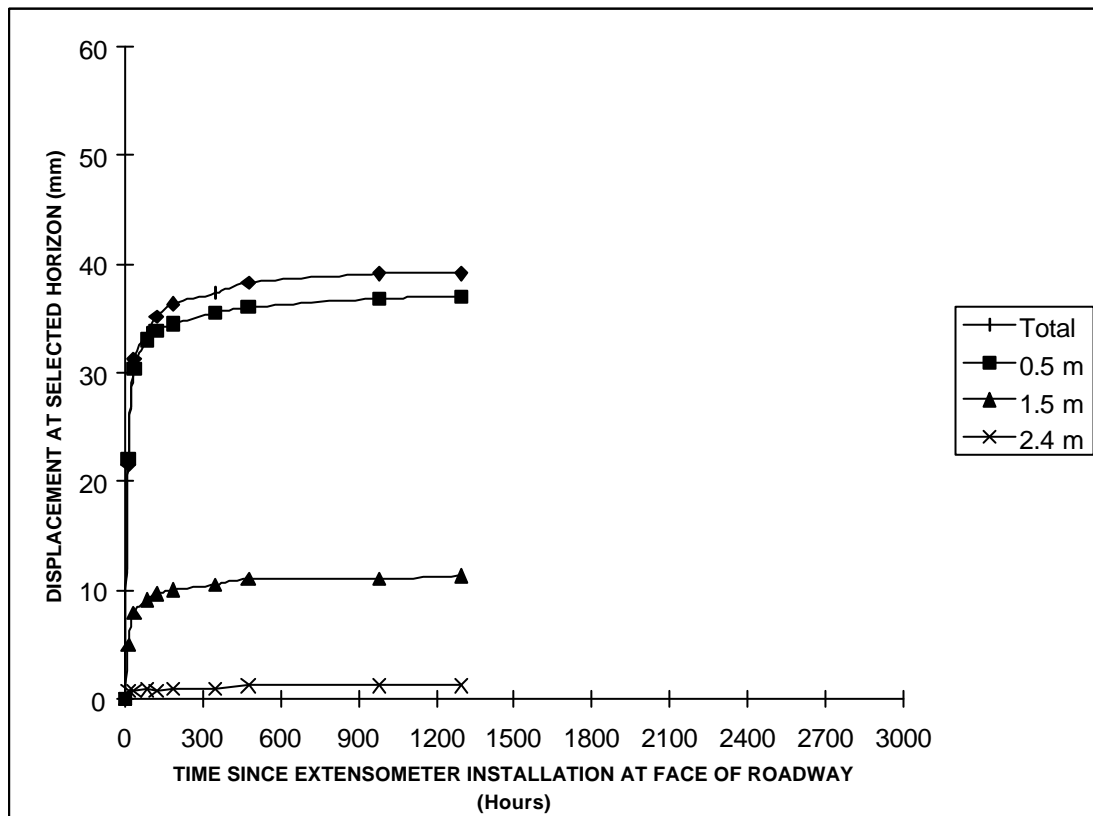
FIGURE 2.2. Schematic Illustration of Buckling Roof and Typical Time Dependent Displacement Trends

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A Euler or buckling beam can be considered as nothing more than a spring which is being end-loaded and whilst like a spring, it will compress in the direction of loading, it also displaces laterally through biased buckling of the slender structure. End loading of the beam is provided by horizontal forces in the roof of the roadway and vertical roof displacement is the lateral displacement component (as illustrated in **Figure 2.2**).
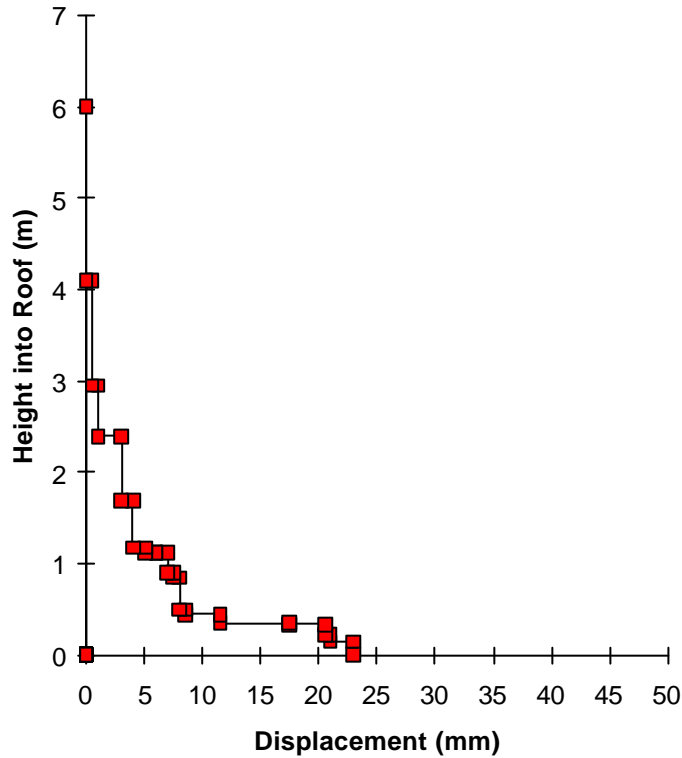
FIGURE 2.3. Sample Borescope Observation Outcomes in a Buckling Roof Showing Propensity for Bed Separation

The end-loading vs lateral displacement curve (ie horizontal load-bearing capacity vs vertical displacement) for a Euler beam of given geometry and material properties is given by the following equation:

$$\mathbf{P = E.I\ [cos^{-1}(e/(u+e)).2/l]^2} \qquad \text{… (2.1)}$$

where P = end loading of buckling beam (MN)
       E = Young's Modulus (MPa)
       I = Moment of Inertia (m^4)
       e = eccentricity (m)
       u = lateral displacement of buckling beam (m)
       l = beam length (m)

Figure 2.4 shows end loading vs lateral displacement curves for three different beam geometries with material properties that are typical of coal measures strata (ie E = 5000 MPa).

In relation to the curves shown in **Figure 2.4**, the following points are made:

(i)   There is a significant variation in maximum load-bearing capacity and elastic stiffness as a function of beam thickness. This is not a surprising result.
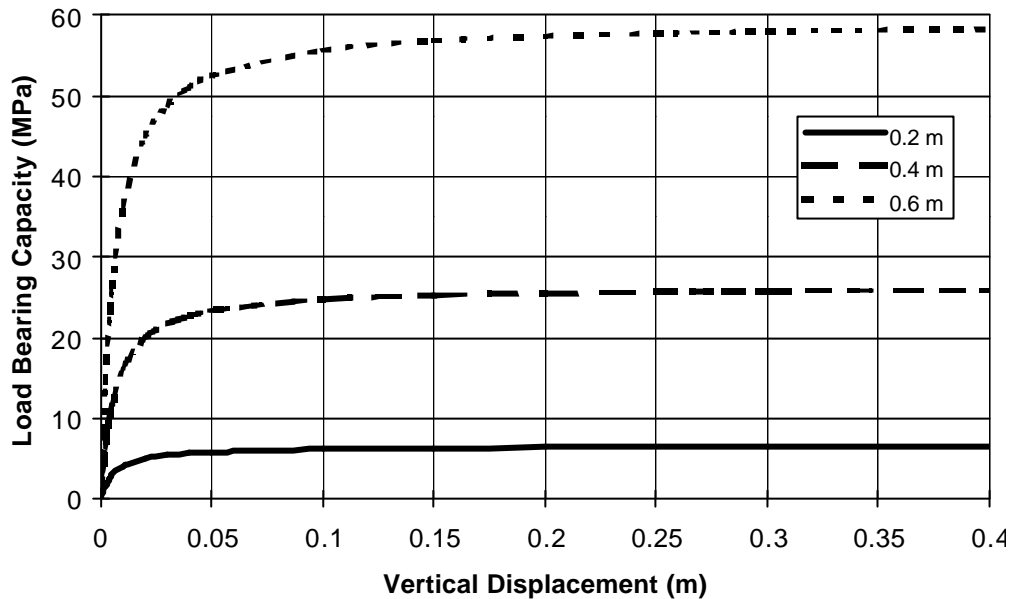
FIGURE 2.4. Sample Euler Buckling Curves for a Typical Coal Measures Rock in a 5 m wide Roadway

(ii)   Even with a beam thickness of only 0.4 m and a beam length of 5 m (ie the roadway width), an end stress of around 25 MPa can theoretically be accommodated at a vertical displacement of around 50 mm. This is not atypical of what is commonly found in buckling environments subjected to high levels of horizontal stress in Australian mines.

(iii)   With a beam thickness of 0.6 m, the maximum end loading capacity of between 50 and 60 MPa is such that this would more than cover most mining environments in Australian coal mines.

Basically, the theory suggests that relatively thin beams of rock material (ie 0.4 to 0.6 m thickness) that are 5 to 6 m long can accommodate end stresses that are within the general range of those that are typically measured in underground coal mines. However in order to do this, they must undergo an amount of lateral displacement (ie the spring must change its state).

Figure 2.5 shows a buckling beam with both the driving force termed P (ie the horizontal stress across the roof) and the resistance (or reaction) offered by the beam termed R (ie as

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defined by the curves shown in **Figure 2.4**). This arrangement can be used to consider how such a beam will behave in a time-dependent sense from original loading at close to zero lateral displacement at the development face, to that time whereby equilibrium is returned such that P-R = 0.

Using the difference in driving force and beam reaction (ie P-R) as the primary consideration of how the beam will behave with time, the following comments are made:

(i)   The rate of movement (ie velocity) in the lateral direction will be a direct function of P-R.


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P - horizontal stress across the roof
R - resistance to buckling offered by roof
                    beam
        u - beam deflection
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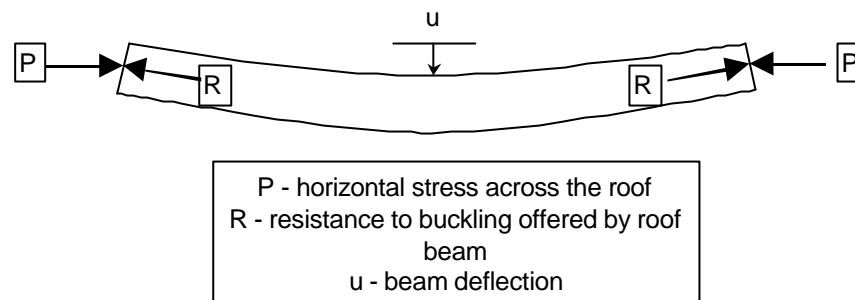
FIGURE 2.5. Schematic of Buckling Beam Illustrating Driving Force (P) and Beam Reaction (R)

(ii)   When u≈0 (ie at the development face), R≈0, such that the rate of movement should logically be at its highest. This is a true statement based on measured outcomes.

(iii)   As the beam continues to laterally deflect, R increases rapidly (see the Euler curves in **Figure 2.4**) such that P-R becomes more balanced and the rate of movement slows down. This is again a true statement based on measured outcomes.

Essentially, the basic form of the measured time-dependent displacement curve for a buckling roof, as shown in **Figure 2.2**, can be explained in a credible manner by the application of Euler Buckling theory to a roadway roof environment being driven by horizontal forces acting across the roadway.
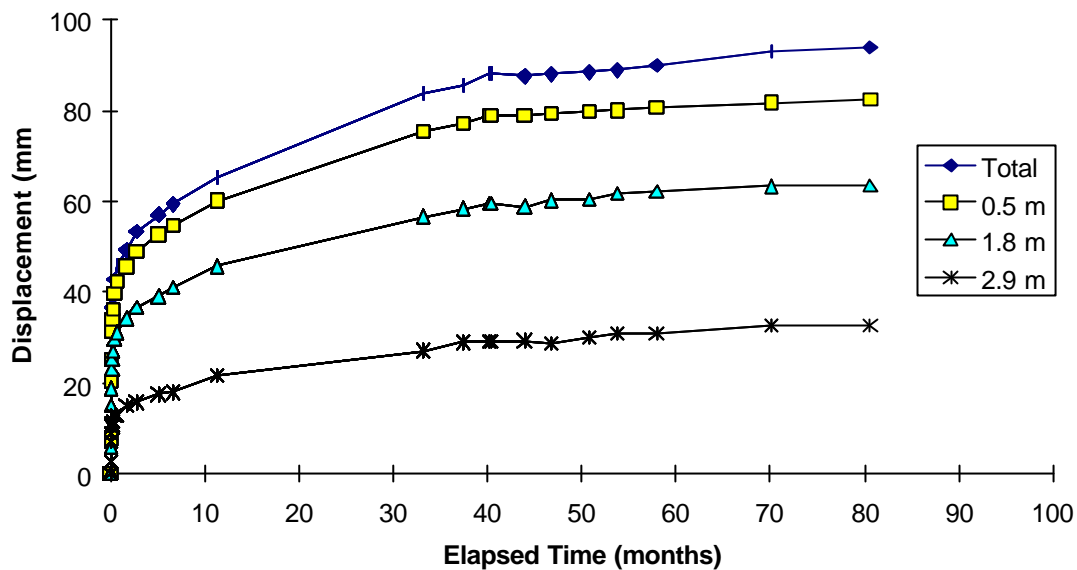
**FIGURE 2.6. Roof Extensometry Data Showing Long-Term Roof Creep Over a
Seven Year Period**

As a further issue, the question is raised as to what will occur if the roof buckles and breaks
down into individual strata units that are of inadequate maximum load-bearing capacity and
cannot accommodate the horizontal stresses driving the buckling (ie P-R > 0 irrespective of
how much movement the roof undergoes).

The issue of structural failure of a buckling beam (through low angle shearing) will be dealt
with in **Section 2.2** regarding roof fall mechanisms. However, the other outcome that is
commonly measured is one of on-going creep of the roof with time (see **Figure 2.6**) and it is
assessed that this is indicative of a situation whereby the maximum available load-bearing
capacity of the beam(s) in the roof are insufficient to fully accommodate the driving
horizontal stresses across the roof (ie P-R > 0). Logic would suggest that the higher the
inequality, the higher the rate of creep.

As a final aspect of strata buckling, it is noted that the transition from a static to buckling
roof is very much a step-wise rather than gradual process. This well-established fact has
been measured on a number of occasions some time after initial roadway development,
whereby a static roof occurred at the face with the onset of buckling occurring several days
later (see **Figure 2.7**).

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FIGURE 2.7. Schematic Illustration of Static to Buckling Transition and Time Dependent Displacement Response

The primary technical outcome from the recognised transition from a static to buckling roadway roof environment is that a very subtle change in either BUCKLING ROOF roadway width or material property can cause a highly significant change in roof condition, should it result in the static to buckling transition taking place.

In summary, the occurrence of buckling roadway roof is a well proven concept within the Australian coal industry and can be explained in a cre   ural engineering principles and a basic engineering assessment of the mechanics of measured roof behaviour with time. Buckling does not constitute roof failure per se as the roof still has a structural strength in its own right, but if not adequately and appropriately reinforced, it will usually result in a roof fall scenario at some point in time. This will all be discussed in more detail in **Section 2.2**.

(Overlaid graph: y-axis labelled "Displacement", x-axis labelled "Time"; curve labelled "STATIC ROOF" rising to "BUCKLING ROOF" with annotation "phase change" transition from static to buckling behaviour)

2.1.3 Other Roof Behaviour Modes

Whilst it is uncommon in the Australian coal industry, it makes logical sense that the immediate roof of a roadway can also bend under its own weight, rather than buckle under the action of horizontal stress (see **Figure 2.8**). However, for bending to be a dominant mechanism in roadway roof behaviour, the horizontal stresses need to be very low, as they would usually pre-dominate over self-weight of the immediate roof. Therefore, in order for bed separation to occur and significant bending of the roof beneath, a very weak bedding plane (or series of) must also be present so that bedding plane failure can take place under the very low vertical stress generated by self-weight.

FIGURE 2.8. Schematic Illustration of a Bending Roof Environment

Bed separation

Bending roof moving as a discrete "block" with minimal bed separation

Roof Displacement
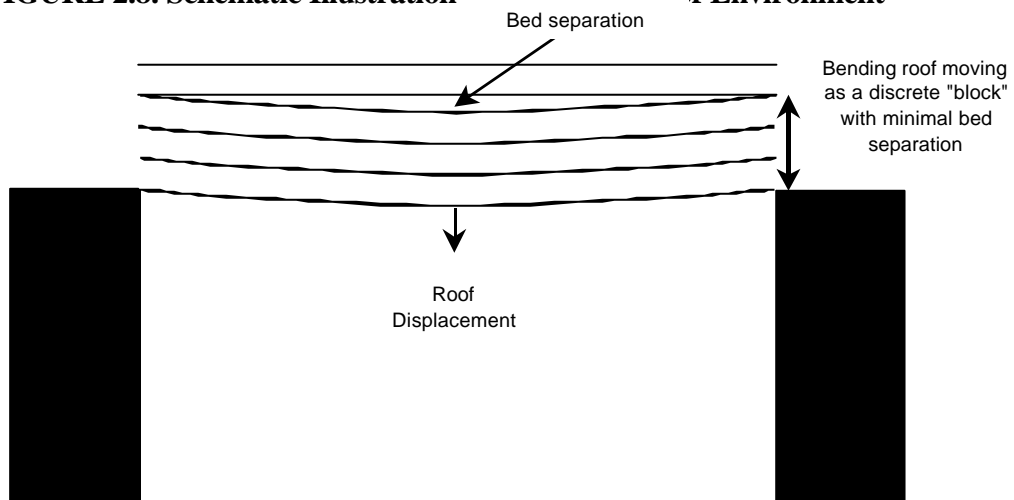
The above statement explains why bending of the strata is generally taken to be such an uncommon occurrence in Australian underground coal mines and hence, why it has received very little attention in terms of control and support. However, as bending is not driven by horizontal stress, it has not been a primary focus of this project and therefore, will not be considered further.

With the various fundamental modes of roof behaviour having been recognised, it is now necessary to consider their impact upon roadway roof stability (i.e. the potential for a roof fall of some form).

2.2   Mechanics of Roadway Roof Falls

As a general roof fall model, it is assessed that all major roadway roof falls have the same ultimate cause, namely that the gravity loading of the material about to fall exceeds the vertical restraint offered by any installed support and the resistance to vertical shear movement within the roof strata at the edges of the imminent fall. The level of vertical shear resistance is governed by both the nature of the shear surface and the level of confinement across it (ie the horizontal stress across the roof). This is referred to as the "three brick" model (see **Figure 2.9**).
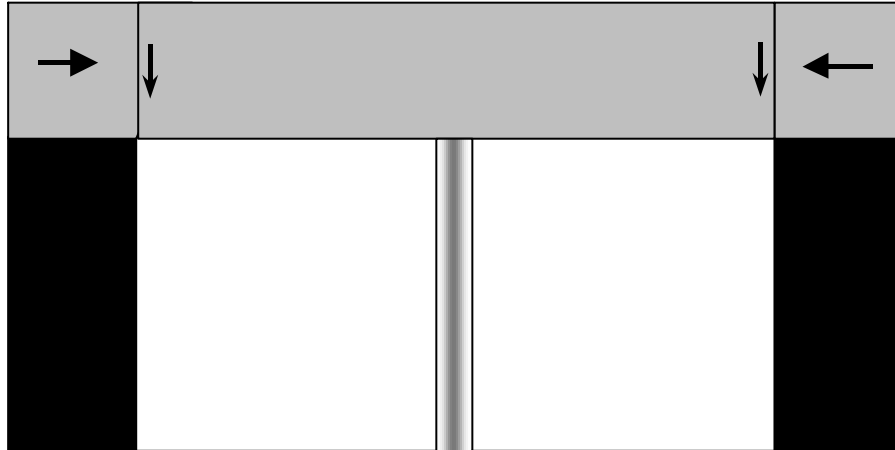
FIGURE 2.9. Basics of "Three Brick" Model for General Roof Stability

As such, it is self-evident that in general terms, horizontal stress acting across the roof has a stabilising rather than destabilising influence. However, this is only true to a point and either too much or too little can result in major roof falls occurring, dependent upon whether and how the roof is controlled with installed support. There are several well-established mechanisms by which the roof can enter a critically unstable state and those that are relevant to horizontal stress are now described in more detail.
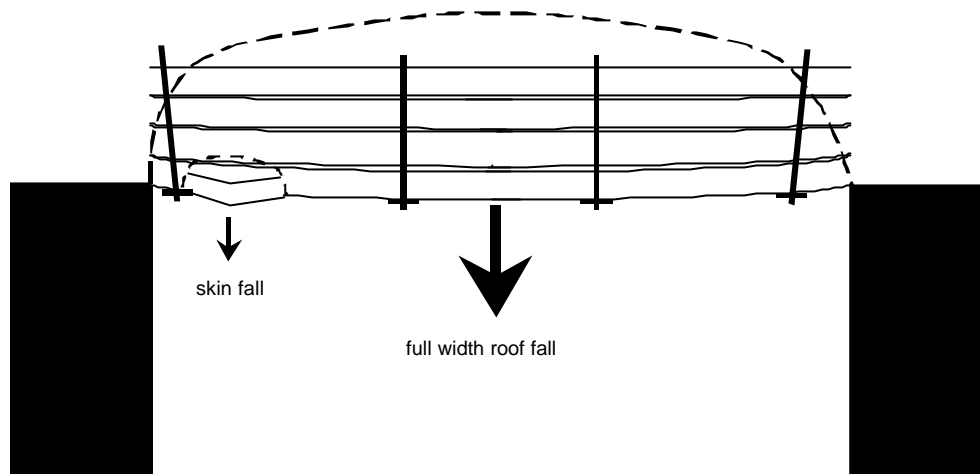
FIGURE 2.10. Illustration of Varying Levels of Roadway Roof Instability (Skin and Full Width Falls of Ground)

It is also important to differentiate between two different scales of roof instability, namely skin instability and major falls across the entire roadway width (see **Figure 2.10**). Both are relevant strata control considerations and their general causal mechanisms are believed to be similar, the most significant difference being the scale on which they occur and the control measures used to prevent them (ie the former relies on sounding and scaling or the use of mesh etc. whereas the latter is controlled by roof bolts, cables and other forms of mass support).

2.2.1 Horizontal Shortening of the Roof and Associated Reduction in Horizontal Stress

In a horizontal stress-driven buckling roof environment, on-going roof displacement will logically result in the continual lowering of the horizontal stress across the roof (due to shortening across the roof – see **Figure 2.11**), such that should sufficient roof displacement take place, a potentially unstable roof block will naturally form. The critical amount of roof displacement will vary according to the nature of the geotechnical environment and the effectiveness of the installed roof support.

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shortening of roof with on-going displacement

low angle shearing across individual beds
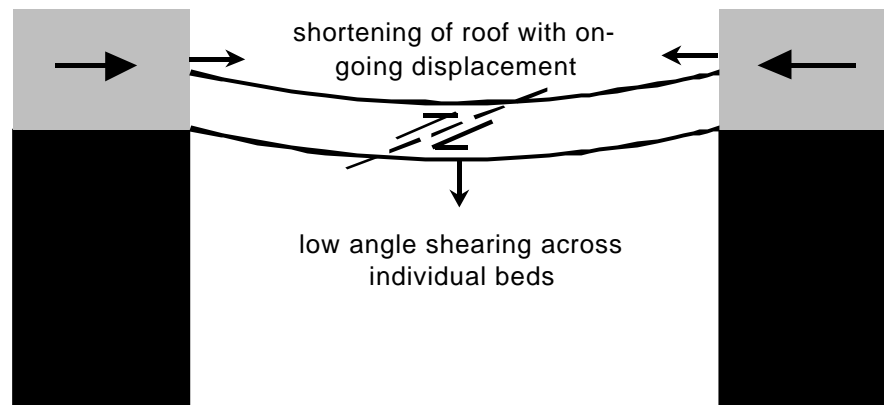
FIGURE 2.11 Basics of Horizontal Shortening and Low Angle Shearing with Buckling Roof

As a general rule, the higher the horizontal stress, the more buckling roof displacement can be tolerated before the roof becomes critically unstable. In this regard, it is interesting to note that during the site visits, trigger levels used on tell-tales generally increased with increasing depth of cover.

Again in a buckling roof environment, a reduction in horizontal stress across the roof will also naturally accompany any low angle shear failure of buckling strata units (see **Figure 2.11**). Such low angle shear planes are commonly observed on one side of a gutter cavity whereby the skin of the roof has buckled between bolts and fallen out. Similarly, they have been observed in areas of roof buckling across the full roadway width (see **Figure 2.12** this having been sketched in an area whereby an unsupported undercut had been taken and the immediate bedded roof was exposed in the face of the heading).

Low angle shearing action can theoretically result in a major roadway roof fall occurring, especially in very thinly laminated strata sequences which are highly prone to this form of buckling failure. Low angle shearing will be referred to in more detail in relation to many of the observations made during the site inspections at the various mine sites visited as part of this project.
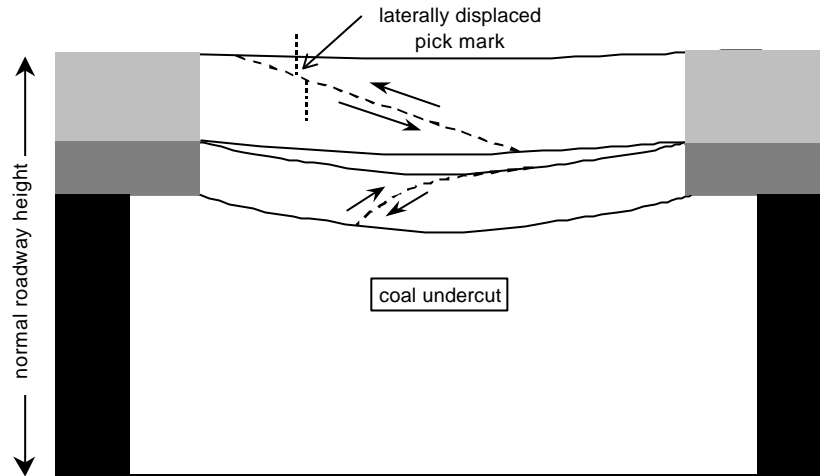
FIGURE 2.12. Sketch of Observed Low Angle Shear Planes and Movements in a Buckling Roof Environment

2.2.2 Low Stress "Plug" Falls

At very low depths of cover, usually in a static roof environment, the *in-situ* horizontal stress itself within the roof can be critically low and a plug-type roof fall occur along pre-existing vertical planes of weakness (ie joints) should bedding plane separation take place either towards the top of or above any installed roof support (this is the basic concept shown earlier in **Figure 2.9**).

Fortunately, this type of fall is rare due to the fact that bedding plane cohesion is usually sufficient to overcome any deficiency in the stabilising influence of the horizontal stress when it is very low in magnitude.

2.2.3 Mid-Angled Discontinuities

In both a static and buckling roof, any discontinuity within the roof with a high potential for shear slip along its surface (this being defined by a combined function of its angle of inclination and shear properties) will naturally cause the line of horizontal stress across the roof to be effectively broken should such shear slip occur. As such, the stabilising influence of the horizontal stress across the roof is eliminated and a detached block of potentially unstable roof is formed with minimal self-supporting ability. The general condition of the discontinuity that makes slip most likely is aligned sub-parallel with and hading over the roadway, close to one rib line (see **Figure 2.13**).

Figure 2.14 illustrates how the horizontal stress across the roof is resolved on to the discontinuity plane and the associated shear slip condition for a surface of assumed negligible cohesion. It is noted that the analysis also assumes that the vertical stress in the roof is insignificant as compared to the horizontal stress and the self-weight of the potentially unstable roof block is ignored. As such, the analysis is used to give no more than an

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indication as to the conditions under which shear slip may occur, rather than an accurate prediction.
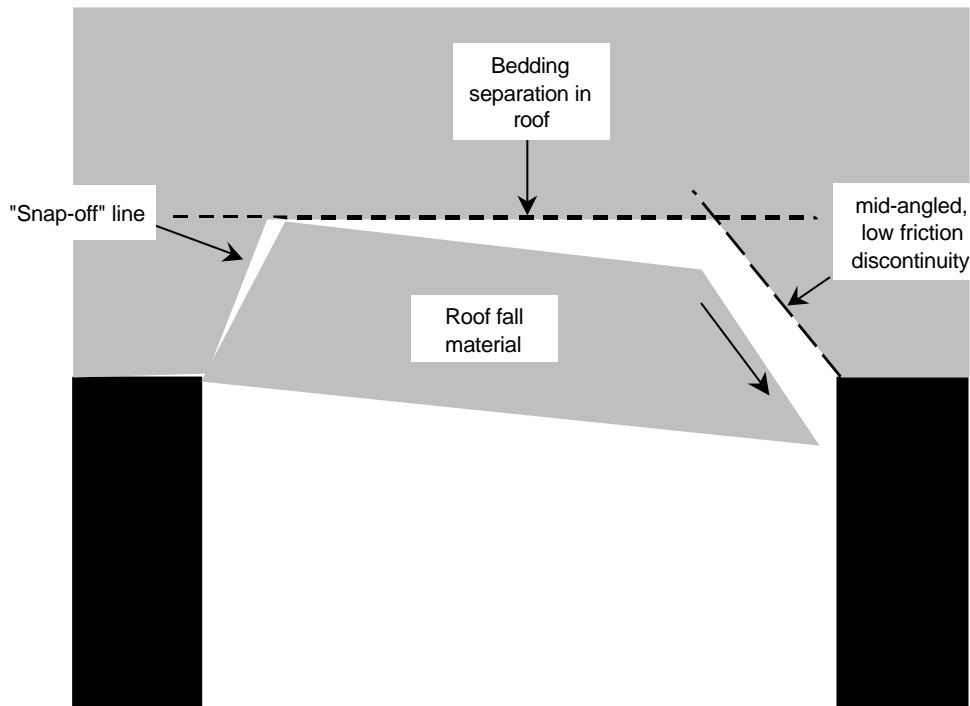
FIGURE 2.13. Schematic Illustration of Roadway Roof Instability Associated with a Mid-Angled, Low Friction Discontinuity

The Friction Angle (ϕ) denoted in **Figure 2.14** is a measure of the friction acting along the surface with the higher the angle, the greater the friction. Friction can also be quoted as a Coefficient of Friction which is given by the tangent of the Friction Angle (ie Tan ϕ).

2.3   Summary

This section of the report has presented a number of the basic principles used within Strata Engineering's roadway roof behaviour and ground support model, all of which have direct relevance to the findings and outcomes of this project.

The primary roof fall or instability mechanisms that are related to both static and buckling roof environments have been described in some detail. They indicate that in general terms a static roof is largely self-supporting whereas a buckling or bending roof requires specific reinforcement in the form of roof support in order to retain adequate stability for more than a short period of time. However, all three modes of roof behaviour can be adversely influenced by localised geological structures and suffer associated instability.

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Shear slip will occur when $\phi < \tan^{-1}(1 / \tan\theta)$

where ϕ = friction angle of plane
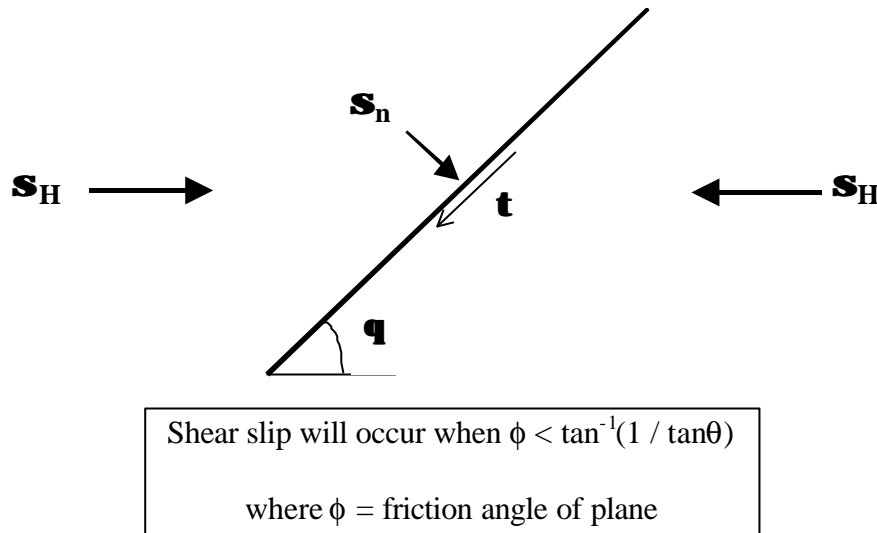
FIGURE 2.14. Resolving of Horizontal Stress Across the Roof onto an Inclined Plane and Condition of Shear Slip for a Surface of Negligible Cohesion

Without digressing into the detailed specific aspects of roadway roof support etc, in practice the two most important control mechanisms for stability across the entire roadway width are:

(i)   limiting roof displacements to minimise the loss of horizontal stress within the roof in a buckling environment through either horizontal shortening across the roof or low angle shear failure, and

(ii)   locally stabilising potentially unstable discontinuities that may be present within the immediate roof.

It is these two control mechanisms that form the fundamental basis for defining the rules by which artificial roof support needs to be considered and designed in order to prevent major roof instability occurring. This includes such issues as roadway width, support stiffness and capacity, support length, pre-stressing, support patterns and timing of installation. However, the subject will not be discussed further herein as it is well outside the scope of this particular study.

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3.0   DETAILS OF MINE SITE VISITS

The primary source of information and data used as part of this project emanated from a series of mine site visits over a three-week period in South Africa. As stated previously, it was not even remotely possible to visit every underground mine site or even visit mines owned by each of the various mining companies. All that could be achieved was to select a representative sample of mine sites so as to gain a reasonable picture of the type and range of mining conditions being experienced.

In order to expedite this process, much use was made of the experience and knowledge of local rock engineering practitioners, in particular in identifying suitable areas of the mines visited whereby both typical and adverse mining conditions could be inspected. Without this input, the project could not have been completed as efficiently as was ultimately the case.

The mine site visits were selected with the following issues in mind:

(a)   Collaboration with several (but not all) of the major coal mining companies. In this regard, mining operations owned and operated by Anglo Coal, Ingwe, Sasol and Eyesizwe were visited.

(b)   Visits to as many different mine sites as possible (a total of 12 mine visits were made) to give a reasonable spatial coverage of the project area (ie Witbank and Highveld Coalfields).

(c)   Visits to each of the primary seams being mined (ie the 2, 4 and 5 Seams).

(d)   Inspection of both typical or normal areas as well as problem or atypical areas at each mine/seam in order to gain a reasonable perspective as to the range of roof conditions.

(e)   A focus on first workings bord and pillar development rather than secondary extraction (e.g. longwall, shortwall or stooping) as the former is where the influence of *in-situ* horizontal stress can be most readily assessed.

Based on the above, bord and pillar workings in the various seams were inspected at the following mine sites:

•   Arnot Colliery – 2 Seam

•   Bank Colliery – 5 Seam

•   Brandspruit South Colliery – 4 Lower Seam

•   Douglas Colliery – 2 and 4 Seams

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- Gloria Colliery – 2 Seam

- Kriel Colliery – 4 Seam

- Matla Colliery – 2 Seam

- New Clydesdale Colliery – 2 Seam

- Nooitgedacht Colliery – 5 Seam

- New Denmark Colliery – 4 Seam

- Rietspruit Colliery – 4 Seam

- Vlaklaagte Colliery – 4 Seam

It is not intended to provide a detailed site description for each mine site visited as the focus of the project is to consider the inspection outcomes in a holistic rather than site specific manner. Therefore, a summary of the range of conditions across these mines will be given for reference purposes:

(i)   Depth of cover range from 25 m to 200 m – average depth in the order of 70 m.

(ii)   Roadway heights between 1.5 m and 4.5m – average height of 3.3 m.

(iii)   Bord widths between 5 m and 7.3 m with typical values between 6 and 6.5 m.

(iv)   Drivage method largely cut and flit in 7 or more headings using cut-out lengths of between 6 m and 24 m dependent upon actual conditions, with 12 m to 18 m cut-outs being typically used in many instances. Several examples of both wide-head miner-bolters and drill and blast sections also visited.

(v)   Immediate roof conditions generally consisted of well-bedded strata (eg shale, inter-bedded sandstone/siltstone) with commonly weak bedding planes (eg carbonaceous bedding containing mica and pyrite) within a fining down sequence. Coal tops of up to 0.5 m were used in a number of instances to protect workings from friable material within the overlying stone strata sequence. Only one example of a thickly bedded to massive sandstone immediate roof. Occasional existence of a thin (ie < 1 m) grit unit within the immediate roof that appears to be a significant control on roof stability according to its thickness.

(vi)   Installed roof support consisted of 16 mm to 20 mm ϕ rebar roof bolts with the majority being 20 mm ϕ. Bolt lengths ranged between 0.6 m and 2 m with 1.2 m to 1.5 m long bolts being typically used. Bolting densities varied from 2 per 2m to 4 per m with 3 to 4 bolts per 2 m being the typical densities used in normal conditions. Spot

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bolting is common with straps and mesh used on an as-needs basis. The majority of roof bolts used were resin anchored with either a single or two resin speed system, plus a variety of drive nut types being in use (eg spin to stall, LH spin and RH tighten, crimp nuts etc.)

These then are the basic and typical properties of the bord and pillar sections visited with the main salient points being the generally average roof quality (ie neither overly incompetent or competent), pre-dominance of high production cut and flit development with long cut-outs in wide roadways and the relatively low capacity and density roof bolting systems in use. The significance of each of these issues will become fully apparent in later sections of the report.

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4.0   COMMENTS ON THE NATURE OF HORIZONTAL STRESS IN THE WITBANK AND HIGHVELD COALFIELDS

This section of the report will attempt to address a number of issues relating to the nature and origins of horizontal stress based on the outcomes of the site visits and an analysis of *in-situ* stress measurement data, as was either supplied to the project by various mining companies or sourced from published literature.

Several key issues will be considered as follows:

- What evidence is there for horizontal stress being a primary control on roof behaviour and stability ?

- A summary of the measured horizontal stresses across the coalfield.

- A proposed conceptual model for the origins and controls of *in-situ* horizontal stress.

Each of these will now be described in detail and substantiated using various components of the available evidence.

4.1   Is Horizontal Stress at Work in Roadway Roof Behaviour ?

The answer to this basic question is undoubtedly "YES" based on a combination of the following:

(i)   Its existence has been measured on many occasions and even though the low stress magnitudes returned appear to have cast doubts over the validity of the measurements in some instances, there are sufficient measurements with reasonable horizontal stress magnitudes to be more than simply a function of the measurement technique used.

(ii)   Resultant horizontal stress effects are clearly visible with localised buckling, guttering (ie the resultant small cavity formed when an area of buckled roof falls out) and low angle shear failure planes being present within the skin of the roof, even at depths as low as 25 m, albeit in rock units of only a few millimetres in thickness. The common propensity for such effects to be located in close proximity to major geological structures is duly noted, although this on its own does not mean that horizontal stress is not a primary controlling factor. This will be discussed in more detail later in the report.

(iii)   Visible horizontal stress-related effects are directional to a large degree, whereby the observed buckling and guttering was far more prevalent in EW oriented roadways as opposed to NS roadways. This will be discussed further when actual stress measurement outcomes are considered.

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There were also a number of localised phenomena that were observed as a result of interaction with other mine workings that could only logically be explained by the presence and significance of horizontal stress within the strata. In this regard, **Figure 4.1** shows in plan and section an area of one of the mines visited whereby a ramp into the adjacent open cut pit passed next to an area of underground workings. One particular area of the underground workings underwent atypical guttering effects, this area being located in the roadway closest to the open cut ramp.
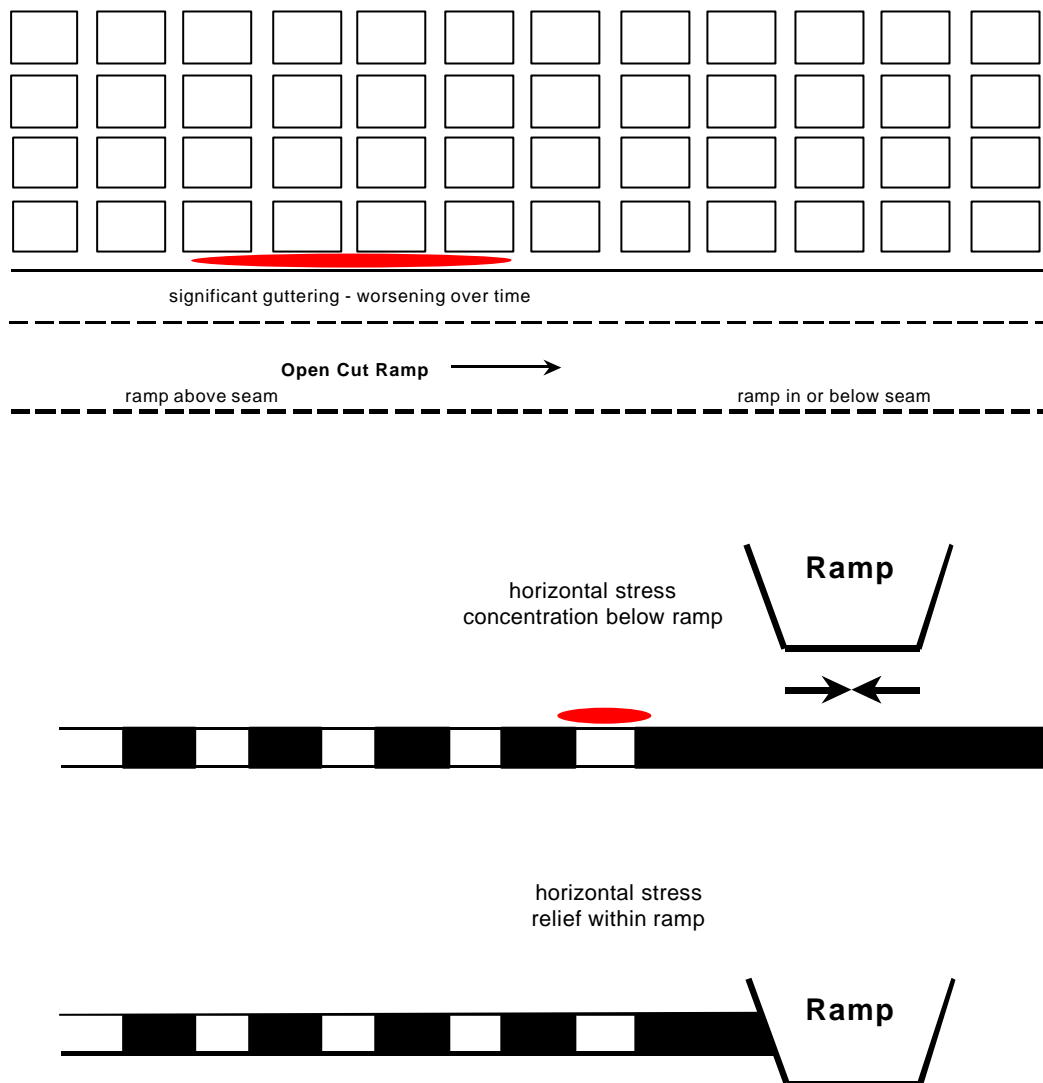
FIGURE 4.1. Plan and Section Showing Geometry of Underground Workings and Open Cut Ramp - Guttering Example

Of further interest is the fact that the area of guttering corresponded to where the open cut ramp was located just above the horizon of the underground roadways. In areas whereby the ramp was at the same level as the workings, the guttering abated as it also did where the ramp was located much higher in the sequence.

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The logical explanation for the observed guttering in an area of the mine that otherwise was generally free from such effects is that the ramp excavation almost certainly concentrated the existing horizontal stress in the strata when it was located just above the underground workings to cause said guttering. However, where it was located below the underground workings, it would act to cause horizontal stress relief in the roof measures and where higher in the sequence, it would have a lessening impact on the *in-situ* horizontal stress.
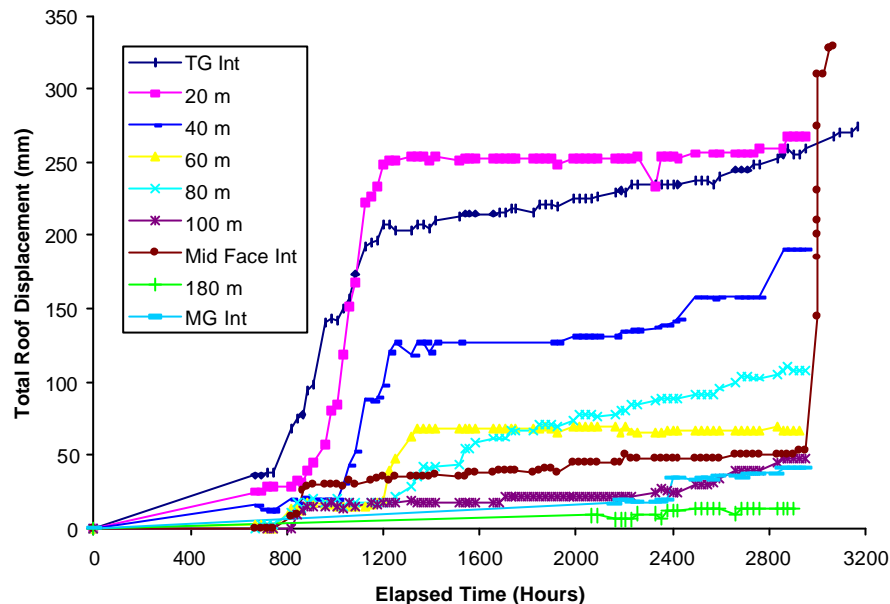
FIGURE 4.2. Tell-Tale Data Showing the Onset of Buckling Progressing along a Mine Roadway

Basically, when the varying location of the open cut ramp is considered, the observed guttering in the adjacent underground workings can be logically explained by its varying influence on the *in-situ* horizontal stress within the roof of the coal seam.

Another feature of the guttering that occurred was that it was observed (by others) to have started in one local area and then slowly progress up into the roof as well as along and across the roadway. This is a commonly found attribute of roof buckling in that once its starts, it has the ability to "run" along a roadway as well as progress up into the roof. **Figures 4.2 and 4.3** illustrate measured outcomes from Australian mines whereby:

(a)   In the case of **Figure 4.2**, the onset of significant roof buckling has been measured to incrementally move along the roadway for almost 100 m until eventually it is dissipated.

(b)   In the case of **Figure 4.3**, the height of fracturing or buckling progresses upwards with on-going roof displacement until it is abated by either a competent strata unit or through natural arching effects.

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The area of buckling and guttering in question displayed both of these particular attributes, albeit at a much smaller scale than the examples across the entire roadway width quoted from Australian mining experiences.

In a general sense, there is little doubt that horizontal stress effects are at work within the Witbank and Highveld Coalfields as the anecdotal and measured evidence cannot be credibly dismissed. However, the key question is the practical and operational significance of horizontal stress to the mining operations and this will be considered in detail in **Section 5**.
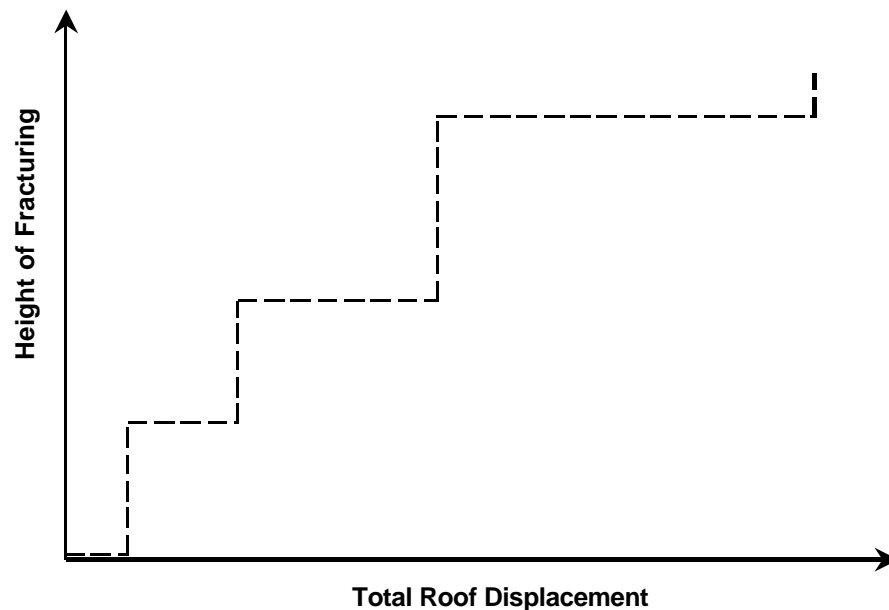
FIGURE 4.3. General Relationship Between Height of Fracturing and Roof Displacement - Buckling Roof Conditions

Therefore, given that horizontal stress has been established as a relevant issue, the remainder of this section of the report will consider its possible origins and likely variations within the coalfields.

4.2   Summary of Measured Horizontal Stresses

As part of this project, Strata Engineering have been provided with a number of *in-situ* stress measurement outcomes from various mines in both the Witbank and Highveld Coalfields. A total of 18 stress measurements from 6 different mine sites were made available to the project with the majority being full 3D measurements and 4 being 2D measurements, whereby only horizontal stress magnitudes and directions were returned.

As with the site visits, the specific details of the stress measurements from any one mine will not be referred to, simply that the measurements as a whole will be assessed for relevant trends and properties.

As a method of evaluation, the ratio between the major horizontal (σ_H) and vertical stress (σ_V) has been calculated for each reported stress measurement and then plotted against other variables in an attempt to identify trends that may give clues as to the likely origin of the horizontal stress. **Figure 4.4** plots the ratio of the major horizontal stress to vertical stress (ie σ_H: σ_V) against the measured vertical stress and **Figure 4.5** plots the same ratio against the Young's Modulus for the host rock type of each measurement.
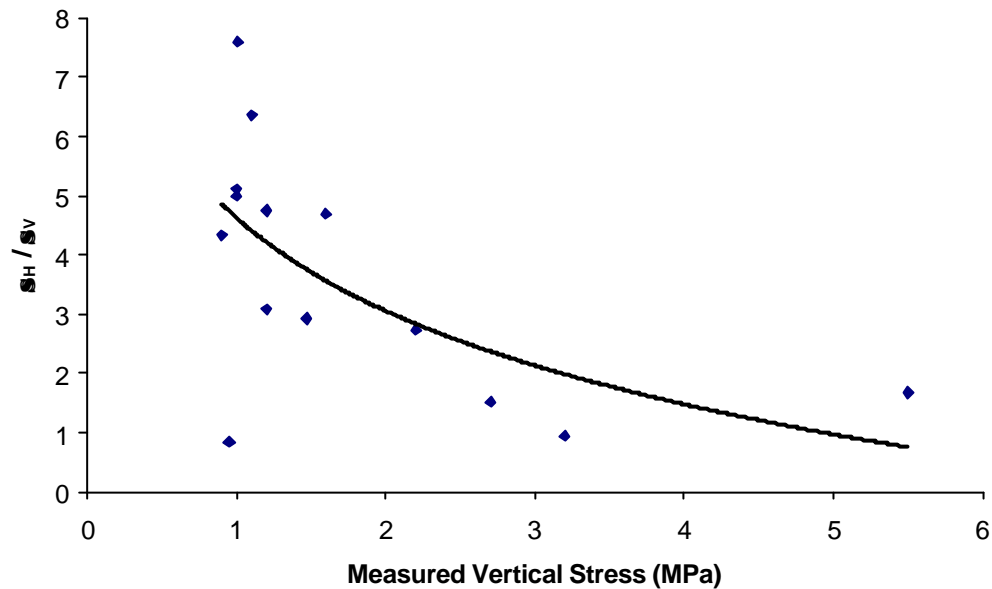
FIGURE 4.4 Relationship Between Major Horizontal to Vertical Stress Ratio and Varying Depth of Cover

FIGURE 4.5 Relationship Between Major Horizontal to Vertical Stress Ratio and

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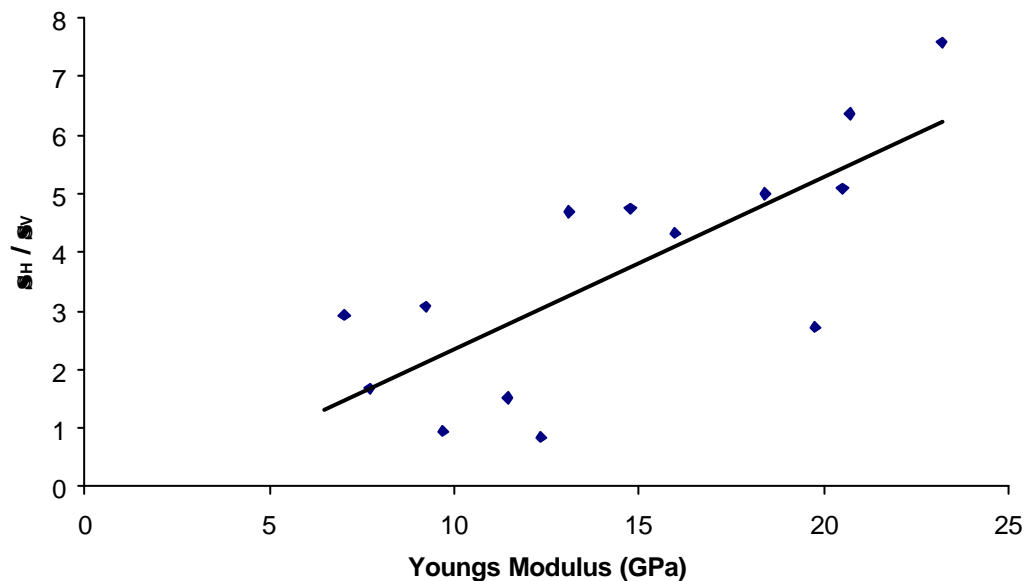
The following comments are given:

(i)   Based on **Figure 4.4** it is evident that the σ_H: σ_V ratio increases with decreasing σ_V.
        If it is assumed that the measured vertical stresses are a reasonable indication of
        varying depth of cover, then the outcome shown in **Figure 4.4** is absolutely consistent
        with the world-wide trends reported by **Hoek and Brown 1980** whereby as the
        depth of cover reduces, so the ratio between the horizontal and vertical stresses
        increases.

(ii)   It is clear from **Figure 4.5** that a very strong relationship exists between the σ_H: σ_V
        ratio and the Young's Modulus of the host rock type with the ratio increasing in
        almost direct proportion.

Point (i) indicates that the horizontal stresses measured are consistent in nature with those
found on a more general world-wide scale (ie there is probably nothing fundamentally
different about horizontal stresses in South African coal mines) and point (ii) will be used as
one of the inputs into the discussion on the origins of horizontal stress in the Witbank and
Highveld Coalfields.
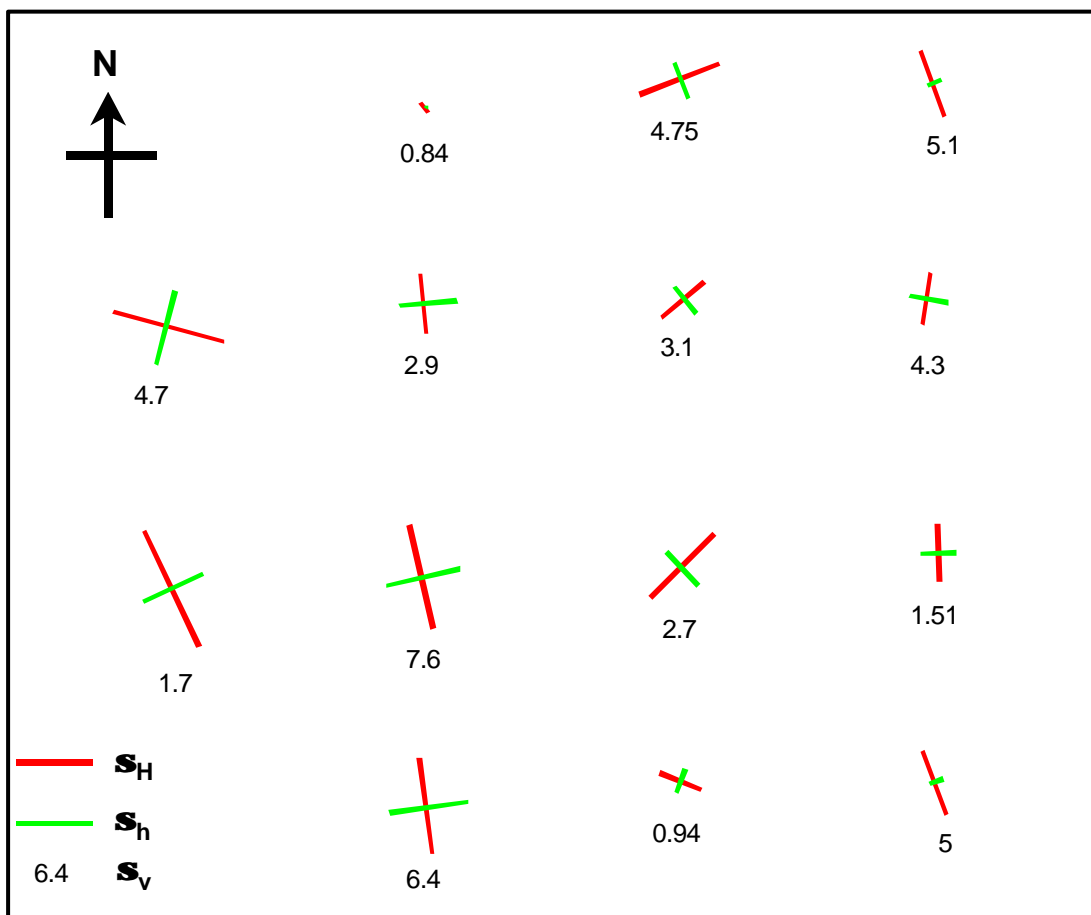
FIGURE 4.6. Plan View Summary of Stress Measurements in Terms of Both Magnitude and Direction

Figure 4.6 takes both the measured major and minor horizontal stresses and compares them in terms of both magnitude and direction. The measured vertical stresses are also quoted in MPa for each individual measurement. It is noted that the measurements are plotted in no particular order and no thought has been given to their actual spatial location within the coalfields.

The following comments are made:

(a)   The overlying general trend is for the major horizontal stress to be aligned close to NS and the minor horizontal stress EW. This explains the comment made earlier regarding roadways oriented EW being more prone to buckling and guttering effects than those in a NS direction.

(b)   Horizontal stress magnitudes vary considerably across the coalfields from as low as 0.2 MPa to 9.2 MPa (ie an almost 50 fold variation) and observed conditions and comments made by mine site personnel reflect this variation to a large degree.

(c)   Three of the stress measurements are characterised by significant rotations in the principal horizontal stress directions. These all relate to one mine site located adjacent to a Pre-Karoo outcrop that marks the northern extent of the coalfield.

(d)   There are several examples of the minor horizontal stress being almost zero (ie 0.2 MPa on at least three occasions).

(e)   Referring back to **Figure 4.4**, it is also interesting to note that the majority of the σ_H: σ_V ratio values are in the range of 3 to 5, which is far higher than the typical values of 2 to 3 found to exist in many Australian underground coal mines. Extreme ratio values are as high as 7.5 and as low as 1.

The conclusion drawn is that the measured horizontal stresses within the coalfields show strong general trends but nonetheless significant local variations occur to the point that it is difficult to generalise over and above the commonly found NS direction for σ_H. This will also be an input into the proposed model for the origin of horizontal stress in the coalfields.

4.3   Proposed Model for the Origin of Horizontal Stress Within the Coalfields

The origin of horizontal stress is a highly complex subject when attempting to explain local variations. This is well outside both the scope of this study and the expertise of Strata Engineering. However, it is evident that in general terms there has been discussion on the subject within the South African mining community, as is clearly evident at the start of Chapter 3 in the recently published Rock Engineering Handbook for Underground Coal Mining by **van der Merwe and Madden (2002)**. Therefore, it is certainly worth

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considering in more detail what can be implied from the various known properties of the horizontal stress about its origin, albeit probably without being able to conclusively establish any one theory in particular.

Van der Merwe and Madden (2002) describe a number of theories used (by others) in an attempt to explain the origins of horizontal stress:

- Plate tectonics.

- Erosion of more than 1 km of overlying lava over geological time leaving "locked-in" horizontal stresses of higher magnitude than that given by k-ratios at present depths of cover.

- Dyke intrusions resulting in localised horizontal stress anomalies.

- On-going cooling and hence, shrinking of the earth's crust.

Of these, the first two are apparently the most commonly quoted, hence the plausibility of both will be given further consideration.

In addition to the comments made so far regarding the nature of the horizontal stress in the ground, there is a further issue yet to be considered which is assessed to be a critical aspect in evaluating the relative credibility of the two theories of plate tectonics and locked in stresses following massive erosion.

It was clearly evident during the site visits and from discussion with mine site personnel that improved roof control in roadways is often achieved by the leaving of a thin coal roof. This is commonly the case in other parts of the world as well.

At face value this is a curious outcome, as if one examines Euler Buckling theory, the propensity for buckling-induced displacement increases with reducing Young's Modulus, which for coal is significantly lower than most rock types. Therefore, if the level of horizontal stress were similar, a coal roof should in theory be more difficult to control than a stone roof. The fact that the opposite is often true indicates that the horizontal stress levels in the coal must logically be lower than in the overlying rock sediments and this can be readily proven by reference to **Figure 4.5**. The question therefore is as to why this should be the case?

If one considers the theory of locked in horizontal stresses after massive erosion over geological time, the issue of low horizontal stress in low modulus strata (ie coal) is absolutely critical.

Figure 4.7 illustrates how horizontal stress is generated from the weight of overlying strata through what is known as "Poisson's Effect". Essentially, under vertical loading, the various strata units expand laterally and as such, generate a component of horizontal stress due to the overall confined nature of the environment.

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The ratio between the induced horizontal stress and the applied vertical stress is known as the k-ratio (as mentioned earlier) and is given by the following equation:

$$K = n / 1\text{-}n \qquad\qquad \dots(4.1)$$

Equation 4.1 indicates that the k-ratio is in fact independent of the Young's Modulus of the host strata, which is in stark contrast to the finding presented in **Figure 4.5**, whereby the major horizontal stress in a particular strata unit is strongly linked to the modulus of the host material.
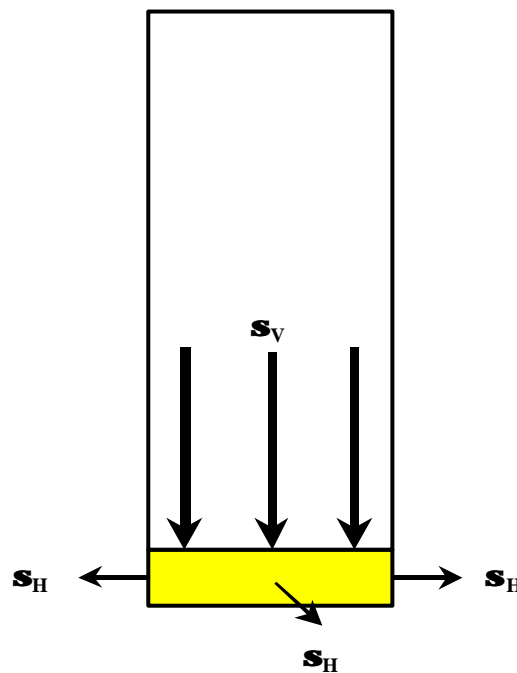
FIGURE 4.7. Schematic Illustration of Poisson's Effect under the Action of Vertical Stress

In fact, if equation 4.1 is used to compare coal and rock in general terms, it is found that coal with a high value for Poisson's Ratio (ie in the order of 0.25) should in fact have higher levels of horizontal stress within it as compared to rock units with a lower value in the order of 0.15. This is clearly contrary to the reality of the situation.

When combined with the general directional trends found within the measured horizontal stresses (ie the k-ratio effect would be expected to act in all directions and therefore not lead to strong directional trends), the relationship between the σ_H: σ_V ratio and the modulus of the host material effectively dismiss the locked-in stress concept as a credible explanation of the origins of horizontal stress in the coalfields.

Returning then to the plate tectonics theory, the question is asked as to whether the idea of far-field horizontal strata movements causing horizontal stress offers any form of rationale

explanation for the nature of the horizontal stress in the coalfields? The answer to that is almost certainly "YES" on the basis that:

(i)   stiffer rock units have been shown to attract higher levels of horizontal stress (all other factors being equal), and

(ii)   the horizontal stresses have clear general directional trends.

Nonetheless, despite all of the evidence indicating that plate tectonics or far field horizontal movements are the likely origin for the horizontal stresses in the coalfields, the point was made during the site visits that the nearest plate boundaries are under the ocean, yet the coalfields are several thousand feet above sea level. This raises the valid question as to how horizontal movements well below the level of the coalfields induce strains and hence horizontal stresses within the local strata ?

The question is well outside the scope of this study, but a concept will be postulated as a basis for further thought.

Figure 4.8 attempts to illustrate how the coal measures are situated above the Pre-Karoo. Having examined the basic structural geology of the area, it is evident that the northern end of the coalfields in question is marked by a Pre-Karoo outcrop in a generally EW orientation and it is understood that others exist to the south. It is also understood that measured horizontal stresses in the Pre-Karoo are similar in direction to those in the overlying coal measures. This could well be more than a simple coincidence.

EW Pre-Karoo Outcrop at Northern
End of Witbank Coalfield ??

Coal Measures
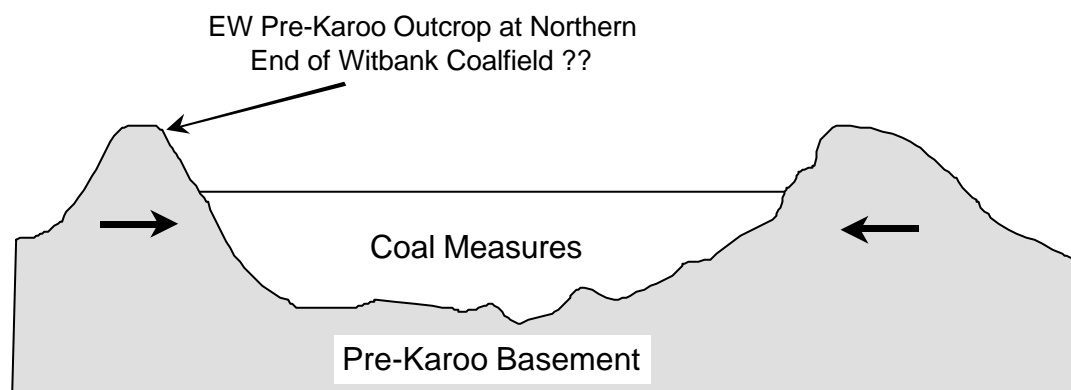
Pre-Karoo Basement

FIGURE 4.8. Conceptual Model of How Stresses in the Underlying Basement are Transferred into the Overlying Coal Measures

The idea is therefore put forward that crustal movements and stresses in the underlying Pre-Karoo strata sequences are translated into the overlying coal measures by the action of Pre-Karoo outcrops surrounding the coalfields, which tend to act as "loading platens". This would also explain to some degree why the horizontal stress directions measured in close proximity to the Pre-Karoo outcrops are significantly different to the general directional trends across the entire coalfield. Basically, areas close to the loading source would be

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expected to be significantly influenced by its geometry and shape (ie akin to the platen end effects in laboratory rock specimens under load testing).

One other issue is worth considering and that relates to the possible origin of the very low minor horizontal stress values returned in some of stress measurements. During one of the site visits, a number of large open joints were observed as shown in **Figures 4.9** and **4.10**. Such features are an obvious source of horizontal stress relief and interestingly enough, the features observed were aligned in a NS direction such that any associated horizontal stress relief would be in the orthogonal or EW direction, which corresponds to that of the general direction for the minor horizontal stress.

Certainly, such structural features are a credible source of horizontal stress relief, which goes to balance the fact that in other areas, abnormally high horizontal stresses are evident. It is noted that once the significance of these features had been recognised at one mine site, others confirmed the existence of similar such features within their mining lease area.

FIGURE 4.9. Open Jointing Observed During Mine Site Inspection

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FIGURE 4.10. Open Jointing Observed During Mine Site Inspection

4.4   Summary

All of the comments made in this section of the report lead to an overall conceptual model for the origins and nature of horizontal stress within the Witbank and Highveld coalfields. **Figure 4.11** attempts to summarise these in one diagram and the following comments are made in support of its credibility:

(i)   The model is essentially one of an end-loaded rock mass consisting of discrete blocks bounded by geological discontinuities in several dominant directions.

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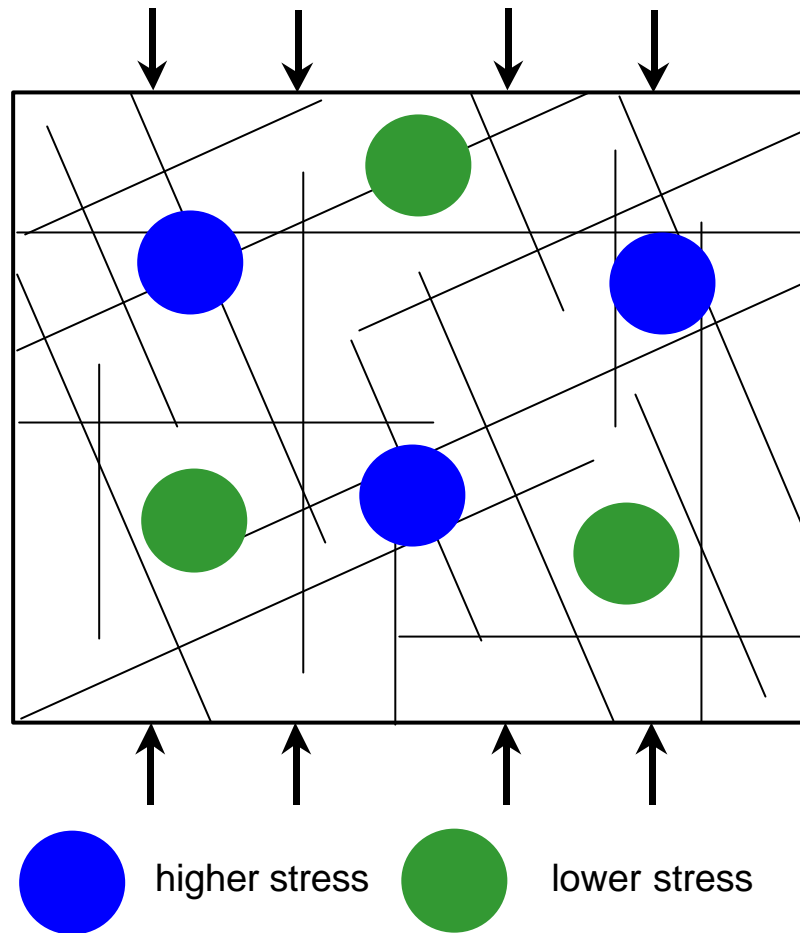
FIGURE 4.11. Proposed Conceptual Model for the Origin of Horizontal Stress and the Significance of Structural Geology

(ii)   Due to the discrete blocks within the rock mass and their varying shape, some would logically be more highly loaded than others such that significant variations in horizontal stress magnitude would be expected, including the opening up of some discontinuities to result in areas of horizontal stress relief.

(iii)   Whilst general directional trends would be apparent within the rock mass, local variations would exist around structures as well as in close proximity to the edges of the rock mass where the geometry of the external loading system would almost certainly have a high level of influence on the resultant near-field horizontal stress directions.

(iv)   Stress magnitudes within various layers of the rock mass would be highly influenced by their individual stiffness with higher stiffness layers attracting higher levels of horizontal stress.

(v)   Igneous intrusions that penetrate through the rock mass could logically influence both localised horizontal stress conditions as well as rock mass quality.

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Each of these statements can be substantiated by reference to comments made earlier in this section of the report. However, the problem is exceedingly complex in nature and it would be almost impossible to quantitatively link structural geology and horizontal stress variations within the coalfield. Essentially, this is as far as one can practically go in terms of linking the stresses in the ground with the structural geology of the coalfield.

It is noted for reference purposes that the significant variations in horizontal stress magnitudes and directions found on a coalfield scale can be used to imply significant variations on a mine site scale as well. None of the mine sites where stress measurements have been undertaken have sufficient data to reliably quantify that variation, but based on the limited data sets available combined with geological common-sense and Australian experience, such variation is almost certainly present.

The reason for mentioning this is simply a note of caution when undertaking detailed geotechnical design studies, especially using numerical modelling where it may be convenient to use locally available stress measurement information as a modelling input and inadvertently treat it as a well defined parameter. The reality is clearly somewhat different and in the same way that numerical modelling sensitivity studies are routinely done on such issues as rock mass variations etc, the same should also be done on *in-situ* stress values if the modelling outcomes are to be credible.

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5.0   OPERATIONAL SIGNIFICANCE OF HORIZONTAL STRESSES

Having established that horizontal stress is almost certainly present in the strata in the Witbank and Highveld Coalfields and provided some guidance as to its origin and form, the final area to consider is its operational significance.

Horizontal stress is a major geotechnical constraint in many Australian coal mines (the majority of which are longwall mines) and due to the need to install relatively high roof support densities to mitigate the threat posed to roadway roof stability, development rates are detrimentally influenced to the point that longwall production is often constrained as a result. **Figure 5.1** shows roof conditions in a roadway adversely influenced by horizontal stress and whilst the severity of the roof condition shown is not typical of all mines, it goes to illustrate the degree to which high horizontal stress can be a major threat to efficient mining.

FIGURE 5.1 Mining Conditions Associated with Adverse Horizontal Stress Effects (Australia)

Unlike Australia, the majority of the South African mines visited were bord and pillar mines operating at shallow depth of cover with no provision for secondary extraction within their mining plan. As such, the viability of the mine is totally dictated by the cost and productivity of first workings development, this being a major difference between the South African and Australian underground coal industries in general terms. It is also a relevant consideration for this project.

The operational significance of horizontal stress will be assessed according to the following general considerations:

•   The stability of the unsupported cut-out.

•   The stability of bolted roof across the full roadway width.

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- Skin instability and guttering effects.

- The stability of brows.

It is noted that relevant safety and production issues will be included in the various deliberations, which have been listed above according to the order in which they are encountered by the mining process.

5.1   Cut-Out Stability

Given that the majority of the development units visited were cut and flit operations in multiple headings, unlike miner-bolter units the stability of the extended unsupported cut-out is a key consideration, as poor stability will inevitably have a major negative impact upon unit productivity.

As stated in **Section 3**, the majority of cut and flit units visited were utilising extended cut-outs of between 12 m and 18 m in length, with one mine using a cut-out of up to 24 m. Only in difficult ground conditions were cut-out distances generally reduced to 9 m and less.

Based on Strata Engineering's roof behaviour and stability model, the only logical explanation for the above operational outcome is that the roadway roof is remaining in a static condition in the cut-out (ie no bedding plane separation occurring) such that the roof retains a high level of self-supporting ability. The antithesis to this has been experienced at several Australian mines, which have found that once significant roof buckling occurs efficient cut and flit development is practically impossible, as stable cut-outs are restricted to no more than about 6 m as a result of the unsupported roof rapidly undergoing low angle shear failure and falling in, thus stopping the cut-out.

Essentially, to even remotely suggest that the horizontal stress in the roof is a significant mining constraint at the mines visited (in general terms) is absolutely inconsistent with the length of stable unsupported cut-outs being routinely formed up in roadways of typically 6 to 6.5 m width. The likely reasons as to why this is the case are fairly self-evident when the absolute magnitudes of the measured horizontal stresses are considered in combination with the general roof quality:

(i)   The average measured major horizontal stress is some 4.6 MPa and the average minor horizontal stress is some 2.6 MPa. Despite the ratio between $\sigma_H{:}\sigma_V$ being quite high (ie 3 to 5) as discussed previously, the low depth of cover means that the absolute horizontal stress magnitudes are still low in general underground coal mining terms.

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(ii)   Whilst the general rock mass quality is not of the highest order, the low magnitudes of the *in-situ* horizontal stress clearly compensate for this, such that static roof conditions are retained in the cut-outs.

(iii)   The common existence of a fining downwards sequence in the immediate roof of the coal seam means that even if the immediate skin of the roof buckles and falls out in the cut-out, the potential for higher level roof falls with the ability to significantly reduce the cut-out length is limited.

Clearly, the above comments do not imply that localised areas will not be subject to difficult drivage conditions due to an adverse combination of horizontal stress and poor roof quality and in fact one mine visited was experiencing extremely difficult general development conditions across a significant portion of the mine for exactly this reason. In addition, it was readily apparent that most mines experienced such difficulties in close proximity to major geological structures, whereby both local stresses and rock mass quality would be expected to be adversely influenced.

However, in general terms the available evidence strongly supports the view that the existing horizontal stresses in the strata are not particularly significant with respect to the stability of unsupported cut-outs and therefore, the efficiency of the mining process.

5.2   The Stability of Bolted Roof Across the Full Roadway Width

This section considers the issue of major roof instability across the full roadway width (as defined earlier in **Section 2** and illustrated in **Figure 2.10**), once primary roof support has been installed.

Based on the outcomes of all of the site inspections, major roadway roof instability across the full roadway width was almost entirely limited to areas, in which significant geological anomalies were present (eg dyke, faults, seam rolls, mid-angled discontinuities etc). There is little doubt that local to these features, the combined influence of both modified horizontal stresses and/or reduced rock mass competence (through shearing and weathering effects for example) logically leads to more significant roof control difficulties both during and following development. However, of the major roof cavities observed, many had clearly formed in the cut-out prior to support being installed.

In general or typical terms, the site visits provided no direct evidence of adverse horizontal stress in isolation causing uncontrolled buckling of the roof as a whole, thus leading to major roadway roof instability. This in fact is not a surprising outcome when it is remembered that:

(i)   Static roof generally persists in the unsupported cut-out (ie there are few if any known examples of cut and flit development using extended cut-outs at the face and experiencing on-going major outbye roof control difficulties due to horizontal stress and buckling effects).

(ii)   The typical roof bolting densities used are fully consistent with the on-going existence of a static roof environment following development and if significant roof buckling under the action of horizontal stress were occurring outbye, the installed support levels are such that significant numbers of major outbye roof falls would almost certainly be evident. This is clearly not the case.

Note that this comment should not be taken as suggesting that installed roof support is inadequate, as quite the contrary, it is clearly fit for purposes for the prevailing conditions. It is further stated that in general terms, the awareness of mining personnel as to the threat to roof stability posed by geological structures was high and in the case of mid-angled discontinuities, support patterns were being appropriately modified to mitigate against the associated roof fall mechanism.

Again, as with the comments made on cut-out stability, the available evidence is strongly supportive of the opinion that in general terms, the roof retains its static condition after initial development, such that the action of horizontal stress is not a significant threat to long-term roof stability across the full roadway width.

5.3   Skin Instability and Guttering Effects

Based on the observations made during the site visits, guttering effects and instability in the skin of the roof are clearly the most obvious horizontal stress effect at work, albeit only in localised areas in most instances. The occurrence of buckling and guttering in the skin of the roof as compared to higher up across the full roadway width can be explained by the following:

(a)   The resultant horizontal stresses will generally be at a maximum in the immediate skin of the roadway roof (all other factors being equal), these being the driving force for buckling and guttering.

(b)   The resultant vertical stresses will generally be at a minimum in the immediate skin of the roadway roof (all other factors being equal), the vertical stresses acting as lateral confinement against strata buckling.

(c)   The existence of a typically fining down sequence means that the least competent roof measures would be expected to exist in the immediate skin of the roof.

(d)   The installed roof bolts are generally spot bolts on a coarse grid, thus leaving quite high spans between bolts, across which buckling of the skin can occur.

With these four factors in mind, the occurrence of buckling and resultant guttering in the skin of the roadway roof between roof bolts is explainable, despite the generally low absolute

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magnitudes of the horizontal stresses at work. **Figure 5.2** illustrates a typical roof gutter profile as observed during many of the site visits, the salient features being:

- Tensile cracking of the roof skin as a result of buckling prior to the gutter forming.

- A low angle shear failure marking one side of the gutter cavity, this being indicative of buckling failure and initiating the detachment of the immediate roof.
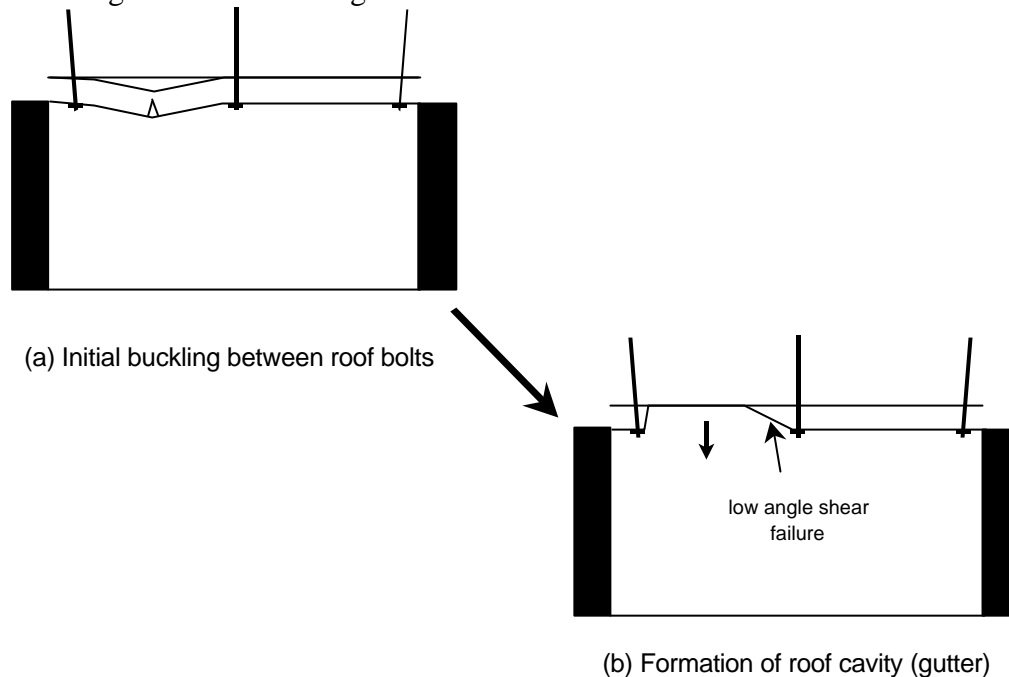

(a) Initial buckling between roof bolts

low angle shear failure

(b) Formation of roof cavity (gutter)

FIGURE 5.2 Typical Guttering Profile Development Observed During Mine Inspection

- The opposite side of the cavity to the low angle shear surface being much steeper through either it being joint controlled or a "snap-off" line due to cantilevering of the material falling out.

During the site visits, it was also clear that mining personnel were concerned about the safety threats of guttering and skin instability and this is certainly worth further thought and comment, especially in comparison to Australian mining practices.

Australian underground coal mining largely comprises longwall mines with varying degrees of buckling roof in development roadways. As a result, roadway widths are typically < 5.5 m, average primary support densities are in the range of 6 bolts/m and the use of w-straps and mesh is common. As such, the spans between installed bolts where guttering can occur are relatively low and in areas of friable roof, full mesh is generally used, such that a hard barrier is often in place to prevent pieces of roof material falling out.

In contrast, South African bord and pillar mines use wider roadways with lower bolting densities and generally do not use w-straps or mesh. When the height of working is also

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considered (4 to 4.5 m in many instances), the safety risk associated with skin instability becomes clearly evident.

At face value, the obvious solution is to utilise higher bolting densities combined with w-straps and/or mesh. However, this could not be sustained by bord and pillar mining, such that less onerous, but nonetheless effective controls would potentially be of industry benefit. It is beyond the scope of this study to consider this in detail, although some initial comments will be made.

If one accepts that the problem of guttering and skin instability is a combined result of horizontal stress and poor immediate roof quality, only two possible solutions are available, over and above a radical change to the primary support densities and patterns used:

(i)   identify areas of likely guttering ahead of instability occurring and install additional support, OR

(ii)   remove or lower the driving force (ie the horizontal stress).

Figure 5.3 illustrates the basic concept of "slotting" or the deliberate formation of a gutter in other words. The net result of forming a slot in the immediate roof would be to significantly reduce the level of horizontal stress acting within the roof skin, thus almost certainly lowering the potential for guttering and resultant skin instability to take place. It would also eliminate much of the collateral damage that occurs to surrounding roof measures when such a slot is allowed to form naturally by buckling and guttering.
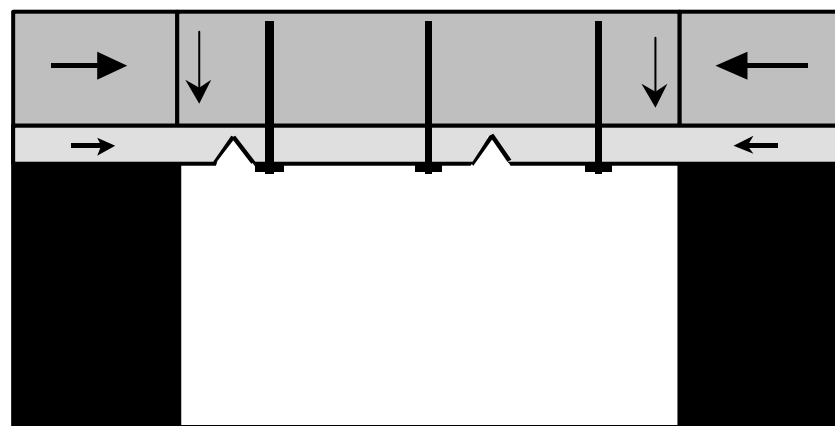
Static / self-supporting main roof
Stress relieved skin with negligible buckling potential
Roof bolts pin discrete blocks in place

FIGURE 5.3 Schematic Illustration of Roof Slotting Concept

It is realised that currently there is no practical method by which such slots could be formed in the immediate roof during development. However, that is not to say that they cannot be

incorporated into the mining process by either a modification to the cutting head of the continuous miner or the pattern used in drill and blast sections.

5.4   Stability of Brows

Whilst falls of ground due to brows were not specifically addressed by the project, it is understood to have been a significant source of injuries in South African coal mines in the past. Therefore, it is worth making a brief comment in the context of the role of horizontal stress.
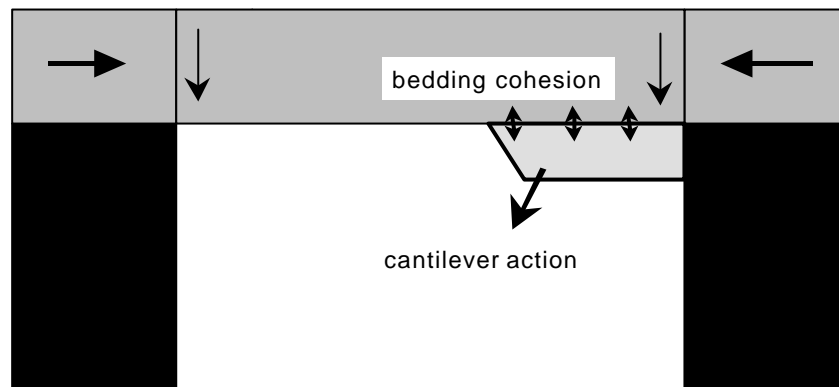

FIGURE 5.4 Schematic Illustration of a Brow and Natural Support Elements

Figure 5.4 illustrates the formation of a brow on the side of a roadway and the most obvious feature is that it is a horizontal stress relieved structure. As a result, the self-supporting ability of a brow relies almost entirely on bedding plane strength and cantilever action from the solid.

In any situation with weak bedding (eg the top contact of a coal seam with overlying sediments), brow instability is a high likelihood outcome as there is no stabilising influence of horizontal stress and jointed materials do not make effective cantilevers. As a result, the artificial support of brows so as to pin them to overlying stable strata is absolutely critical to their stability, a fact well understood at the mines visited.

5.5   Other Issues

As part of this project, two other roadway roof behaviour issues related to horizontal stress are worth mentioning for reference and discussion purposes:

(i)   the influence of varying thicknesses of grit within the immediate roof, and

(ii)   the role of bord width on induced horizontal stresses in the roof.

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One of the mine sites visited had recognised that a primary control on roadway roof stability was the thickness of a grit unit within the immediate roof. Essentially for thicknesses > 0.5 m, roof stability was quite benign, whereas at < 0.5 m, roof control difficulties commonly occurred.

This all makes logical sense when the outcomes of this project are considered, in that:

(a)   The grit material is understood to be a relatively stiff strata type such that it would be expected to attract a higher level of horizontal stress (all other factors being equal) as compared to surrounding less stiff strata units.

(b)   The propensity for buckling of the grit to occur will be closely related to its thickness, with the lower the thickness, the higher the propensity for buckling.

(c)   The step-wise nature of the static to buckling transition is such that a minor change in grit thickness would logically be expected to result in a significant change in overall roof stability, if buckling were to occur as a result.

Basically, the sensitivity of roof stability to minor changes in the thickness of the grit unit makes logical sense within the principles of the buckling roof behaviour model used herein.

In terms of the relationship between bord width and induced horizontal stresses in the roof, it was observed at one particular mine site that when bord widths were reduced in an attempt to improve overall roof stability, buckling and guttering effects in the skin of the roadway actually got worse rather than better. At face value, this is a surprising outcome and worthy of further comment.

In a general sense, the propensity for roof buckling and associated roof stability is highly influenced by roadway width, with stability reducing as the width is increased. However, in the case of a static roof environment, roadway width increases would not be overly significant with respect to roof stability providing that it did not result in the onset of buckling.

Frith et al (1990) proposed the concept that as mine roadways were made wider, the induced horizontal stress in the roof measures would actually reduce as a result. This was based on the outcomes of basic numerical modelling and physical models of roadways of different widths subjected to the same basic stress fields, although at that time, anecdotal evidence was not available to support the theory.

Based on the buckling model now in use, in most situations the positive effect of lowering the horizontal stress would almost certainly be totally swamped by the increased buckling potential of the wider roadway. However, in otherwise static roof conditions, the theory presented would indicate that guttering and associated skin instability may well worsen with a narrowing of the roadway width due to a rise in the horizontal stress levels acting across the roof.

The fact that this very effect has been observed in practice is an interesting outcome and if nothing else, suggests that narrowing of mine roadways is not necessarily an effective control for reducing the propensity for buckling and guttering between bolts in the immediate skin of the roof and the safety threat such instability poses.

5.6   Summary

Having considered in detail the operational significance of horizontal stress effects during roadway development in mines in the Witbank and Highveld coalfields, the following summary points are made:

(i)   The common use of 12 m to 18 m unsupported cut-outs during development indicates that static roof conditions generally pre-dominate, such that horizontal stress effects have a negligible impact at this stage of the mining process.

(ii)   In bolted roadways following development, no credible evidence of horizontal stress-induced roof instability could be identified, apart from in the vicinity of significant geological anomalies, whereby adversely altered stress and strata conditions would logically be expected to exist. In addition, a significant number of the observed major roof fall cavities almost certainly formed in the unsupported cut-out during development, rather than following the installation of roof support.

(iii)   Instability associated with buckling and guttering of the roof skin between roof bolts was the most obvious horizontal stress effect observed, but even then, this was often limited to areas in and around defined geological structures. However, despite the small-scale of such instability, the height of roadways and lack of hard barriers result in it still being a significant safety concern of operators. Slotting of the immediate roof, so as to reduce the potential for buckling and resultant guttering of the skin has been put forward as a possible control that could also have minimal negative impact upon the efficiency of the mining process. In fact, it may actually assist development efficiency by improving the stability of the immediate roof in the unsupported cut-out, providing that the slots can be formed as part of the coal winning process.

Several other interesting phenomena were also discussed, including the stability of brows and the significance of minor changes in the thickness of very stiff strata units within the immediate roof.

In an overall sense, general comments have been made as to the adequacy of roof bolting practices observed to be in use and the ability of the mine sites to adapt support practices to the prevailing conditions. General roof bolting practices were appropriate to a static main roof environment, and the general awareness of mining personnel as to the need to identify significant geological anomalies and adapt support practices accordingly was of a very high order.

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6.0   STRESS MAPPING RECOMMENDATIONS

One of the primary objectives of this project was to evaluate horizontal stress mapping techniques for application in South African coal mines. Having undertaken the mine site visits and considered the overall role of horizontal stress, the conclusion is drawn that the basic stress mapping techniques already in common use in South African mines are generally more than adequate and that there would be little benefit in attempting to increase the sophistication of said methods.

Relevant points supporting this outcome are as follows:

(i)   In general terms, horizontal stress effects are not critical in the majority of mining areas, whereby stress mapping is effectively impossible due to a lack of visible signs.

(ii)   In those areas whereby buckling and guttering effects do occur, their common proximity to significant geological anomalies means that they may not be fully representative of stress conditions remote from such structures.

(iii)   The use of a two-pass development sequence (ie two parallel cut-outs with a narrow head miner) may also potentially confuse the apparent outcomes of subsequent stress mapping as the location of a roof gutter after mining can be dictated to some degree by where the buckling first commences, even at a very low level. Once the buckling has commenced, a bias has been established such that this will logically determine the location of the subsequent gutter, should one form. On the basis that the location of the gutter across the roof is the first indication of the likely direction of the major horizontal stress with respect to the drivage direction, consideration must be given to the cut-out sequence used in forming the roadway for the interpretation to be fully credible. This is a variable that cannot always be reliably quantified in practice.

(iv)   It is apparent that mine layout planning is yet to routinely incorporate horizontal stress considerations and given its low overall significance, this is a reasonable outcome. In an overall sense, it is assessed that major geological discontinuities and other relevant considerations (eg coal quality etc) are far more important to the mine planning process than subtle variations of the *in-situ* horizontal stress. The most likely scenario whereby mine planning would prioritise horizontal stress aspects is in fact prior to mining taking place, in that the presence of abnormally high horizontal stress levels over an extensive area would be a key consideration. However, such knowledge could only emanate from stress measurements in surface boreholes, rather than stress mapping outcomes.

Overall, the mine workforce being aware of the existence and likely manifestation of horizontal stresses in the roof is an operational benefit and being able to gauge approximate stress directions is of definite value. In this regard, the preceding comments should not be taken as being dismissive of stress mapping, simply that it should be kept in context with

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what it can usefully achieve. The finding of the project is that the current stress mapping methods are more than adequate for rock engineering purposes and there would be limited value in attempting to improve the accuracy and sophistication of the techniques used.

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7.0   OVERALL PROJECT SUMMARY

As part of summarising the project outcomes, it is first necessary to re-state the project objectives as follows:

(i)   to undertake a peer review of available *in-situ* stress measurements relating to the Witbank and Highveld coalfields in South Africa;

(ii)   to undertake inspections and mapping of roadway roof and related geotechnical conditions at a number of coal mines within both coalfields in order to consider the influence of horizontal stress (and variations thereof) on actual mining outcomes;

(iii)   to provide a technical explanation of the link between horizontal stress in the roof and the occurrence of falls of roof in mine roadways;

(iv)   to summarise regional and local trends in horizontal stresses and consider their practical significance using the outcomes of (iii) in relation to roadway roof stability and ground support;

(v)   to comment on the use and limitations of stress mapping for practical mine management purposes.

Accepting that the required field work and analytical studies have been undertaken as intended, the project outcomes are summarised in point form as follows:

• Horizontal stresses are clearly present within the Witbank and Highveld Coalfields, at maximum levels generally well in excess of the vertical stresses as determined by weight of overburden considerations. The stresses have been measured in a credible manner and their resultant effects can be clearly identified in mine workings.

• An in-house developed conceptual model for roadway roof behaviour and resultant instability has been used as the fundamental basis for assessing the significance of horizontal stress in local mines. This model is commonly used and is well-accepted by much of the Australian coal industry. A detailed description of relevant sections of the model has been given for reference purposes.

• Site inspections were undertaken at twelve local mine sites covering both typical and adverse strata conditions. Emphasis was placed on first workings development where the effect of *in-situ* horizontal stress can be most readily assessed.

• Based on the available evidence, a credible model for the origins of horizontal stress has been presented. The model indicates that the horizontal stresses at work are almost certainly "tectonic" in origin in that they are a result of far-field horizontal movements. However, it is assessed as unlikely that the direct driving mechanism is a plate boundary, but the transfer by some means of movements within the underlying

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Pre-Karoo basement rocks. A conceptual model as to how this may occur has been put forward for discussion purposes.

• Accepting that the true origin of the horizontal stress is not fully resolved, the more important aspect is to understand its nature within the coalfields. In general terms, relatively consistent directional trends are evident (with the exception of the edges of the coalfield) although the actual horizontal stress magnitudes are influenced by a number of variables including strata stiffness and proximity to geological structures. A fifty-fold variation in horizontal stress magnitude is evident within the measurement outcomes, such that the ability to make credible predictions of horizontal stress levels in new mining areas from remote measurements is highly questionable.

• In terms of the operational significance of the horizontal stresses in the ground, the evidence indicates that cut-out stability and roadway roof stability across the full roadway width are typically unaffected by horizontal stresses, remote from geological structures. Major roof instability is almost entirely confined to being local to geological anomalies, where both the stress and rock mass conditions are almost certain to be affected as a result. In general terms, the successful use of high production cut and flit roadway development using unsupported cut-outs as long as 24 m is conclusive proof that horizontal stress and resultant strata buckling are not generally major constraints to the mining process.

• The most obvious source of horizontal stress-induced roof instability relates to the immediate skin of the roof, whereby localised buckling and guttering occurs on a more frequent basis. This is primarily a safety rather than production concern, largely as a result of the large spans between spot bolts and high roadway heights in use. Additional roof bolting and/or meshing is probably not a practical or economically viable option for improving the control of these effects and a conceptual suggestion utilising slotting of the immediate roof has been presented as a basis for further discussion.

Overall, the project findings are entirely consistent with the basic principles of roadway roof behaviour and control that are used by Strata Engineering as well as many mines in the Australian coal industry, the primary issues being firstly the scale of the instability and secondly the significant differences in mining systems in use in terms of their sensitivity to roadway roof instability.

In general terms, the primary roof support practices observed, whilst being fundamentally different from those in use in Australian mines, are nonetheless considered to be fit-for-purpose when the generally benign (ie static) nature of the roof environment as a whole is considered. Similarly, the awareness of mine operators as to the significance of geological anomalies to roof control and how to respond in terms of modifying support practices was of a high order.

The only area whereby horizontal stress effects are occasionally subject to less than adequate control relates to instability in the skin of the roof due to buckling and guttering between roof bolts. The challenge for the industry is to develop more effective controls for such instability without detracting from the efficiency or cost of roadway development. This is unlikely to be achievable through the use of more effective roof bolts or modifications to roadway geometry as the only reliable method would be to remove or severely restrict the driving force for such instability (ie the horizontal stress in the immediate roof). The optimum solution for this is not clear at present, however a prototype idea involving roof "slotting" has been presented as a starting point for any future research and development that the industry may commission in this area.

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