

# The Value of Early Geotechnical Assessment in Mine Planning

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## ABSTRACT

Valuable data for geotechnical interpretation and integration into effective Australian underground mine planning may often be available, yet is not always fully appreciated or utilised, particularly in the early stages of mine planning or in due diligence studies. There may be considerable benefits associated with early prioritisation of geotechnical evaluation and impact on mine planning.

Unidentified, misinterpreted, or ill-defined adverse geological and related geotechnical resource characteristics can pose significant business risk to underground coal projects and operations. Preliminary resource definition in the early conceptual mine planning stages attributes significant focus (entirely warranted) on resource quality and structural geology constraints. Yet detailed geotechnical data analysis and interpretation, which may have a substantial downstream impact and sensitivity with respect to future mine planning strategies, at times is given lower priority, or scoped and resourced in the later stages of a bankable feasibility study. Through extensive mine planning experience and observation of downstream process impacts, it has been found there is often data available for geotechnical analysis that does not readily stand out or is not adequately understood or utilised, available at the early (conceptual) stages of mine planning. Part of the issue may be that exploration geologists are not necessarily experienced geotechnical engineers and do not necessarily recognise or understand all important parameters. Subject to appropriate application of experienced professionals data can be manipulated to provide key geotechnical hazard assessment at minimal cost, and provide a framework for understanding and optimising the mine planning process.

Although there is no single prescribed strategy for resource evaluation from a geotechnical perspective, potential business risks and mitigation approaches can and should be adopted at the conceptual mine planning stage. There has been a recent focus in the metals industry to provide a reporting framework for geotechnical classification of mining projects. This paper outlines the strategies and gives examples of key analyses adopted in mine planning and discusses the relative merits of adopting a reporting framework as a tool for geotechnical classification in mine planning.

## INTRODUCTION

A well known, but not necessarily implemented, fact is that geotechnical assessment forms a key driver in project viability. Primary consideration should be given to the likely mine planning implications arising from geotechnical interpretation. Significant expenditure is often attributed to the acquisition of exploration data, yet at times there appears an imbalance between resources attributed to data acquisition, processing and presentation, compared with that dedicated to comprehensive interpretation and risk assessment of relevant geotechnical data and subsequent integration into mine planning processes. There is almost always relevant geotechnical detail that can be manipulated from any form of geological exploration, that should be appropriately assessed in the conceptual mine planning process onwards.

This paper outlines experience with respect to geotechnical assessment in the context of mine planning and balanced against

other key drivers. It is non-specific with respect to case histories, but rather, examines generically the experiences gained through numerous sources including:

- practical operational mining experience;
- due diligence studies, in particular auditing resource and reserves and assessment of attributed valuation and risk assessment;
- designing, costing and project managing exploration programs;
- analysing and interpreting data from exploration, in particular with respect to geological interpretation and associated geotechnical analysis at all stages of mine planning;
- completion of geotechnical evaluation at concept, pre-feasibility and feasibility study levels for coal projects.

A discussion outlining specific forms of geotechnical data that can be interpreted to add significant value at the early stages of mine planning is outlined. In mine planning, it is desirable to establish an appropriate level of geotechnical risk assessment balanced against other key drivers at each stage of the mine planning process. In conclusion, the relative merits of a reporting framework for geotechnical classification of coal mining projects are debated.

## THE MINE PLANNING PROCESS

### Stages of mine planning

The major stages of mining project development are set out below in Figure 1. At the end of each stage, a business case is generally made to justify progression to the following stage. A subsequent increase in exploration, data compilation, analysis and interpretation and mine planning input is required as the project development process unfolds, with an associated increase in committed human and physical resources and total cost.

At each stage in the planning process, the level of certainty with respect to project value and confidence in the specific resource and reserve characteristics increases. The prime consideration is project value and ability to achieve the projected production levels, operating cost and sales price. Geotechnical aspects affect two of these three primary determinations. Key measures of project value include:

1. *Fair market* value of each project under consideration, determined by current market conditions and price.
2. The *intrinsic* value of each project under consideration, determined by current worth and potential future earning power. Intrinsic value can be assessed at a conceptual stage using appropriate Valmin Code guidelines, however, detailed intrinsic valuation is usually estimated from pre-feasibility onwards, where net present value can be attributed over a given timeframe with discounted cash flows.
3. The *strategic* value, usually reflecting a higher value attributed due to such factors as geopolitical advantages, economies of scale or reducing competition. Strategic value may also be in the context of brownfields expansions that may reduce overall unit cost of total production output and/or make exploitation of nearby deposits more attractive or more competitive to the company than its peers.

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Typical project ranges with respect to the accuracy of project valuation during each of the mine planning stages are illustrated in Table 1.

Conceptual mine planning studies are typically based on a level of established exploration data, historical information and inferences from regional and benchmarked experience. From the perspective of project viability this level of analysis generically represents a broad-brush assessment of possible viability, considering as wide a range of alternative scenarios and options as necessary. None the less, a business case must be made to proceed to pre-feasibility, which upon approval often requires substantial commitment of expenditure to advance the project through pre-feasibility.

When assessing either a single project or considering a portfolio comprising a number of potential projects with a strategy to narrow the field for further development, there is

considerable justification in utilising all available data sources and committing to comprehensive use of all valid data and key screening criteria at this time.

This is a fundamental requirement for:

- minimising costs and resources otherwise dedicated to projects or resource areas that may not ultimately be viable;
- presenting a balanced and authentic assessment of project potential such that viable projects are not overlooked at the outset, particularly with respect to previous resources where preconceptions may exist.

An analysis using appropriate valuation tools on various scheduled mine plan options is justified at this stage of the project, and is either presented as a case for proceeding with project development or otherwise discarding. When assessing larger project portfolios, a matrix incorporating value and other

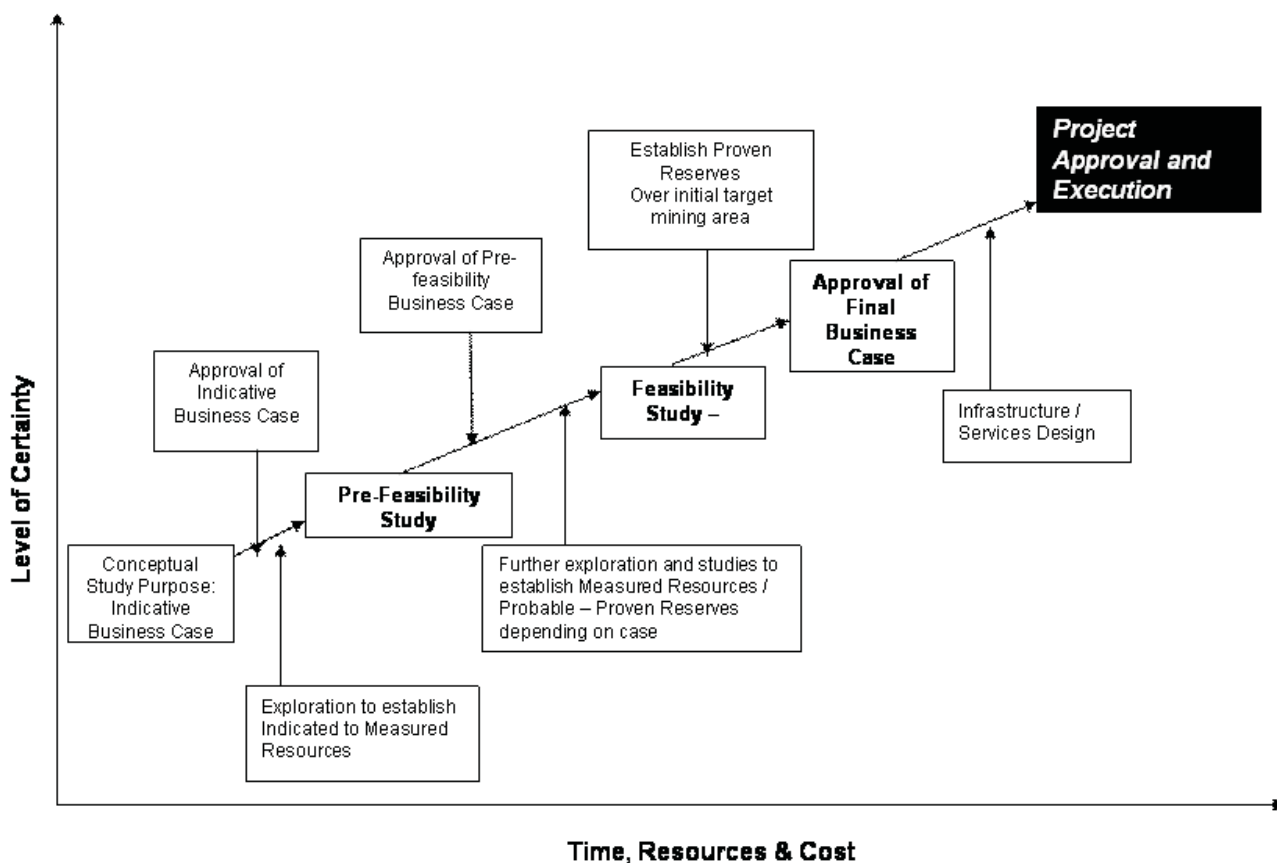


FIG 1 - Typical stages in mining project development.

TABLE 1  
Estimation of project valuation accuracy by stage.

Type of estimate	Conceptual	Pre-feasibility	Full feasibility	Definitive
Purpose	Indicative business case for JV	Establish project scope and criteria	JV approval	Project cost control
Resource status	Inferred to indicated	Indicated to measured	First ten years measured	First ten years measured
Reserve status	Possible to probable	Probable	First ten years proven	First ten years proven
Possible range of costs around central estimate	30%	20%	15%	5%
% of design effort required to produce estimate	0.5% - 5%	5% - 30%	30% - 45%	45% - 65%
Normal estimating method	Scaled historical data	Factored budget quotes	Engineering estimates, firm quotes	Engineering estimates, full take-offs

strategic factors may be compiled and allow for ranking and comparison across a range of projects. Quantifying, qualifying, and benchmarking project geological and geotechnical risk should be conducted at this stage. If the business case is verified, additional resources are committed to develop a project to a pre-feasibility level of assessment.

A *pre-feasibility* level of study allows for detailed comparison of key mine planning and strategic alternatives and usually facilitates confirmation of one or two of the most attractive options presented at concept level. Cost estimates and economics should be sufficiently accurate to select options and justify expenditure to bring the project to bankable feasibility.

A *feasibility* study is used to secure a commitment to finance. It presents a summary of the risks and mitigation strategies allowing a company or bank to risk weight lending rates. Cost estimates and economics should be sufficiently reliable and robust for decision on project approval to be made. Project valuation accuracy should be targeted at ten to 15 per cent at this stage.

Often bankable feasibility study (BFS) mine plans become set in stone. Operations personnel may use limited initiative to revise or review, particularly if not privy to or informed of the key drivers leading to the derivation of the plan. If these key drivers change, then the BFS layout, schedule, and economics should be reviewed, and if warranted, revised.

### The mine planning team

In a typical mine planning process, resources are assessed based on (minimum) industry guidelines. Such guidelines include:

- Australian Standard for Metallurgical Coal Projects,
- The Australasian Institute of Mining and Metallurgy Monograph 12, and
- internal company or corporate advice or structured guidelines.

Mine planning options are formulated, and productivities and costs are assigned within an economic model and scheduled to arrive at an estimated value. This may resemble more a comparative fair market value at the conceptual stage, and an NPV through discounted cash flow/rate of return over a fixed period from pre-feasibility onwards. Care should be taken as there will often be a tendency to overestimate value at this stage, unknown conditions may present a lower hurdle rate for screening. The typical involvement of relevant parties in this process is as follows:

*Qualified geologists* assess the resource quality, seam characteristics and structure, provide a resource status classification and, in combination with others, devise and manage exploration programs to reach required resource status classification.

*Qualified mining engineers* assess reserves based primarily on geological constraints provided, usually by way of a plan from geologists. Underlying geotechnical concepts are factored in, often based on a broad assessment of regional stress data and anticipated ground conditions, from the information provided by the geologists. In general, mining engineers are responsible for generating mine planning options and economic models from which reserves are generated and classified based on the assessed recoverable (economic) resource.

*Business analysts and coal quality experts* traditionally have a role in assessing key economic assumptions and sensitivities flowing forward, usually in the form of market placement and exchange rate or price fluctuations.

*Marketers and corporate personnel* who may identify a market niche and gain commitment from buyers.

As with consideration of mine planning components and parameters, a holistic approach should be used with individual

parties working together as a team, rather than in isolation in defined roles on projects, as critical for delivery of an impartial and comprehensive mine planning process.

The team of professionals dedicated to resource and reserve assessment and project valuation at progressive stages of the mine planning process will clearly depend on the nature and characteristics of the project being assessed. Consistent with the mine planning approach as previously outlined, be it open cut or underground mining assessment potential, the most important point at which comprehensive analysis and risk assessment by mining professionals with appropriate relevant experience from available data is warranted is, arguably, at the conceptual stage. This is consistent with a philosophy of presenting a balanced (and in the case of multiple projects fair comparison) of project potential.

Dedicating comprehensive expertise at this stage will assist in minimising the expenditure committed to projects, which are not ultimately viable, and reduce the potential for ill-considered relinquishment of potential projects. One of the fundamental areas to minimise downstream mining risk that should be most comprehensively assessed at the concept stage, is that associated with analysis of structural geological, geotechnical and hydrological/hydrogeological parameters.

Opportunity and constraints with respect to resource coal quality, structure (faults), and resource recovery are always (rightly) key drivers in determination of project viability and mine layout. However, other geotechnical parameters may often be overlooked at the concept stage. The first mine layout option(s) is extremely important, as it forms the blue print for each successive stage of project development. Once committed to paper, it can be difficult to change, particularly if the change results in reduced resource recovery.

In keeping with the above argument, there are major benefits in utilising and integrating a team of experienced professionals in concept mine planning studies who have a broad range of exposure and skills in:

- practical geological/geotechnical open cut or underground operational mining and exploration experience;
- conceptual through to bankable feasibility level mine planning studies and due diligence studies for an extensive range of resources and clients; and
- economic evaluation and project financing.

The major benefits in applying appropriate expertise and strategy at concept level relate to:

- providing capacity (through experience base) for formulation of hazard plans, risk ranking, and risk assessment from a comprehensive review of all available data, such that critical issues and strategies are developed and integrated into the mine plan process;
- targeting future exploration and scoping feasibility studies to ensure that critical issues are addressed in appropriate depth and in a timely fashion with respect to landmark requirements in project development; and
- evaluating and comparing mine planning options and sequences incorporating assessed geotechnical risk parameters against other key drivers such as optimising resource extraction, resource quality and economic return.

### Assessment of parameters

With a suitably selected team, preliminary assumptions and measured risks relating to the parameters assessed from available data can then be developed. The key in achieving a balanced assessment of parameters is to integrate the major components under the same analysis, rather than treat each in isolation.

Assessment at this stage (in addition to economics based on resource quality), should include as a minimum:

- site-specific tenement constraints or future project risks, for example subsidence under rail, road or waterways, strata title issues, property ownership etc;
- potential hydrological or hydrogeological risk associated with water ingress due to perching aquifers, surface to seam flows or associated slope stability issues in open cut mining;
- approximations of significant (mine plan constraining) geological structure from observed major RL displacements and regional knowledge;
- approximations of joint/cleat orientations from regional inferences and the associated impact on mine planning options; and
- overburden, seam and floor characteristics; more specifically rock mass and material properties and their impact on slope stability and bench orientation in open cut mining or heading stability or caving characteristics in underground mining.

Due consideration, risk analysis and sensitivity analysis of various planning options at conceptual level based on comprehensive analysis and interpretation of available data including resource quality, economic, geological and geotechnical parameters is essential to deliver:

- An assessment(s) of project risk and value that is more likely to be validated than refuted by future (down stream) exploration studies and analysis.
- Should business approval progress to pre-feasibility, an exploration program and study design can be delivered with sound logic based on the conceptual study findings and identified areas for further investigation. This can incorporate adequate and appropriate data collection and testing requirements, procedures and analysis/reporting requirements to maximise the understanding of project risks. In depth detailed team planning will almost certainly optimise exploration expenditure through prioritising exploration and analysis requirements relating to project development needs.
- Reducing the surprises in downstream project development. Getting it right here may even go a long way to delivering everyone's ultimate goal; a mine plan that evolves into a mining operation that optimises economic return and delivers few surprises.

### KEY GEOTECHNICAL ASSESSMENTS AT THE CONCEPTUAL STAGE OF MINE PLANNING

There are a number of key data sources that frequently exist at a conceptual mine planning stage, from which priority geotechnical assessments can easily be made and assessed in balance with other important factors, (including hydrological, gas, etc). The following presents a descriptive general approach in such assessments and includes hypothetical examples.

Geology and geotechnical inputs at concept mine level are clearly interlinked and not mutually exclusive. The scope of a concept study would clearly reflect the type of mining being considered – open cut or underground. For example an underground longwall conceptual study may include the following sections:

- coal quality (impact on reserves and various);
- geology:
  - description of target formation,
  - regional geology, structural trends and coal measure sequence,
  - specifics of exploration undertaken, exploration history and current resource status,
  - structural trends,

- intrusives,
- description of coal measures and individual seams,
- topography,
- hydrogeology, and
- seam gas;
- geotechnical considerations:
  - roof and floor conditions,
  - seam conditions,
  - stress magnitude and orientation,
  - jointing and cleating,
  - pillar dimensions,
  - ground support requirements,
  - consideration of longwall cavability,
  - multiple seam mining implications, and
  - consideration of *in situ* horizontal stress on mine layout.

Once relevant geological and geotechnical inputs have been scoped for the deposit and mining method being considered, analysis of each parameter is required. The following outlines some of the data and associated analysis regarded as essential to address key issues at this stage.

### Previous research, back analysis and benchmarking previous industry experience and learning

Internet and library sources provide a ready source of publicly available information in Australia, the US, and elsewhere on everything from multi-seam mining experience and associated panel/pillar design history and methodologies, to benchmarking productivities relative to different geotechnical environments. Where appropriate and comparative, such information can be used to benchmark performance and anticipate likely ground behaviour with respect to resource and reserve assessment. This can be further used to influence downstream decisions on such factors as mining method, mine layout, and equipment selection. If possible, assess using a range of methods to achieve this, and compare and identify why different results may be derived.

In many instances when considering a conceptual mine planning study in an area not previously mined, there may be very little site-specific data relating to likely operational performance in the particular resource under consideration. In these instances however, parallels can be drawn through assessing productivity and other risks impacting operational performance, particularly when considering previous mining experience in the same seam, or in a seam with similar geological/geotechnical characteristics. This can be drawn from international experience and data. It does not necessarily have to be documented experience from a similar Australian resource as long as it can be demonstrated with confidence that the empirical comparisons are justified.

When assessing the strength of comparison with respect to geotechnical experience in comparative environments, particular parameters to comprehensively check should include, as a minimum:

- *System of mining.* Ensure that the operational data being compared derives from the same system of mining. This may sound like the obvious, however the geotechnical environment, open cut or underground, is highly sensitive to mining method. The impact of the geotechnical environment will differ subject to mining method. With any empirical comparison of mining data, this should be the first check prior to others to establish that an overall comparison is indeed valid, prior to further analysis.

- *Resource characteristics.* Check that general seam structural geological characteristics, seam thickness, seam rolling and horizon, rock mass and material strengths, and likely nature and density of seam cleat and jointing, for the resource being assessed are in the same general range as the study data being considered.
- *Stress environment.* Check that the range of cover depths and anticipated horizontal and vertical stresses are in the same general ranges for the resource being assessed as the comparative study data being considered.

### Regional geological structural trends

Regional structure can be reviewed from publicly available government sources. Aeromagnetic, satellite photos and gravity surveys may also give an insight into regional anomalies. Interpretation of geological structure over a resource area should always be checked and balanced against the wider existing regional trends and structural styles prior to more detailed structural interpretation from available exploration data.

Earlier generation seismic structural interpretation through a target area, although less advanced than more recent seismic technology, can certainly assist in structural interpretation. Often, the seismic interpretation can be enhanced through reprocessing of base information using more current technology.

Once a geological interpretation has been established, mine planning constraints, in particular based on trends, locations and displacement of faults or significant folds are normally applied.

However, in addition to fault location and displacement magnitude, assessment of the nature of interpreted geological structure with respect to orientation and dip relative to the coal seam/panel layout is important. For example, interpolated discreet near seam low-angle compressive thrust faults may have a more adverse impact (over a greater lateral extent) on strata stability, roof support requirements and potential mine planning constraints than subvertical normal faults of limited lateral extent. Structure can also have an adverse impact on roof/rib stability for both longwall and development mining.

It is largely the *nature* of the geological structure with respect to its orientation relative to longwall faces or development headings and associated dip with respect to the roof, rather than simply magnitude of displacement, that forms the major constraint with respect to mining. There now exists a number of Australian examples of demonstrated longwall retreat through significant faults, which have been achieved through appropriate hazard assessment and operational practice. Significant displacement faulting, although a risk, should therefore not automatically be a planning constraint. Care should be taken when assessing the risks associated with fault mine through related to seam displacement considered in the context of seam thickness and roof and/or floor strength. For example a +5 m seam displacement in a 1.5 m seam with strong roof and floor when fully assessed may present substantially more risk than a +5 m seam displacement in a 5 m seam with weak roof and floor.

For example a seam displacement of greater than 5 m in a 3 m thick seam with strong roof and floor when fully assessed may well present less risk than a 2 m seam displacement in a 5 m seam with weak roof and floor.

Where possible, attempting to assess the variations in rock mass characteristics associated with structures, to facilitate a more comprehensive assessment of geotechnical implications and associated mining risk, is also justified.

### Seam splitting and rider seams

The geotechnical impact of seam split areas, particularly in the near roof of underground longwall and development headings should never be underestimated. There are numerous documented

examples of major roof cavity and productivity delays associated with immediate seam splitting. Seam split zones in Australian underground coal mines are often associated with:

- Channelisation of strata and associated variation in rock mass characteristics and stress distributions where rider seams diverge.
- Differential compaction features. These are often (wrongly) interpreted as low angle shear zones, although the impact can be similar but more localised. Differential compaction is a geological depositional feature associated with basin development and sinking of overlying strata into the coal formation.
- Localised seam thinning.
- Increased density of jointing in the immediate roof.

All of the above can combine to form highly variable and low strength rock mass and cohesion in the immediate roof environment which may require tailored strata management and ground support practice. Preliminary hazard plans and risk assessment should most definitely incorporate the lateral extent of interpreted seam split zones and the associated consequences with respect to both specific ground support requirements and/or mine planning constraints. Geotechnical hazard plans can be used to generate mine planning schedules zoned for variation in mining rates using appropriate de-rating factors.

### Exploration core and geophysical log signatures

It is relatively easy and appropriate to manipulate these forms of exploration data to interpret rock material composition and rock mass characterisation (using selected appropriate industry standard rating schemes), of the entire overburden section for immediate roof strata assessment and higher. Such information is particularly relevant to assessing the risks and likely requirements associated with ground control, longwall cavability characteristics, mining method, productivity, and mine sequencing.

In many instances it is possible to use existing geophysical logs or electronic LAS files, and correlate these with lithological logs. Material strength in the form of unconfined compressive strength (UCS) may be estimated if existing conversion formulae for the assessed seam in the same area to convert Sonic Velocities into UCS are available. Sonic velocity is a function of rock elasticity, and this can be correlated with rock strength. By plotting the sonic velocity for the immediate overburden to the seam, the rippability of the overburden can therefore be assessed as illustrated in Figure 3 through use of industry standard generalised rock strength correlations as illustrated in Table 2.

**TABLE 2**

*Example of sonic velocity correlations with rock strength.*

Sonic velocity (m/sec)	Rock strength
<1500	Very low
1500 - 2500	Low
2500 - 3500	Medium
3500 - 4500	High
>4500	Very high

Such correlation facilitates estimation of the immediate roof, floor and seam material strengths. Figures 2 and 3 illustrate (relatively straight forward) LAS file manipulation to produce valid graphical output in the form of valid industry recognised geotechnical characterisations for underground and open cut scenarios.

Geophysical logs when assessed with geological (lithology logs) can be particularly useful in assessing the extent and position of any Rider seams and the extent of laminated or low strength

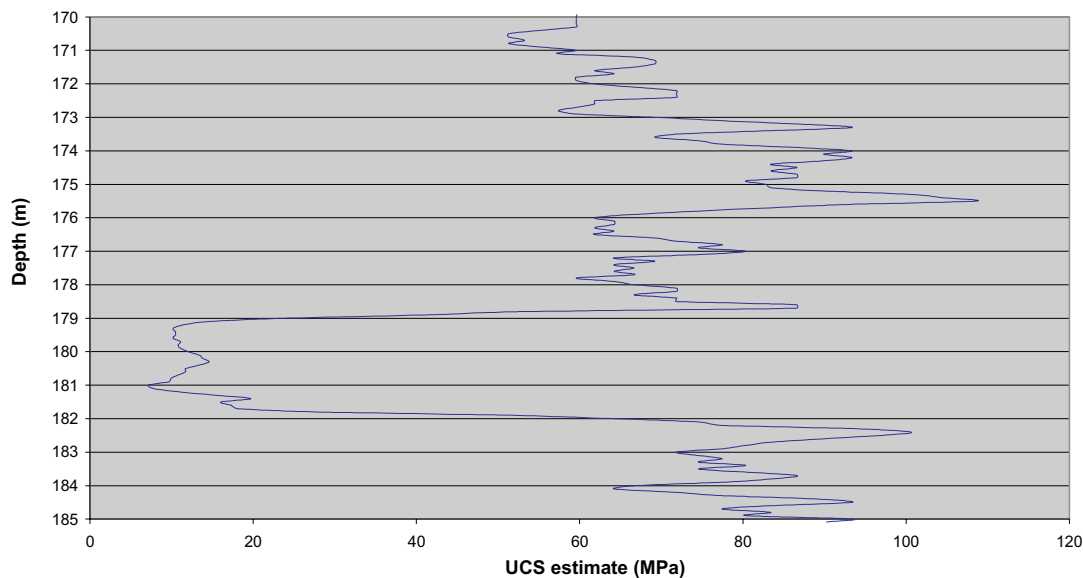


FIG 2 - Example IMC plots of estimated UCS from manipulated LAS files.

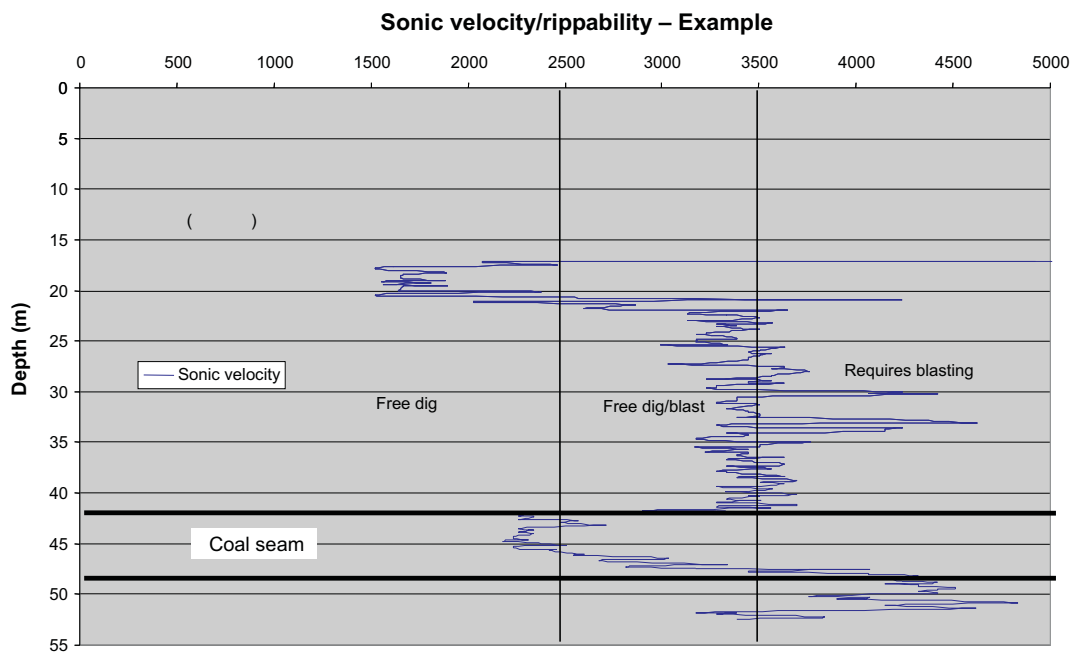


FIG 3 - Example IMC plots of seam rippability from manipulated LAS files.

roof units for likely support scenarios. Both of these factors warrant due consideration as they can have particular impacts on the geotechnical mining environment. Estimation of coal mass roof ratings (CMRRs) from available exploration data can easily be achieved through appropriate industry methodologies, and can facilitate early detailed geotechnical characterisation even at a very early stage of mine planning.

**Assessment of floor stability from available exploration data**

Weak and/or easily degradable floor may in certain instances constrain open cut or longwall mining potential, and therefore mine layout. In the case of underground development, the mining risks associated with trafficability in development headings, pillar behaviour and floor heave in such conditions warrant consideration at an early stage.

**Assessment of joint and cleat orientation with respect to mine layout**

In many instances detailed geotechnical interpretation of cleating/jointing from petroleum and gas exploration data, core logging, core orientation, and acoustic scanner information is possible. Such interpretation can assist in the assessment of optimum panel layouts with respect to roadway heading and longwall face stability.

Inappropriate panel layout with respect to cleat/joint orientation can have adverse rib stability impacts on development mining and under longwall abutment loading and can also result in unstable longwall faces. The risks and implications associated with cleat/joint orientation and density with respect to mine layout should be regarded as a priority geotechnical parameter warranting consideration in mine planning. Risk assessment of

anticipated cleat and joint orientation with respect to panel layout is therefore necessary at the earliest possible stages of mine planning.

In the assessment of open cut geotechnical mining risk, interpreted jointing/cleating should be considered in combination with preliminary rock mass and material assessment and interpreted bedding plane orientation relative to mining direction. This can be assessed through consideration of typical failure mechanisms and in general terms, the impact and extent of potential failures will be exacerbated if the discontinuities strike parallel with the pit face. A preliminary risk assessment incorporating standard potential failure mechanisms (as outlined by Hoek and Bray, 1981), from data interpretation or inference, should be incorporated at concept level, making a preliminary assessment of the following as illustrated in Figure 4.

- The potential for toppling failure from vertical/subvertical joint sets.
- The potential for planar failure due to low angle dipping discontinuities. This can present a particular problem where low angle discontinuities intersect subvertical joint sets as illustrated in Figure 4.
- Planar failure due to low angle structures intersecting subvertical joints.
- Wedge failures due to intersection of opposing discontinuity sets.
- Mass slump mechanisms in overburden soil or heavily fractured rock.

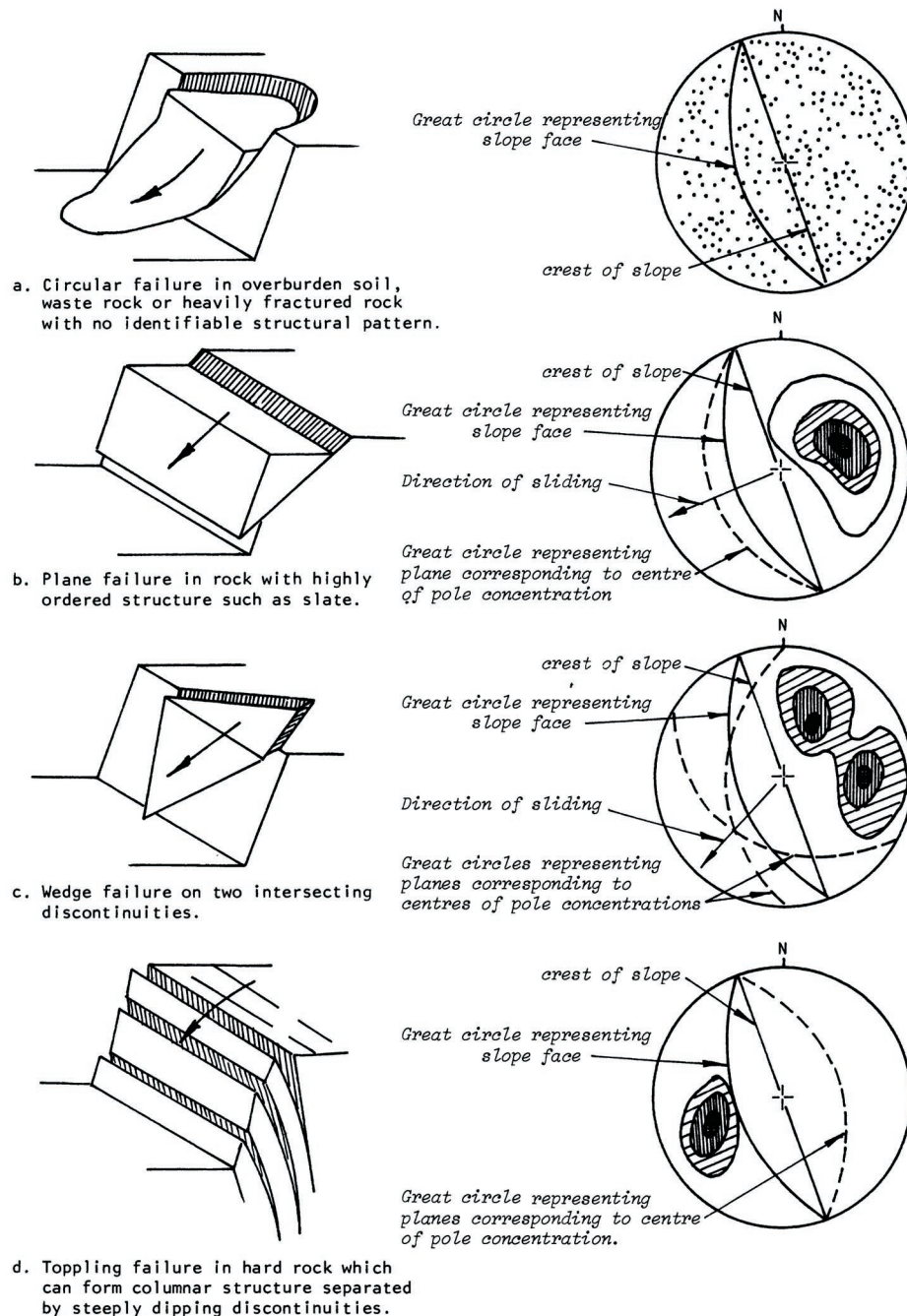


FIG 4 - Preliminary open cut slope stability assessment (from Hoek and Bray, 1981).

In addition to the impact of joint and cleat orientation, both low wall and highwall stability should consider the risk associated with the following parameters relative to mining method:

- geometry, including floor dip, slope angle;
- placement sequence with respect to spoil;
- material properties including (if available or inferred) strength, shear strength, weathering, plasticity, fabric structure, saturated and unsaturated unit weight;
- floor material strength and degradability;
- identification and categorisation of discontinuities, shears or weak bands, assessment of failure potential along these surfaces and the potential for and reactivation with increased hydrostatic surcharges;
- standing water table, aquifers and general groundwater conditions; and
- blasting practice and impact on stability.

In consideration of underground mining, orientation and density of jointing and cleating can impact on the stability of the roof and rib from a geotechnical, and therefore mine planning perspective. Well developed cleating and/or jointing running near parallel to planned mining development operations will likely impact adversely on roadway rib and roof stability. Orientation of cleating relative to proposed longwall panels may also have an adverse geotechnical impact on longwall face behaviour.

Experience shows that a heading orientation of at least 20° to the cleat/joint direction is required to minimise adverse impact with respect to both roof and rib stability. However the optimum underground panel layout should be cognisant of both the predominant joint and cleat orientation, the major and minor principal horizontal stress orientations and consider the orientation of geological structural zones. Figure 5 illustrates a hypothetical longwall gateroad panel layout considering joint/cleat orientation and *in situ* principal horizontal stress.

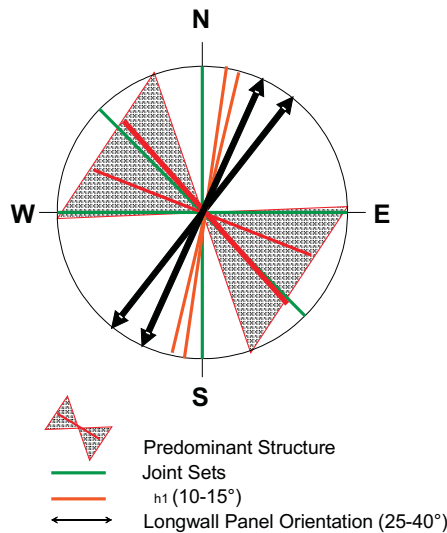


FIG 5 - Hypothetical optimum mine layout with respect to interpreted joint/cleat orientation.

### Existing geological models

If existing geological models are available at concept level, gains can be made from comprehensive analysis of existing geological strata models from a geotechnical perspective. In many instances the seam, as well as overburden strata is modelled in the form of a three dimensional model. Mine planning is also three-dimensional. Assessing the consistency of seam thickness

and interpretation of immediate roof lithologies and overburden characteristics from the existing geological model can deliver key data which can be used for preliminary hazard and risk analysis of geotechnical parameters including:

- rock mass and material assessment of the immediate roof, seam and floor characteristics for both open cut and underground mine planning purposes;
- rock mass and material characterisation of the overburden for analysis of goaf cavability and associated impact on pillar extraction, abutment pillar loading, and longwall face performance; and
- assessing broad scale variations in dip which may pose a risk to both horizon and ground control, particularly for longwall mining.

### Stress orientation and magnitude

Information on stress magnitude and orientation may be available from a number of sources, including coal seam hydrofracturing methods which are often commonplace in petroleum/gas field evaluation. In such instances, major principal horizontal stress magnitudes and orientation can be approximated by formula and assessed in the context of mine layout. Stress orientation may also be derived from caliper logs or acoustic scanner analysis using borehole breakout.

Such information can prove useful in assessing or testing the assumption of regional horizontal stress fields. Approximated horizontal stress magnitudes should be considered with caution, as they are entirely dependant on the modulus properties (stiffness) of the rock material being considered. Stiffer materials will inherently attract higher *in situ* stresses. When approximating horizontal stress magnitude from available data and assessing likely ground behaviour/reaction, it is therefore critical to make the assessment in the context of the materials being considered. Further, a number of stress domains may exist across the resource, modified in particular by intrusives and faulting. If sufficient information is available and providing like materials are being assessed and compared, approximated horizontal stress magnitudes can reasonably be compared and variations/anomalies identified over a resource. Any differences in stress orientation or magnitude (measured or predicted) over the resource may flag the potential for adjacent associated geological structural influence which may, in itself, prompt the targeting of further exploration investigation and analysis.

Assessing the impact of *in situ* stress orientations *relative to underground development* driveage and strata management requirements should take into consideration:

- an estimation of *in situ* vertical stress from cover depth and consideration on rib stability and support requirements;
- assessment of the regional horizontal stress field and typical horizontal to vertical stress ratios for the seam under consideration; and
- assessment of available *in situ* stress orientation measurements, inferences or estimations from exploration data as described above.

Assessing the impact of *in situ* horizontal stresses *relative to longwall panel and face orientation* is also an important consideration. It has previously been found (Hasenfus and Su, 1995) and continues to be observed in Australian longwall operations, that the maingate is stress relieved when  $\emptyset$ , the angle between the *in situ* principal horizontal stress direction and the maingate orientation, is between 90° and 180°, with the best conditions prevalent at  $\emptyset = 160^\circ$ . Conversely, the maingate is stress concentrated when  $\emptyset$  is between 0° and 90°, with the maximum concentration at  $\emptyset = \sim 70^\circ$  and negligible concentration between 0° and  $\sim 25^\circ$ . Figures 6 and 7 illustrate a model of this relationship between  $\emptyset$  and the relative horizontal stress increases or decreases in the maingate.



Stress notching of *in situ* horizontal stress (eg on approaching a previous goaf leading to a 'superstressed' situation) is an important consideration for mine planning, pillar design, and tailored secondary support requirements. The degree of impact in this situation is dependant on the orientation of maingate or tailgate and/or virgin goaf areas with respect to *in situ* principal horizontal stresses. It is important to assess the risk of unfavourable panel orientation and to consider the preference for maingate or tailgate in stress notch (if panel orientation unfavourable) and preferred direction of retreat and mining sequence, balanced against other factors.

Assessment of anticipated vertical stresses on the longwall face. Variations in vertical stresses on the immediate longwall face will be anticipated as planned longwall panels advance from shallower supercritical through critical range to deeper

subcritical scenarios. Preliminary assessment of subsidence profiles at various depths at assumed angles of draw could then be estimated as illustrated in Figure 8.

The progression may not necessarily translate into increased anticipated loading on the longwall face. A critical factor in such an analysis is the likely goafing behaviour associated with overburden strata and the absolute vertical stress increase associated with the proposed panel face width. Sufficient overburden lithological data may well be available at a conceptual stage to assess (and in the case of multiple projects compare) likely face loading implications associated with longwall width taking into consideration overburden and caving characteristics.

**Lack of horizontal stress**

There are incidences of roof failures, that have been attributed to lack of confining stress, in particular where influenced by the presence of jointing. The general style of failures in these instances may be confined by parallel running joint sets and attributed to a lack of confining stress acting on the joint surfaces and therefore strata inability to maintain stability. Lack of confining stress may also be associated with proximity to geological structure (eg on the crest of seam rolls), or around faults.

The impact of potentially low magnitudes of confining *in situ* horizontal stresses and impact on the mine layout should be incorporated into hazard assessment, particularly in shallow underground environments or with limited competent material cover. In some instances, the assessed risks associated with limited competent rock cover may be of sufficient magnitude to preclude mining potential. A common rule of thumb is to maintain a minimum of 25 m to 30 m of competent material in the mining seam roof.

**Longwall caving characteristics**

Proposed longwall panel width against overburden depth ratios directly impact longwall caving characteristics, face conditions, surface subsidence profiles and chain pillar design, together with anticipated ground support requirements and productivity assumptions. A number of industry recognised empirical methodologies exist to assess estimated pillar loading, strength

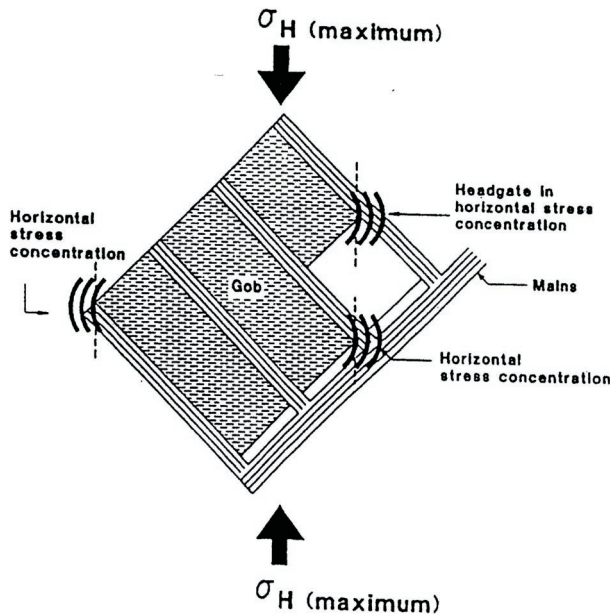


FIG 6 - Horizontal stress notching in longwall mining (from Chekan and Listak, 1992).

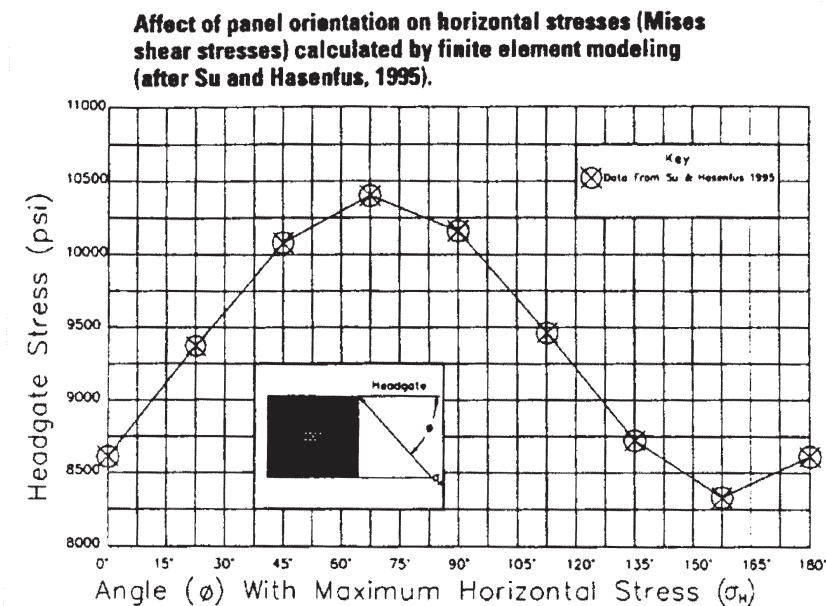


FIG 7 - Effect of panel orientation on horizontal stresses (from Hasenfus and Su, 1995).

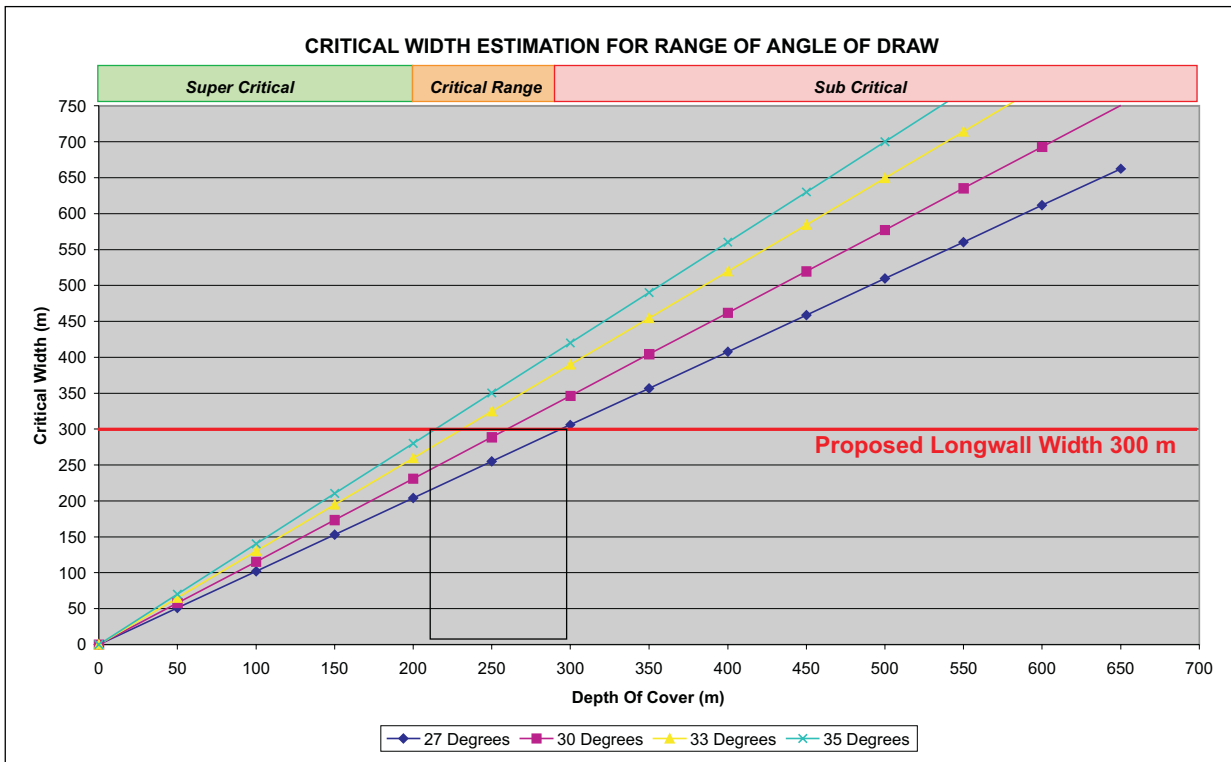


FIG 8 - Hypothetical case illustrating anticipated ranges in behaviour with depth.

and design requirements which incorporate depth of mining and face width. Empirical design methodologies and bench marking mining experiences in similar geotechnical environments utilising available geological information can be used at the conceptual level of mine planning to establish base roadway development and longwall requirements and other potential impacts. Previous pillar design experience and stress modelling from the same seam in similar mining environments should be incorporated where available.

Specific interpretations/inferences to assist in assessing likely goafing and longwall face behaviour and associated geotechnical risk can be made at preliminary mine planning level. This can be assessed through the combined influences of cover depth, overburden lithology, and joint/cleat orientation relative to the longwall. Specific initial considerations may include:

- Assessing the nature of the overlying strata with respect to rock material and rock mass strength, rock composition, and bedding plane characteristics and the potential impact on longwall face and abutment loading. A broad interpretation of overburden lithology can be made through manipulating electronic LAS files to produce geophysical plots of characteristic overburden for assessment with respect to anticipated goafing behaviour.
- The longwall panel width against overburden depth ratio will impact on the caving characteristics, face conditions and surface subsidence profiles as previously discussed.
- Joint orientation with respect to proposed longwall face orientation is regarded as potentially having a significant impact on longwall face stability and goafing behaviour.
- A potential high level of risk exists in any longwall system if longwall specification based on anticipated ground behaviour is ill considered. At conceptual level, a broad assessment of the overburden behaviour based on interpretation from (in some cases limited) exploration data and benchmarking this against behaviour in comparable environments for existing longwall operations can be undertaken.

In potentially more complex or challenging geotechnical environments, more detailed numerical modelling may be justified at a later stage of mine planning when adequate high confidence geotechnical parameters can be established from exploration test work. This is likely to assist in validating empirical assumptions with respect to goafing and loading behaviour made at concept level.

### Pillar design assessment

Industry recognised and current empirical pillar design methodologies (eg UNSW, various ALP based methodologies) can be undertaken at the conceptual level of study to gain an appreciation of likely mine pillar requirements based on available input data and parameters. With limited available input data this approach in general is justified at conceptual level. In the later stages of mine planning, more sophisticated measures such as numerical modelling may be used. In any geotechnical design there is value in applying and comparing separate methodologies based on available input parameters, rather than use of simply one or other methodology. This provides a check on the validity of the design tool used specific to the resource characteristics, highlights any variations and sensitivities associated with site specific input parameters and design formulae used, and provides a more considered and auditable design process. Particular care should be taken in adequately assessing the quality and sensitivity of input parameters in any geotechnical design process used.

### Multiple seam mining implications

Interactive problems due to stress redistributions in multiple seam longwall operations, particularly due to transfer of stress from overlying gateroad pillars to underlying gateroad pillars where superimposed, or to the underlying longwall face where superpositioned (Figure 9), can have an adverse impact on longwall face strata control or pillar performance, unless

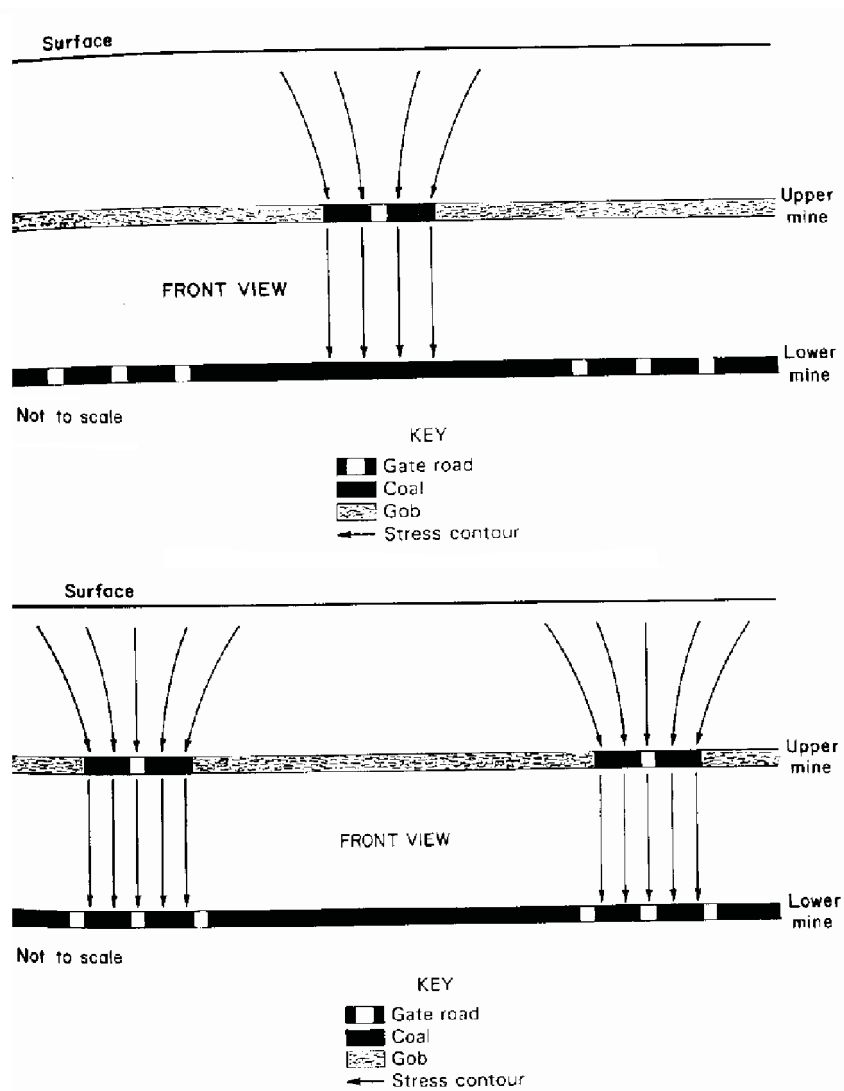


FIG 9 - Schematic illustrating offset and superimposed panels and associated loading (from Chekan and Listak, 1992).

appropriately considered and designed for in the mine planning process. Gale (2004), has recently completed an ACARP study reviewing overseas data relating to empirical experience and undertaking geotechnical modelling work in multi-seam longwall environments. From this work, Gale indicates that in general offset compared with superimposed layouts may be preferable in Australian conditions and certainly from the perspective of subsidence minimisation. The risk of adverse longwall face control under overlying chain pillars should, however, not be under-estimated.

In a case study conducted by Chekan and Listak (1992), concentrating on pillar design considerations for underlying superimposed pillars (based on ALPS pillar design methodologies calibrated with modelling), it was concluded that the two most important parameters influencing the proportion of abutment stress transferred from the upper to the lower mine pillars (referred to as the multiple seam factor – MSF) were, in order of sensitivity, interburden thickness followed by pillar width. Pillar length was found to be a far less sensitive parameter. This study was based on three and four heading gateroad scenarios.

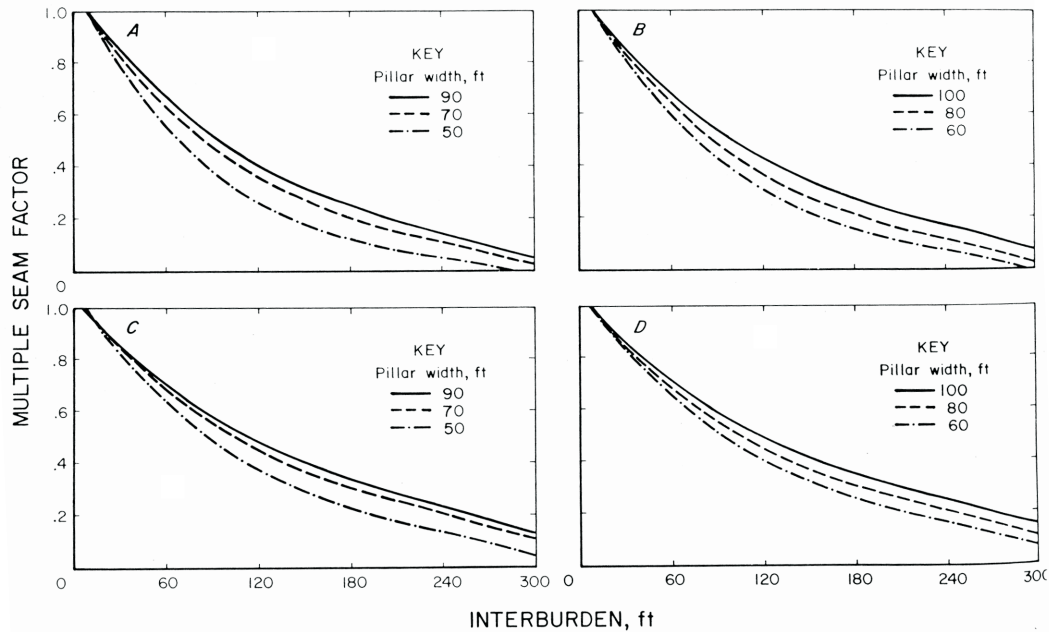
In a hypothetical situation, assuming an interburden thickness between superimposed pillars of 50 m (165 ft) and upper pillar sizes of approximately 100 ft (30 m), the USBM studies

(Figure 10) indicate an approximate MSF of around 30 per cent. That is, 30 per cent of the calculated abutment load from the upper pillars can be anticipated to be transferred to the lower pillars in this situation. Although specific to American pillar design calculations (ALPS) and multi-seam longwall mining conditions for three heading gateroads, and also calculated for smaller pillar sizes, the example none the less serves to illustrate that, where the interburden between seams is less than 50 m, there is likely to be a component of load transfer requiring that can be estimated and considered further in designing chain pillars for superimposed panels.

More recently Ellenburger, Chase and Mark (2003), NIOSH conducted an empirical study into case histories involving undermining previous longwall panels involving 12 different coal seams with seam heights ranging from 1.2 m to 2.1 m and overburden thicknesses ranging from 75 m to 620 m. A strong empirical relationship was established between the amount of damage to the lower seam caused by load transfer from the upper seam, and the overburden to interburden ratio (Figure 11).

The US database study concluded the following:

- No significant damage to the lower seam was recorded when the overburden-to-interburden (OB/IB) ratio was less than approximately seven.



Multiple-seam factor for three-entry (A-B) and four-entry (C-D) gate roads.

FIG 10 - Abutment load transfer to lower superimposed pillars (from Chekan and Listak, 1992).

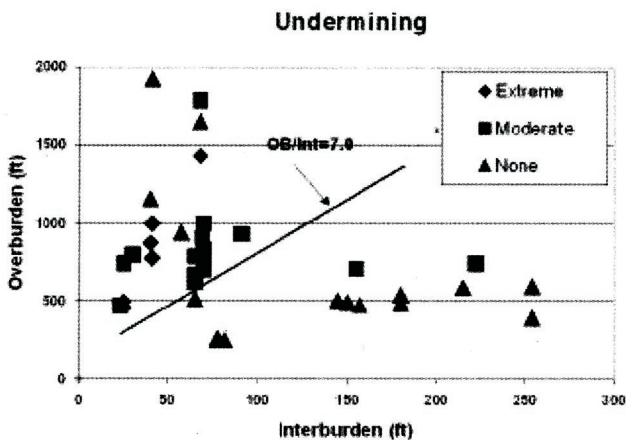


FIG 11 - US case studies for undermining longwall panels (Mark et al, 1997).

- It is possible to successfully mine, even at high cover and with large OB/IB ratios, when the mining is carefully planned to take place in the stress shadow beneath fully extracted goaf areas.

In summary, there is a need to not over generalise and to recognise the complexities associated with stress redistributions in multi-seam mining operations specific to local conditions, mining timing/sequence, local geotechnical parameters, and in the context of what the mine design is trying to achieve. Nonetheless, at conceptual level with limited data and in the absence of a record of mining history, assessing mining experiences in comparable geotechnical environments using published data may deliver a valid and logic based assessment of likely behaviour in a multi-seam environment. Given local specific conditions however, further assessment which may take the form of geotechnical modelling may be warranted in down stream mining studies when sufficient high confidence input data is available to validate initial assumptions and interpretations made regarding stress interactions.

### Subsidence considerations

A number of alternative approaches to subsidence prediction are available, using empirical or mathematical relationships. At conceptual mine planning level, the primary purpose of this evaluation may be in regard to environmental impacts, an assessment of the further requirements of mining approvals, or to assess the potential lateral impacts on adjacent lease ownerships and associated mine layout constraints.

Analysis at conceptual level should include:

- review and back-analysis of previous regional subsidence history;
- determination of approximate subsidence magnitudes and lateral influence for the proposed mine layouts;
- potential impact with respect to perched aquifer breaching and associated inflow;
- generation of post subsidence surface contours across the proposed mining area (if sensitive and required); and
- a preliminary assessment of potential subsidence impacts and recommendations for further study should the project progress. Typical mitigation and remediation measures (including design, and pre/post mining) may be included at this stage.

A number of subsidence predictive tools, including for example empirically derived subsidence curves (eg Holla, NCB), can be used as a tool to complete analysis. However care should be taken to select the most appropriate method for the seam environment being considered. A second check analysis using a separate methodology may be warranted at this level depending on the level of mine planning sensitivity and risk in relation to projected subsidence.

### A REPORTING FRAMEWORK FOR GEOTECHNICAL CLASSIFICATION OF MINE PLANNING PROJECTS

As previously outlined, there are clear input requirements for effective project valuation at various stages of the mine planning cycle. The author has argued the case for comprehensive

geotechnical assessment of coal reserves at the conceptual stage, siting specific data interpretation methodologies, which can be utilised. This is particularly relevant in the case of observed trends in Australian underground coal mining which in a number of instances include assessment of resources and reserves:

- at increasing depths of cover with associated increased adverse stress acting on the roof and ribs;
- in structurally more disturbed areas;
- incorporating multi-seam extraction; and
- with complex resource characteristics including seam splitting and recovery of isolated fault bounded blocks.

There has been recent discussion, focused primarily on the metals industry, regarding the potential advantages of reporting frameworks for geotechnical classification of mining projects. A recent AusIMM publication (Haile, 2004), argued strongly the case for such a framework and proposed a classification scheme.

Table 3 illustrates the proposed data interpretation requirements at various stages of geotechnical categorisation, from implied to verified. Although focused primarily on metals orebody assessment, such a framework specific to coal could provide mining and financial Institutions with a guide to the level of geotechnical input required for a project at any particular stage of development.

From the perspective of geotechnical risk sensitivity in the process of mine planning and project development, the author raises the following questions to the industry in search of debate and feedback:

1. How well are resources currently assessed in mine planning and during project development, particularly at the early stages of assessment, from the perspective of geotechnical risk, *relative to* other key drivers including coal quality and valuation? How sensitive is such assessment in determining the success or otherwise of a project?

**TABLE 3**

*Example proposed reporting framework for geotechnical projects (from Haile, 2004).*

Data type	Implied	Qualified	Justified	Verified
General requirements and geotechnical model reliability	No site-specific geotechnical data necessary	Project-specific data are broadly representative of the main geological units and inferred geotechnical domains, although local variability or continuity cannot be reliably accounted for.	Project-specific data are of sufficient spatial distribution (density) to identify geotechnical domains and to demonstrate continuity and variability of geotechnical properties within each domain	Site-specific data are derived from local <i>in situ</i> rock mass.
<b>Geological model</b>				
Stratigraphic boundaries	Inferred from regional geology	Reasonable knowledge of major units and geometry	Well constrained in the vicinity of the mine excavations and infrastructure	Mapped in the field
Weathering/alteration boundaries	Inferred from regional geology	Based on geology model	Well defined grading of weathering and local variability	Mapped in the field
Major structural features	Inferred from regional geology	Major 'dislocations' interpreted	Drilling sufficient to be well constrained in continuity, dip and dip direction	Mapped in the field
<b>Rock mass data</b>				
Discontinuity	Based on general rock type characteristics	Estimates of RQD/FF and number of defect sets from resource data (will probably contain directional bias)	RQD/FF statistics and number of defect sets representative of all geotechnical domains and directions	Multi directional FF from <i>in situ</i> mapping and visual count of defect sets
Intact material strength/deformation characteristics	Based on general rock type characteristics	Field estimates	Field and laboratory estimates and variability	Field and laboratory estimates
<b>Defect data</b>				
Orientation	Inferred from regional geology	Orientation inferred from geological model	Dip and dip direction statistical data from drill holes.	<i>In situ</i> measurement of dip and dip direction from excavation mapping.
Surface characteristics	Estimated on precedent experience	Estimated on precedent experience	Statistical estimates from core logging for all defect sets. Laboratory shear strength testing of critical defects.	Statistical estimates from <i>in situ</i> measurements. Laboratory shear strength testing of critical defects.
Volumetric distribution (continuity and spacing)	Estimated on precedent experience	Estimated on precedent experience	Estimated on precedent experience	Persistence and spacing measurements
<b>Stress regime</b>				
Principal stress field	Estimated on precedent experience	Mean regional trend	Local magnitude and orientation based on local experience or modeling	Measured or inferred from <i>in situ</i> performance
Seismicity/earthquake	Based on general experience	Based on general experience	Based on regional trends	<i>In situ</i> experience
Geotechnical model/domains	Based on geology model	Based on geology model	Based on geotechnical data.	Based on <i>in situ</i> data
Hydrogeological model	Based on general experience	Based on general experience	Hydrogeological study	Local observations/measurements

2. Given the traditional role and required (defined) competencies of persons traditionally used to assess a project with respect to resource and reserve definition generally to JORC Code guidelines, is there a real justification for the involvement of experienced geotechnical practitioners and more defined input at the various process levels?
3. In view of both the above factors, are there reasonable grounds for developing a reporting framework, which can be used as a guideline for geotechnical classification of mining projects, specific to coal, which could prove beneficial to resource companies?

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