# Groundwater Control and Strata Investigations to Allow Total Extraction of Coal by Underground Methods in the Collie Basin (Western Australia)

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## ABSTRACT

A research programme has been undertaken to evaluate the effect of total extraction of coal by underground methods on superimposed aquifer systems in the Collie Basin sediments, Western Australia.

The research programme has incorporated comprehensive field monitoring of surface, and subsurface subsidence and groundwater levels along with empirical modelling techniques. Results have identified that ground curvature can be used to predict - ahead of mining - the likely impact on the Permian sediments and potential water inflow into the mine. Research is continuing on development of this approach using more sophisticated modelling techniques :-

a) displacement discontinuity boundary element mathematical models.

b) centrifuge modelling.

Early results indicate both methods have good application to the subsidence processes noted in the Collie Basin.

## INTRODUCTION

The Collie Basin contains one of the few near surface coal bearing Permian sediments in Western Australia.

Historical deep coal mining techniques (bord & pillar) in the Collie Basin gave poor recovery (30 - 40%) and had the basic philosophy of maintaining good roof and mining conditions. Consequently, surface subsidence has been poorly documented and relatively uncommon or unnoticed.

With the increasing pressure for higher extraction ratios (from underground reserves of this valuable, finite commodity), and for more efficient mining methods, the frequency of caving and the potential of subsidence damage to surface features and the complex aquifer systems has increased. Consequently, a research programme has been proposed to develop a composite model which can accurately forecast surface and subsurface subsidence profiles and corresponding strains resulting from underground mining in the Collie Basin. The model will incorporate empirical, mathematical and physical (centrifuge) modelling.

Empirical modelling has been based on field data relating to surface and subsurface subsidence, and water inflows into the mine at various stages of extraction. Results from this phase of modelling have been very promising.

Mathematical modelling, which is in its early stage of evaluation will be based on the relatively new 3D boundary element computer program "SUBSOL". These models will be used to further validate assumptions made from the empirical modelling and can be used to evaluate any number of mine geometries and geologies.

Physical modelling, (using the Acutronic 661 centrifuge at the University of Western Australia) is again in its early stages of assessment. Results from preliminary runs gave confidence that this technique can be applied to mining and subsidence processes in the Collie Basin. Centrifuge modelling promises to be very useful in understanding the caving processes, effects on aquitard integrity and the influence of water pressures.

This paper deals with the effects of subsurface subsidence on aquifer systems in the Collie Basin and developments in the research proposal toward developing a predictive model for aquifer response to total extraction of coal.

## REGIONAL GEOLOGY

The Collie Basin sediments are chiefly cyclic, high energy fluviatile sandstones with thin gravel and conglomerate lenses. Silts and shales occur as overbank, lacustrine or paludal deposits. Coal seams are remarkably uniform in thickness and composition over considerable distances.

In general, the sediments can be described as saturated and weak and have been altered through weathering or post depositional processes. A more detailed description is given in Lord, 1952.

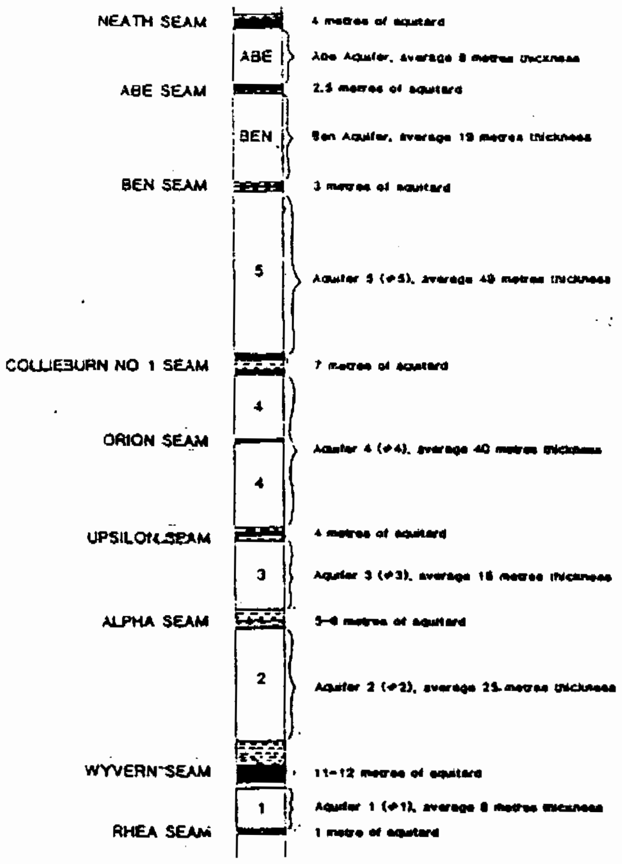
## REGIONAL HYDROLOGY

The whole Collie Basin can be thought of as an interrelated groundwater system bounded by basement topography and geology, and modified by the location and extent of coal measure sequences (modified from Hammond, Misich, and Boyd 1983).

Permeable aquifers comprise fine to granular quartzose sandstones with little to no fines content. Moderately permeable material consists of silty/clayey sandstones. Siltstones represent the low to moderately permeable aquifers, mudstone and shale the aquitards, and coal seams represent system aquicludes.

All coal seams are bounded by aquifers, in some locations situated directly above or at the floor of the seams. However, most areas have aquitard barriers of variable thickness separating the mining seam from neighbouring aquifers (see figure 1).

Figure 1. GENERALISED HYDROSTRATIGRAPHY



Typical aquifer material properites (from Hammond, Misich and Boyd 1983) are listed below :-

- permeablility - about 3-5 metres/day
- storage coefficient - 0.0001
- specific yield - 15-20%
- transmissivity values are a product of permeability and aquifer thickness.

Aquifer heads of water can be very high. Water heads of 80 and 98m have been measured (Hebblewhite & Humphreys, 1987) in existing workings and heads greater than 200m are inferred in deeper, unmined areas.

The effect of total extraction on these aquifer systems is obvious. Caving of roof material will interconnect the mine workings with saturated and possibly pressurised aquifers which could easily flood the mine and cause abandonment.

## GEOMECHANICAL PROPERTIES OF STRATA

The geology of the Collie Basin can vary within short intervals, both vertically and laterally. There is also marked variation within the major lithologies (sandstones, shales, siltstones, laminites and coals). Each has a wide range of engineering properties, dependant on past and present geological processes.

Table 1 below lists typical ranges of compressive strengths, elastic modulus, cohesive strength and friction angle for each major lithology of the Collie Basin sediments.

Table 1

TYPICAL MECHANICAL PROPERTIES OF COLLIE BASIN SEDIMENTS

| Lithology | | UCS (MPa) | Elastic Modulus (MPa) | Cohesive strength (MPa) | Friction angle (deg.) |
|---|---|---|---|---|---|
| Sandstone | Range | 0.2 - 16.4 | | | |
| | typical | 5.2 | 300 | 0.5 | 32 |
| Siltstone | Range | 0.4 - 14.2 | | | |
| | typical | 4.7 | 600 | 0.6 | 25 |
| Laminite | Range | 0.5 - 16.4 | | | |
| | typical | 4.7 | 700 | 0.7 | 25 |
| Shale | Range | 2.0 - 14.9 | | | |
| | typical | 7.0 | 1200 | 0.8 | 25 |
| Wyvern | Range | 7.1 - 26.4 | | | |
| coal | typical | 19.8 | 2000 | 1.0 | 42 |

This table demonstrates the general weak and plastic nature of Collie sediments and also illustrates that coal strengths are in the order of 3-4 times greater than non-coal lithologies.

In terms of subsidence, the resistance to movement of non-coals is small, and thus there is the possibility that coal seams will deform differentially and lead to bed separations at coal contacts.

## SUBSURFACE SUBSIDENCE

A study by Singh and Kendorski (1981) defined four zones of strata behaviour vertically above an extraction panel (figure 2). Listed in ascending order from the seam these zones are summarised as :-

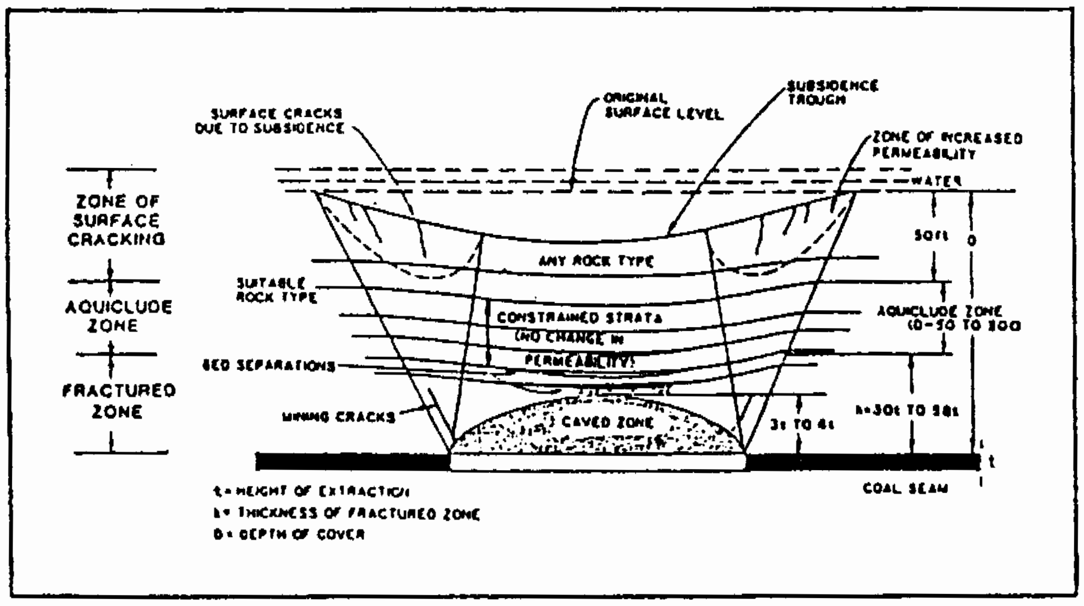
1. A caving zone; where the strata immediately above the seam caves and fills the void left due to extraction (by a bulking process).

2. A partly fractured zone; where the stratigraphic layers are supported to some extent by the caved rock below and allows this zone to sag without complete rupture.

3. A zone of constraint; where beds are sufficiently confined by strata above and below to prevent the development of open fractures.

4. A surface zone; where the uppermost layers are insufficiently constrained, and consequently are very susceptible to horizontal strain. Surface cracking is common. The estimated depths of fractures, from Reynolds, 1976 is generally confined within the first 20m.

Figure 2. Generalised Strata Behaviour With Total Extraction (After Singh & Kendorski, 1981).



## PREDICTION OF SUBSURFACE SUBSIDENCE EFFECTS ON AQUIFER SYSTEMS

Prior to early 1991, aquifers overlying total extraction panels were effectively drained prior to extraction. Drainage had taken place by one of two methods:-

i) planned dewatering/depressurising programmes via surface borehole pump bores and in-pit drainage holes above and immediately surrounding proposed extraction panels

ii) natural leakage via roof falls or fractured coal in surrounding bord and pillar and wongawilli panels,

Consequently, water inflows into the mine area have been manageable. The maximum water inflow in any panel was 7,000m$^3$/day. This was, however only a peak flow and quickly eased to a constant rate of 4,000m$^3$/day and can be regarded as the recharge rate into the caved area. It was postulated that the majority of water make came from aquifer 3, some 35m above the extraction level, however this could not be proven due to the extent and success of dewatering.

Since that time, it has become increasingly evident that to remove all ground water from above future, deeper extraction panels with greater initial heads of water, would be difficult to plan and very expensive. (Two years were spent on dewatering/depressurising aquifers above the first extraction panel in the Collie Basin.)

Consequently, the viability and planning of future extraction panels will depend on :-

a) timing of dewatering strategies,

b) the cost of dewatering.

In order to assess either of these points, it has become necessary to investigate the subsidence mechanisms in the Collie Basin sediments and the impact of subsidence on the complex aquifer systems of the region.

Therefore the question arises :- to what level is dewatering required in the upper aquifers to prevent groundwater influx into the underground mine workings ? If strata fracturing extends to a defined height above the workings (according to the strata mechanical properties) then dewatering above the limit of fracturing would be unnecessary.

Wardell, 1975 suggests that mine design be based on a limiting horizontal strain of 7.5mm/m at the bed of stored water in the Eastern coalfields of Australia, while the NCB recommends a limit of 10mm/m for the United Kingdom. This problem is clearly not well understood in any mining region.

Research carried out by Bhattacharyya and Gurtunca, 1984 suggested that to mine safely beneath bodies of water, the intervening strata should contain an adequate thickness of aquiclude (mudstones and clays which can absorb larger amounts of strain energy) free from open cracks and fissures as well as at least one bed with low permeability. Additionally, there should not be any geological anomalies such as faults, fissures etc, along which water may flow.

Application of such limiting strains to mining in the Collie Basin could preclude coal extraction of any form which initiates caving. Hence, the need for a detailed study.

## RESEARCH APPROACH

In all, eight extraction panels have been monitored for subsidence development to date. Subsidence measurements were taken at routine intervals using :-

- survey levelling of grouted pegs, installed in grid format above the panels for surface subsidence,
- borehole extensometers (with strategically located anchors at specific depths or heights above extraction) for subsurface subsidence monitoring.

A total of three extraction panels have been researched for subsurface ground responses to "total extraction" of coal by the Wongawilli method. Of these, only "Blue" panel results could be used in the investigation. (Ground movements in the other two panels were complicated by mining anomalies.)

A summary of the anchor movements at varying stages of panel development and heights above the extraction seam level is illustrated in figures 3 & 4. From figure 4, it appears evident that the degree of flexure above the position the panel edge decreased incrementally for sequentially higher anchors. This observation led to the premise that aquitard integrity could be dependant on the magnitudes of curvature.

It is well documented that strain is directly proportional to the curvature of the subsidence trough at the surface (e.g. Karmis, 1976). Assuming this is true, and that rock material can tolerate only a given amount of strain (as for all other materials) before yielding, then any rock can only withstand a definable amount of curvature before yielding.

**Figure 3** EXTENSOMETER ANCHOR MOVEMENT RELATIVE TO DATUM PLATE

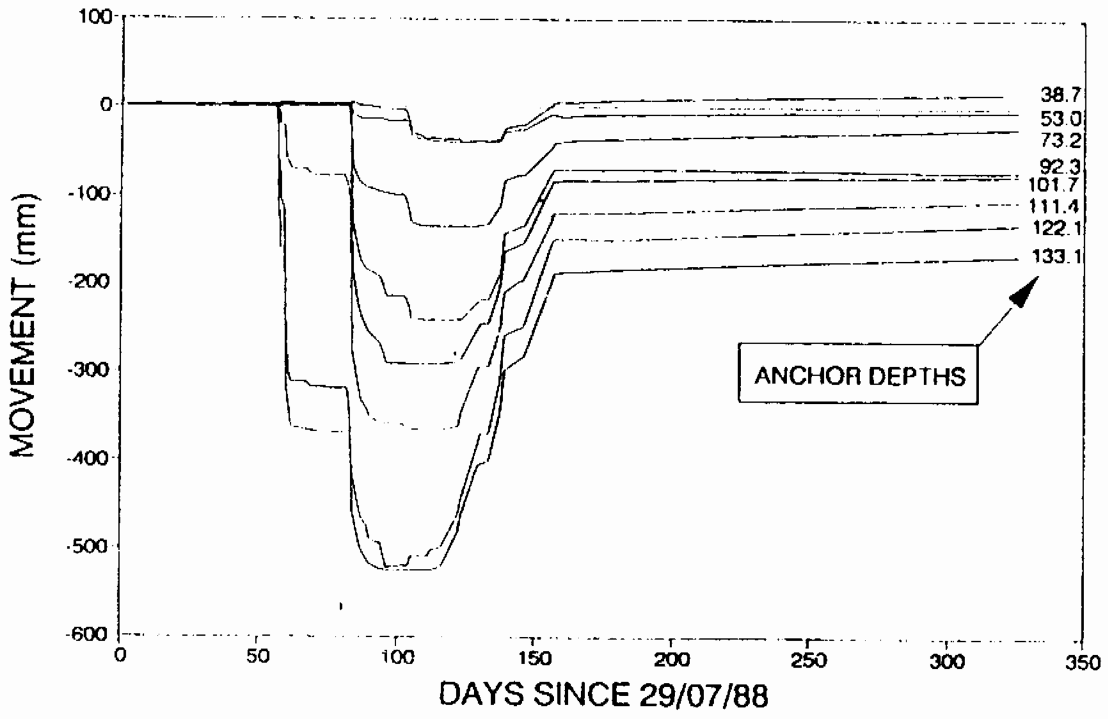
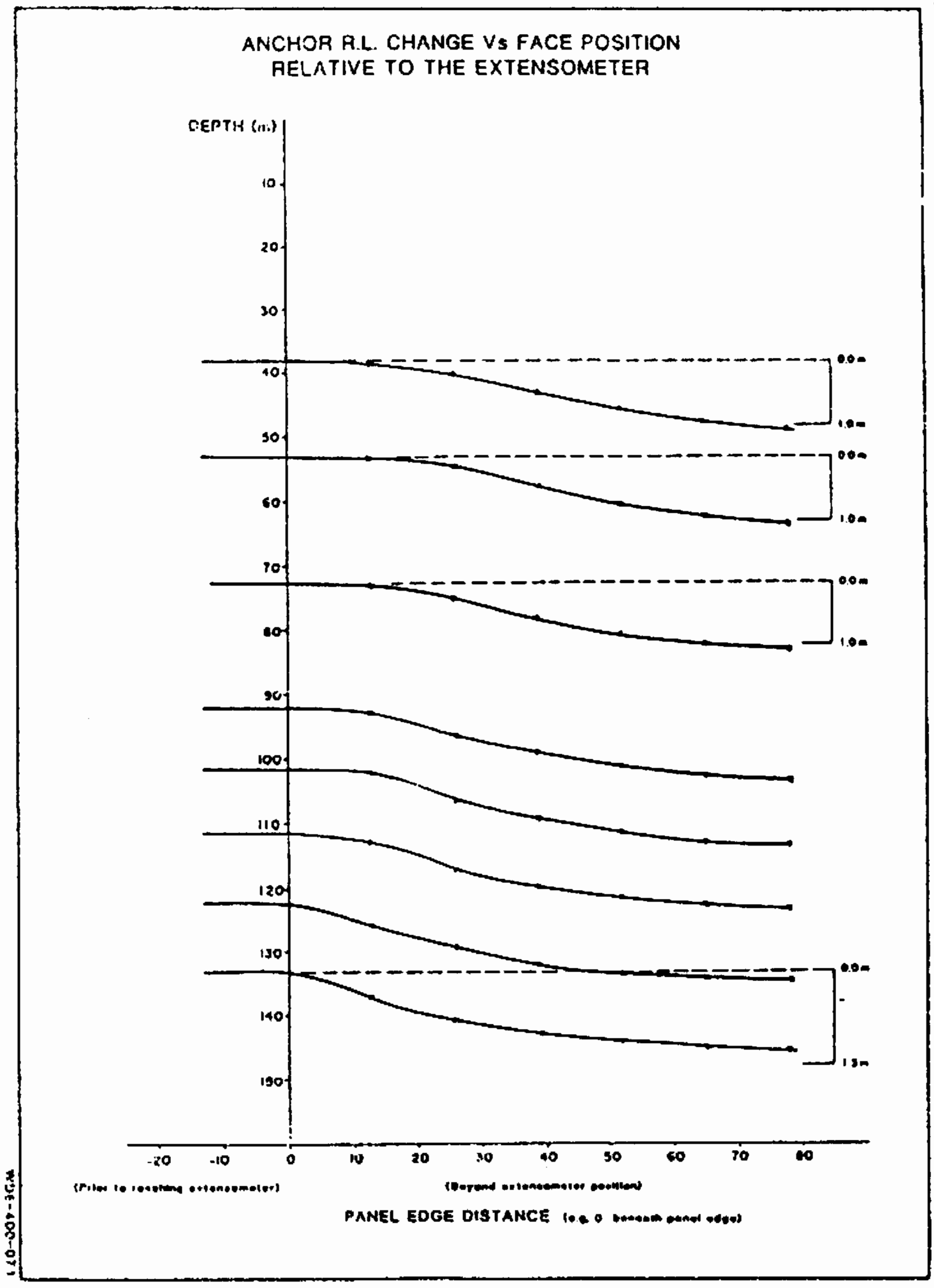


**Figure 4**



The relationship between curvature and strain is very site specific as it is very dependent on the local geological conditions. Karmis (1976) demonstrated large differences in the curvature - strain relationships between the United Kingdom and the U.S.A.. It is well established that the Collie Basin strata are unique. Consequently, it was necessary to develop a mathematical relationship between curvature and strain for the site specific Collie Basin sediments before this empirical technique for strain prediction can be attempted. The procedure adopted to determine the Collie curvature-strain relationship is summarised below.

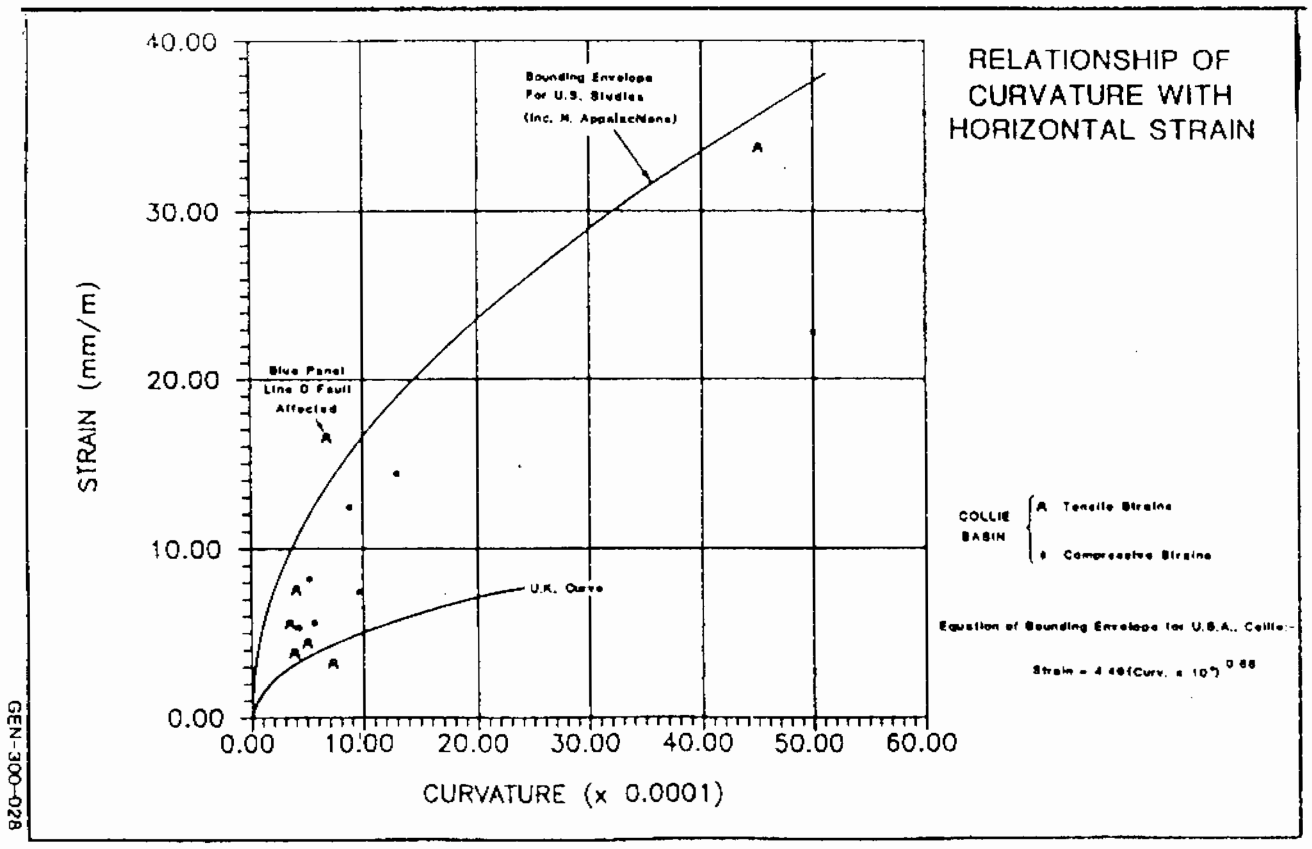
a) Curvatures at the surface were calculated by double differentiation of the curve fit equation which accurately represents the shape of the surface subsidence profile.

b) Maximum calculated curvatures for each profile were then plotted against measured maximum strains.

c) Using this plot, establish a mathematical relationship describing the bounding strain envelope for any given value of curvature. (It is necessary to take the bounding envelope because the exact position of maximum strain rarely coincides with the location of surface survey points.)

Figure 5 illustrates that the curvature-strain relationship for Collie conditions is very similar to that suggested for the U.S.A. by Karmis. Hence the U.S. curve has also been adopted for Collie Basin sediments.

**Figure 5**



## SUBSURFACE HORIZONTAL STRAIN PREDICTION

The approach adopted to predict subsurface horizontal strain was similar to that explained above (calculating curvatures from subsidence profiles and relating them to strain), however instead of using surface survey grids, extensometer anchors were used as datum points to plot the shape of the subsurface subsidence. Subsurface subsidence was plotted against distance from the goaf edge as the extraction panel develops. Polynomial lines of best fit were then adapted to each profile to enable the calculation of curvature.

To simplify prediction of subsurface strains, it was decided to :-

. assess only the maximum curvatures and strains.

. ignore the area of compression (as it is widely recognised that the tensile strains are responsible for damage to water resistant layers e.g. Wardell, 1975.)

(This approach appears valid, as it is only necessary to know the magnitude of the maximum tensile strain at the aquitard, the positioning of maximum horizontal tensile strain is not considered to be important.)

The next step was to attempt to develop a predictive method that will give maximum curvature at any level above an extraction panel. Two parameters were identified as having an influence on the shape (and thus strain) of each anchor subsidence profile:-

(a) The magnitude of maximum subsidence at any one level, which has a well defined relationship with surface subsidence.

(b) The height above the seam, as illustrated in figure 4 which represents the anchor-subsidence profiles for all extensometer anchors above extraction block "Blue Panel".

Using these two parameters, the technique adopted for the prediction of strain was to :-

i) plot calculated curvature (from each anchor's subsidence profile, as in figure 4 above) against measured maximum subsidence, normalised by height above the seam (figure 6), and

ii) fit a curve (polynomial algorithm), which represents the maximum expected curvature for a given subsidence at a certain height above the seam.

Again, a mathematical expression was developed for the bounding envelope of curvature. The equation adopted for this envelope is :-

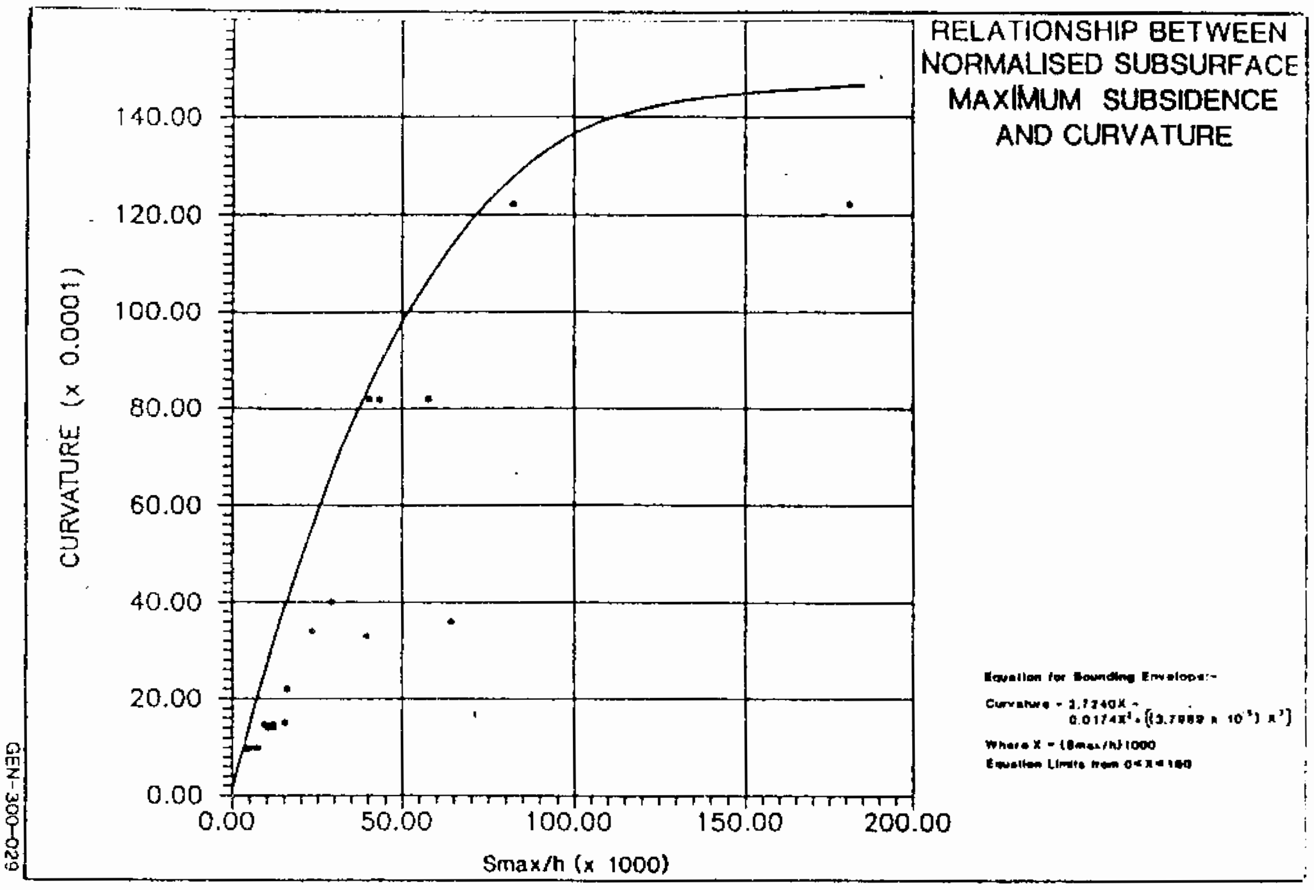
$$\text{Curvature} = 2.724X - 0.0174X^2 + [(3.80 \times 10^{-5})X^3],$$

where, $X = (\text{Smaxh}/h)1000$

Smaxh = maximum subsidence at height h above the seam

h = height of anchor/aquitard above the seam

Figure 6



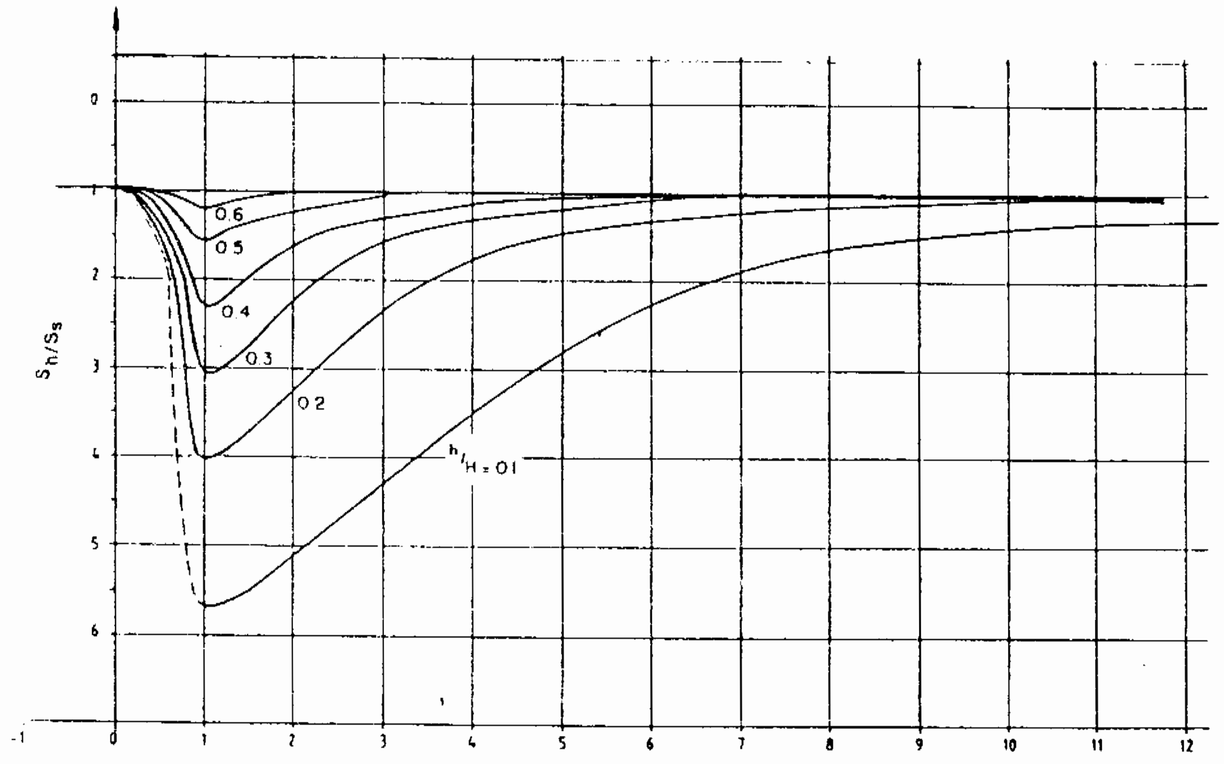
By being able to predict maximum curvature for a subsurface profile with a known maximum subsidence, the maximum horizontal strain may be estimated at any horizon above the extraction panel (assuming the relationship between surface curvature and strain is valid for subsurface movements).

In order to predict subsurface subsidence, measured extensometer anchor movements were analysed in detail. The following trends were observed :-

- subsidence was greater nearer the mined seam,
- the variation between subsurface and surface subsidence was greatest when the position of the anchor approximated the line of the angle of break (predefined as $17.5^0$ to the vertical) from the panel edge,
- as the goafed area becomes large, the difference between surface and subsurface subsidence reduces.

Figure 7 represents a normalised plot of anchor movements at differing heights above the seam for varying goaf edge positions in relation to the position of the extensometer. Each of the above mentioned trends are well illustrated in this figure.

Figure 7



Nomogram for Predicting Maximum Subsurface Subsidence

The X axis, Goaf-Extensometer Distance (GED) x Cotan(break angle)/h, represents the position of the anchor in relation to the position of the line of break at any horizon above the seam (h). The Y axis represents the ratio of subsidence at h (Sh) against surface subsidence (Ss).

Each curve on the graph represents an anchor position as a ratio of height above seam (h) to the depth of cover (H). When this ratio is small (nearer the seam) ground movements are far greater than surface subsidence. As the ratio approaches one (the anchor/aquitard is near the surface) the ground mass obviously moves in similar magnitudes to the surface.

The structure of the curves in figure 7 are such that subsurface subsidence magnitudes and profiles can be predicted at any stage of goaf development at any point above the mine (knowing the maximum surface subsidence). These predicted subsidences can then be used to estimate the maximum likely ground curvatures and ultimately the maximum ground strain at any horizon above the extraction panel.

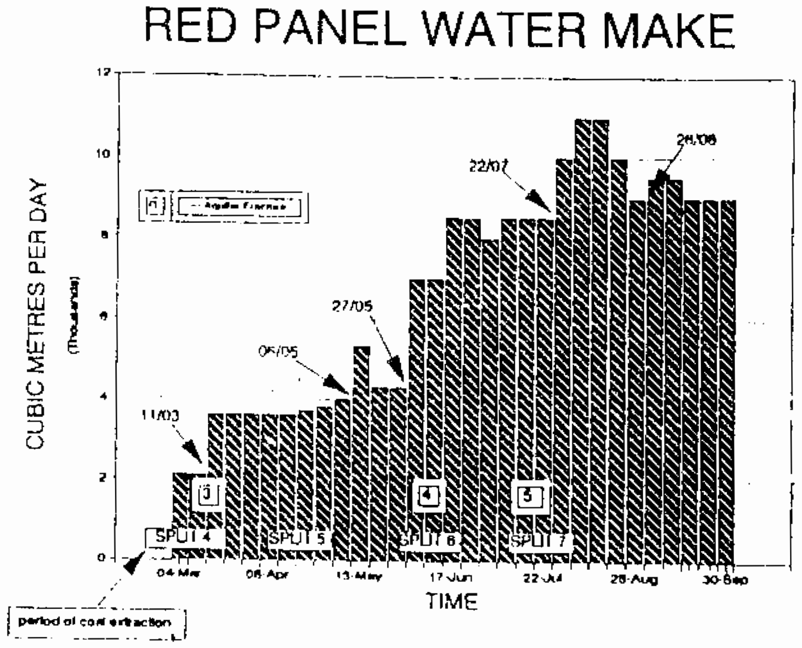
The impact of these strains on the integrity of superimposed aquitards may be estimated from known material properties. Existing laboratory tests on confined compressive strengths on aquitard materials indicate a yielding strain of 2.1%. It is reasonable to assume that when predicted strains exceed this laboratory limiting strain, aquitard rupture can be expected. (Three point bending strength tests better indicate the yielding strain due to flexure, however there is insufficient statistical data available to give in this paper.)

This method of prediction of aquitard response to the subsidence process in the Collie Basin was then cross-checked against the next extraction panel (Red panel) which, fortunately for the study, was not fully dewatered in aquifers 3,4 & 5 and was located in the same mining block as Blue panel. Aquifer 2 (in the immediate caving zone) was effectively drained.

A close check was kept on the water inflows into the panel (noting both the time of additional flows and the volume and rate of water ingress), and changes in standing water levels in piezometers located around the panel.

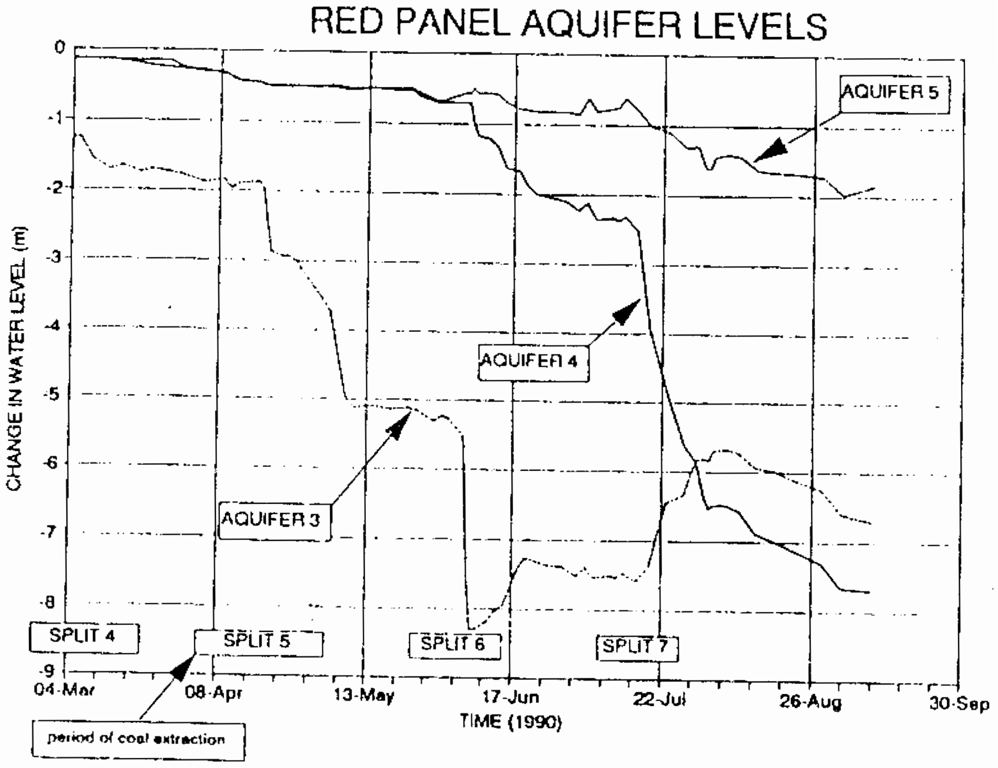
The results of the water level and flow monitoring are summarised by figures 8 and 9. It is clearly evident that water inflows from overlying aquifers were dependent on the width of the goaf (caved area of the extraction panel).

**Figure 8**



RED PANEL WATER MAKE

**Figure 9**



RED PANEL AQUIFER LEVELS

The timing of major events in water level and flow were then back analysed against the predicted curvatures and laboratory yielding strains. The results of back-analysis were very favourable. For example :-

> At an extraction width of 60m the predicted maximum subsidence is 0.12m (at 160m depth of cover and effective mining height of 2.4m). Using figure 7, with the middle of the panel (assumed extensometer position) 30m from the advancing goaf edge, the maximum subsidence at aquifer 4 (h = 55m) is 0.28m
>
> Using figures 6 and 5, with this amount of subsidence at this distance above the extraction seam the expected curvature related strain is 20mm/m, which compares well with failure strains in the laboratory. Predicted strains for aquifers 3 and 5 are 28mm/m and 8mm/m respectively. Both are confirmed by piezometer monitoring.

Therefore even if the aquitard is infinitely thin, unless it exceeds a limiting curvature within the subsidence trough, it should maintain its integrity. The important characteristic of aquitard material is its ability to tolerate curvature/strain.

The ramifications of these analyses to Western Collieries are severe. It is clear that depressurisation is necessary for at least aquifers 2 - 5 and there is a great possibility that other higher aquifers will require attention with wider panels or larger extraction heights.

## Summary of Predictive Method

The procedure to predict the maximum horizontal strain at any horizon above an extraction panel of any dimension and depth is to:-

(a) Determine the maximum surface subsidence using the nomogram developed by Misich in the 1989 internal report to Western Collieries LTD,

(b) Calculate the maximum subsurface subsidence at that particular height above the seam using figure 7.

(c) Determine the likely maximum curvature resulting from the maximum subsidence using figure 6.

(d) Calculate the potential maximum horizontal strain using the maximum curvature value from (b) in the expression or the graph derived in figure 5.

These predicted strains can then be compared to laboratory yielding strains to determine the potential for rupture of aquitard material.

It must be noted that this approach, due to the limited information available at present, has the following short-comings :-

i) Figure 7 represents the goaf - extensometer distance which means that there is already a substantial goaf adjacent to the extensometer. This will result in measurable subsidence with little or no goaf edge distance and consequently may not be valid for small panels. In order to solve for very small panels, one or two additional extensometers are required, sited between the middle of the panel and the panel edge.

ii) The maximum subsurface subsidence close to the seam should approximate mining to the height (have an S/T ratio of one). Two explanations for the small S/T ratios measured are:-

- that mining problems resulted in coal stooks being left beneath the extensometers which prevented full caving close to the seam.

- rilling of the adjacent goaf from the previous lift beneath the overhang at the abutment of the moving extraction edge.

iii) Variations in local stratigraphy, water pressure, and mining height cannot be accounted for.

iv) Data available to date has been limited to sub-critical width panels and the full extent of subsurface subsidence damage to aquifers is not known.

v) Yield strains are based on triaxial strength tests. It is possible that yield strains will change (due to changes in confining stress) on encroachment of the line of break. More information is required on yielding/bending strains and the effects of confinement.

## FUTURE RESEARCH AND CONCLUSIONS

Because extraction panels take quite some time to set-up and mine, and monitoring conditions are never ideal, the unknowns mentioned above must be solved analytically. Future research (currently underway) will combine sophisticated mathematical and physical (centrifuge) modelling along with additional detailed field monitoring to further develop existing assumptions and answer targeted questions. A brief summary of the research proposal and progress to date follows.

### Mathematical Modelling

Research on mathematical modelling packages available in Australia indicate that the most suitable computer program to the study is the MINCAD Systems developed program "SUBSOL".

Specifically, the three-dimensional programme SUBSOL has the following features:

- incorporation of surface/seam topography
- capability for modelling slip and separation on multiple parting planes
- incorporation of the detailed stratigraphy (unlimited number of material layers)
- modelling of isotropic and anisotropic material properties including non-linear seam properties and goaf models
- input of detailed mine plans such as panels, pillars and roadways, and
- can provide results for variable panel, pillar and cover depth conditions.

Once calibrated to Collie Basin conditions this model has enormous potential for prediction of aquitard curvature/strains at any level above the mined seam and for any mining situation.

## Centrifuge Modelling

The centrifuge modelling technique is the most effective and versatile method of producing realistic small scale model test data which can be related directly to a prototype situation. This is due to the fact that the behaviour of geotechnical materials such as soil and rock is very dependent on stress level. In a conventional model test, performed in the earth's gravitational field, it is not possible to maintain similarity with prototype situations and to ensure that the stress levels in areas of interest reach prototype values. A geotechnical centrifuge can subject small scale models to centripetal acceleration.

Under this increased acceleration field the self weight of the material being tested is increased by the same proportion by which the model dimensions have been reduced. This makes it possible to create full scale stress levels in the small scale model and ensure correct stress induced responses from the model.

With the acquisition of an Acutronic 661 centrifuge by the Department of Civil and Environmental Engineering, the University of Western Australia is now one of the few establishments worldwide (the only one in Australia) with the capability of performing geotechnical centrifuge model tests.

Future research will have the basic aim of evaluating the subsurface subsidence processes and influences on aquifer systems in the Collie Basin sediments :-

- at varying depths of cover (and stratigraphy),
- with and without saturated strata,
- using different mining techniques (e.g. no stooks, larger mining height)

Results from the centrifuge programme will be used to validate the mathematical analyses and vice versa.

A pilot study to assess the applicability of the centrifuge process to mining in the Collie Basin has proven the potential of this modelling technique.

All aims have been met by the pilot study:-

- A versatile mechanical system has been developed and proof tested which enables a variety of mining methods to be studied.
- Whilst only a limited amount of work has so far been undertaken on the feasibility of modelling site specific strata - i.e the Collie Basin sediments - it is clear that the use of artificial rock of any required strength can be reproduced by careful design of gypsum/sand/water mixtures.
- The response of the equivalent model materials to "mining" concur with measured and inferred ground movements in the prototype.
- Centrifuge model measurement techniques have proven successful.

Research into the prediction of surface and subsurface subsidence profiles and strains have proven very successful. A tentative method has been derived which can predict for any panel width the maximum subsurface horizontal tensile strains at any height above the extraction panel and hence the likely impact on aquifer systems.

It must be emphasised however that these predictive methods (with special reference to the subsurface movements) are based on limited information and will require updating as more data becomes available and all the mechanisms leading to surface subsidence in the Collie Basin become more evident.

The general approach used in this paper is valid and can be followed at other mining regions where :-

- the geology is consistent and has no major structural features,
- sufficient surface and subsurface field data exists to formulate site specific relationships.

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