Subsidence and Groundwater Management Through "Panel/Pillar" Mining in Western Australia

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ABSTRACT

Management of mining subsidence in the Collie Basin is of great importance, particularly with reference to: -

a) sensitive surface features, and
b) the high levels of groundwater present in the area.

Water inflows of up to 12,000m^3/day have been interpreted from individual "total extraction" panel pumping records to date, with potential for up to 30,000m^3/day groundwater to infiltrate into future panels from superimposed, pressurised aquifers. The need to be able to predict the magnitudes and effects of mining subsidence to manage these inflows or protect sensitive surface features such as haulage roads is obvious. In response, a research program was set up to firstly identify subsidence characteristics of the unique Collie Basin sediments, and secondly to develop a subsidence model which can be used to predict, and thereby manage mining subsidence and subsidence effects.

Extensive field monitoring from 1985 until the present has enabled the researchers to establish a sound database from which empirical models have been developed and used for predicting surface and subsurface subsidence in the Collie coalfields. These predictive charts have since put into practice, and coal is being extracted according to the subsidence tolerance limits for individual extraction panels.

The most effective method of subsidence management was achieved by the adoption of "panel/pillar" coal extraction methods where a series of sub-panels are mined by "Wongawilli" total extraction techniques, each being separated by individual "inter-panel" pillars. The design widths of both the sub-panel and inter-panel pillars are essentially controlled by the mining depth, superincumbent strata caving angle, and flexural properties of significant layers above the panel.

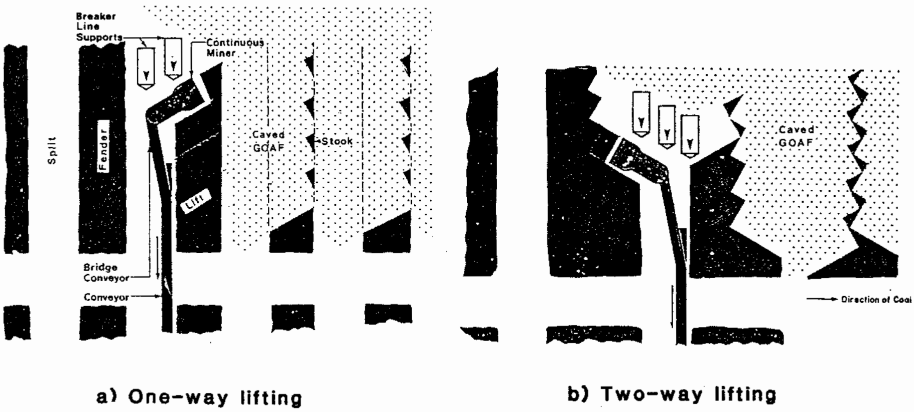
INTRODUCTION

The Collie Basin is located 200km south of Perth and is situated approximately 200m above sea level. Collie Basin coal can be classed as sub-bituminous, and is ideally suited for burning in power stations and other industries in Western Australia due to its low sulphur (~0.5%) and ash (~6%).

The very weak and water-saturated coal bearing sediments are of Permian age and have been preserved within a down-thrown Archaean rock basin of the Yilgarn Block [1]. This regional setting has given rise to a unique geological and hydrological mining environment - by both Australian and, arguably, world standards.

Hydrologically, the whole basin can be thought of as an inter-related groundwater system of interbedded silts, sands and clays separated vertically by a number of significant, extensive coal seams, bounded by comparatively impermeable Archaean basement. These saturated sediments have historically limited underground coal extraction to bord and pillar mining; in order to limit roof collapse and inflow of large volumes of concomitant groundwater into the mines. (Several coal mines in the past were abandoned due to excessive water ingress from roof and floor aquifers.)

In 1987, at the completion of favourable dewatering trials [2], total extraction (in the form of a modified Wongawilli method, Figure 1 - from Kapusniak [3]) was successfully trialled by Western Collieries LTD (WCL). As "total extraction" mining extended into more undrained areas, greater volumes of water were being handled by the mines. It became obvious that any benefits gained by total extraction of coal could be outweighed by pumping costs. This led to the establishment of a research project into subsidence characteristics of Collie Basin sediments with the aim of subsidence prediction and management.



(from Kapusniak [3])

Figure 1 Wongawilli method

Subsidence prediction/management has three benefits to WCL :-

i) for keeping groundwater ingress (and therefore pumping costs) and surface subsidence damage to a minimum,

ii) for discussion with respective government bodies, when planning extraction panels beneath significant surface features and any possible remedial actions at completion of coal extraction, and

iii) for producing coal at optimum extraction rates and costs, according to subsidence limitations.

There are basically two forms of subsidence in the Collie Basin :-

i) Deep subsidence: continuous trough-shaped subsidence , resulting from uniform bord and pillar mine collapse or total extraction of coal over a large area ; usually at a depth of more than 40m.

ii) Shallow subsidence: discontinuous forms of subsidence, where the surface is stepped; with a cover depth usually less than 40m. This form of subsidence, not being relevant to the paper, is not discussed here.

SUBSIDENCE MONITORING RESULTS AND EMPIRICAL MODELLING

Subsidence monitoring techniques used to form a sound database for empirical model development included :-

- EDM, aerial, and spirit levelling survey techniques for surface subsidence,
- Borehole extensometers, using mechanically installed wire-line anchors for detecting subsurface subsidence, and
- Borehole piezometers, V-notch weirs, and pumpage rates in the mine for groundwater movements.

Monitoring techniques proved successful for all panels (with the exception of aerial surveys) and allowed for the development of empirical charts and equations which could be used to predict the maximum surface subsidence and complete subsidence profile in the Collie Basin for any range of mining width, height and depth (Figures 2 and 3).

Both functions are a form of double exponential "growth-curve" with less than half the maximum subsidence at the point of inflection, a relatively uncommon feature for mining subsidence in most other mining regions. These equations supersede polynomial and single exponential equations used previously and can be used to predict tilts, curvature and strains at any point along the subsidence trough (as given by [4]&[5]).

These predicted subsidence parameters can then be used to predict the likely damage to surface and subsurface features as determined by each major coal mining country in the world. Some of the more accepted models for surface subsidence damage classification are listed in [6] & [7].

Figure 2 Maximum subsidence prediction

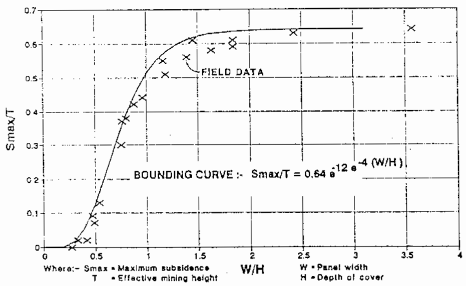
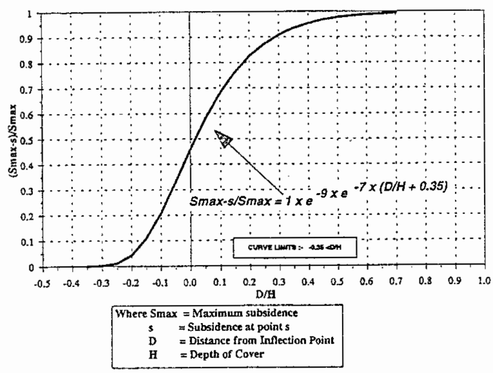


Figure 3 Subsidence curve profile function



The nomogram illustrated in Figure 4 relates the surface subsidence to subsurface subsidence at aquitard layers, for any height above the extraction level. Subsurface subsidence profiles derived from this nomogram can then be used to predict the aquitard strains and potential for aquitard rupture and likely groundwater influx from superimposed aquifers. This nomogram is only suitable for mining widths greater than 0.25 times cover depth - when surface subsidence is first manifested **[4]**.

From local experience, the viability of underground coal extraction using current mining techniques is severely hampered with water inflows greater than 2,000m^3/day. Water ingress from extraction panels, (typically 200m x 400m), can greatly exceed this value, depending on the depth of cover, actual panel dimensions and degree of saturation of superimposed aquifers. Groundwater inflows predicted from nomograms and laws of hydraulic gradients **[4]** suggested that in order to limit groundwater inflows below 2,000m^3/day in the panels remaining in the WD6 mine, and keep surface subsidence to less than 50mm, extraction had to be limited to widths less than 0.3 x cover depth.

Evidence from borehole extensometer monitoring during extraction of the first "research" extraction panel - 1North Panel - and small "trial" panels within the WD6 mine indicated that aquitard rupture would be minimised if coal was mined by panel-pillar methods, similar to that illustrated in Figure 5, adapted from **[8]**.

This approach to mine design can also be used for mines which have to protect public groundwater supplies or limit subsidence due to fluid withdrawal in urban areas. If the correct sub-panel and inter-panel pillar widths are selected, surface subsidence can also be controlled or prevented, if necessary.

Brauner implies that a blanket mining width/depth ratio of 0.25 can be applied with success, however in the Collie Basin, this design limit does not apply to all conditions when superimposed groundwater is the main concern.

Figure 4 Nomogram for predicting subsurface subsidence

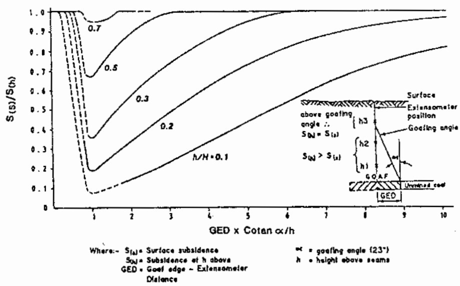
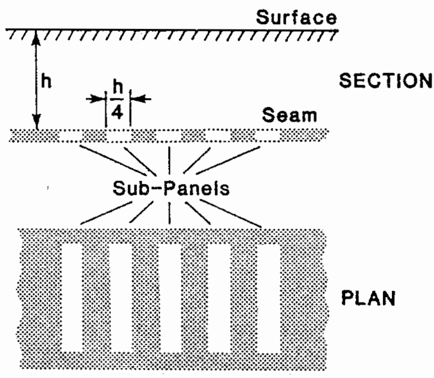


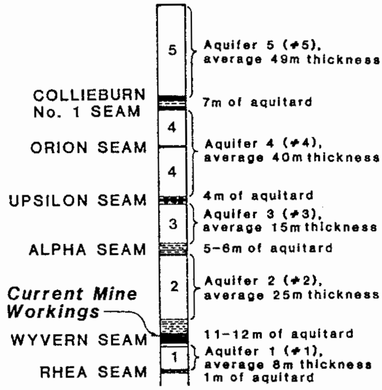
Figure 5 Partial extraction system



A mining width/cover depth ratio of 0.25 in deep workings will result in a large mass of unsupported strata, and consequential ground fracture, collapse and water infiltration from upper aquifers. (For example a panel at 300m depth, designed by Brauner's method would be 75m wide. The resultant caving - at the designated goafing angle of 23-24 degrees **[4]** - would extend more than 80m to three aquifers above. Groundwater ingress into the mine in this case would be intolerable.)

Consequently, it was decided to set-up a trial panel within the Western Collieries WD6 mine - North West B3 Panel - the second of the "research" extraction panels. The relevant design parameters for this panel were a cover depth of 145m with four superimposed aquitards. Figure 6 illustrates the typical hydrostratigraphy in the mine area.

Figure 6 Generalised stratigraphy



The panel-pillar extraction design was based on existing field data and fracture limit projection, calculated from the accepted goafing angle and the ability of the separating aquitards to both bridge above the collapsed area, and to tolerate bending and bending stresses. Panel design also accounted for the imposed restrictions on panel width and shape from previous mining in the area. The resultant design was to mine a series of five 40m wide sub-panels, separated by pillars 20m wide. (Due to operational problems, there was some minor variation from this design, as illustrated in Figure 7 however these variations did not adversely affect the project.)

Apart from the need to minimise subsidence induced water infiltration, WCL also had a requirement to protect a sealed haulroad, sited directly above the panel.

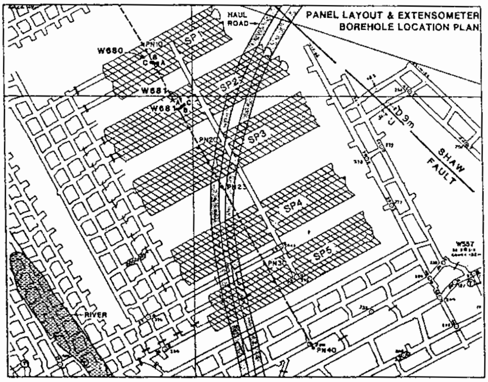
In order to evaluate the success of the trial panel, a number of monitoring facilities were set up, as for previous panels. The major variation from previous monitoring devices was the installation of both individual extensometer anchors and piezometers within the individual boreholes, targeting particular aquitards/aquifers, rather than installing separate multi-piezometer and multi-anchor holes.

The reasons for this novel piezometer and anchor installation were :-

i) to maintain the integrity of aquitards separating the four superimposed aquifers and thus prevent any groundwater leakage and ensure truly representative measurements of groundwater responses to mining;

ii) to minimise drilling costs.

Figure 7 Panel layout & extensometer borehole location plan



GEOTECHNICAL CENTRIFUGE MODELLING

It was recognised that empirical models established from the initial research program did not have the capacity to predict the degree of interaction of goafed material and sandstone above both the collapsed roof and inter-panel pillars (There was concern that interaction between individual sub-panels could greatly affect subsidence development and therefore result in significant rupture of major aquitards and give rise to intolerable surface subsidence for the sealed haulroad above the panel.) Due to the significant ramifications of any additional subsidence, it was decided to use geotechnical centrifuge modelling techniques to establish a mine model with the objective of qualifying the potential for this interaction.

It was decided to use physical modelling for investigation of inter-panel interaction (rather than mathematical modelling) because of :-

i) the inability of analytical models to accurately represent the caving process and goaf edge material characteristics,

ii) the success of previous work with centrifuge modelling during the early stages of the research project [9].

The centrifuge modelling technique is an 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 accelerations which are many times the earth's gravitational 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 better represent induced stress responses from the model.

The critical factor to the success of centrifuge modelling is the correct application of dimensional and material property scaling. Centrifuge scaling laws have been described extensively elsewhere, e.g. Stone *et.al* (1987). Consider a small scale geotechnical centrifuge model with dimensions - d_m; where the prototype dimensions (d_p) have been reduced 'n' times such that $d_p/d_m = n$. If 'n' is chosen as the gravity scaling factor, where the centrifuge model is operated at 'n' gravities and made from the same material as the prototype, then the basic scaling relationships associated with centrifuge models using actual prototype materials are as given in Table 1.

Therefore, if both the model and prototype materials are the same then the similitude of stress levels at corresponding points in the model and prototype will result in a model response directly analogous to that of the prototype.

TABLE 1.

Centrifuge Scaling Relationships.

Parameter	Units	Scaling Relationship
Gravity	m/s^2	n
Length	m	1/n
Stress	Pa	1
Strain	%	1
Force	N	$1/n^2$
Time$^+$	sec	$1/n^2$

\+ **This relationship applies to laminar flow processes such as consolidation.**

Early centrifuge modelling used intact blocks of *insitu* material, taken from goaf rill within the deep mines. These tests were necessary to assess the behaviour of 'real' material in a scaled centrifuge mode. Given the restrictions, of the size and weight of the centrifuge strong-box, these insitu material tests could only be applied to shallow depths. (Up to 80m cover given the current configuration of the UWA's Accutronic equipment.) In order to construct models representing greater depths of cover, and larger mining areas, it was necessary to manufacture equivalent materials models, scaled correctly to prototype materials' properties. Following an investigation into the techniques for fabricating equivalent materials, it was found that the most applicable materials were mixes of sand, water and building plaster.

The centrifuge model used to represent panel/pillar mining was then developed according to scaling laws assuming an operational G-force of 200 gravities. (The geometric scale factor was 1:300 model/prototype.)

To simulate the extraction of coal at depth, an assemblage of 18 hydraulic actuator units was designed and built and fixed in six rows of three (representing plane strain conditions through a slice of a panel of supercritical width). Each actuator is composed of a circular piston unit with a rectangular top cap. The plan dimensions of the top caps are 67.5 by 67.5 mm which represents a prototype area of 20 by 20 m. To represent the proposed extraction panel design, the "mining" steps were :-

i) lowering two adjacent rows of three pistons on the leading edge side (representing 40m goaf width),

ii) leave the third row of pistons (in succession) fully extended, and

iii) lower, again in succession, two more rows of pistons.

iv) The centrifuge test was then stopped, the strong-box sides dismantled and the model examined for fracturing characteristics and displacements.

v) Following examination , the strong-box sides were reassembled, and the model was again spun up to 200G where the sixth row of pistons was lowered.

These mining steps represent two sub-panels, separated by a 20m wide pillar. The first sub-panel scales to 40m wide in the prototype, the second sub-panel, initially also 40m wide, is later widened to 60m; to check the impact of mining wider sub-panels.

The strong box used for model tests is fitted with a perspex window through which deformations of the model can be observed. The actuator units have been designed to cater for the provision of stooks by allowing pillars to remain standing to support the overlying strata as the actuator is lowered. These stooks can be removed if not required - i.e for "Longwall" mining simulation. (Figure 8 illustrates the arrangement of the actuator units in the centrifuge strong box for earlier tests).

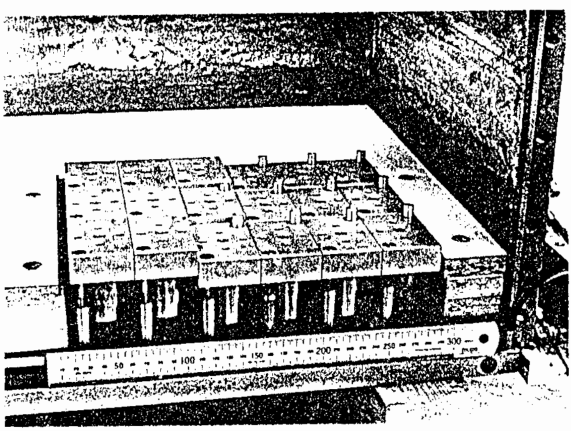


Figure 8 Actuator assemblage with stooks.

Each actuator unit is connected to a miniature solenoid valve which in turn connects to a manifold on the outlet side from which a connection to a fine metering flow control valve is made. Thus each actuator unit can be dropped individually or collectively at controlled rates set by the orifice of the metering valve. The control of the solenoid valves is performed by a computer.

Data collection from the models include :-

- load cells - adapted to the walls of the hydraulic pistons - to evaluate the redistribution of stresses on unmined "pillars" with "total extraction ".

- strain data on superimposed aquitards - from strain gauges glued to the surface of each aquitard.

- detailed mapping and measurement of the model once the centrifuge tests are completed.

To assist with data collection and identification of subsidence mechanisms, two miniature CCD cameras are mounted on the package. This makes it possible to record the sub-surface movements of the model via the perspex window and the surface disturbance of the model resulting from the dropping of the actuator units. An imaging system has also been developed which is presently capable of monitoring the real-time motion of up to eighteen discrete points visible through the strong box window. This system is also capable of back analysing video footage of the model tests to produce displacement records of visible markers.

The results from the centrifuge study largely supported previous design assumptions, with relatively small aquitard strains on all aquitards, with the exception of the first aquitard, (~35m above the extraction panel) where horizontal strains approached the ultimate failure strain of these materials (16-20mm/m); as established from laboratory testing. Furthermore, there was no evidence that interaction between separate goafs would connect the two collapsed areas above each sub-panel. (For interest, once the third row of pistons was dropped in the second "sub-panel" the magnitude of subsidence and strains greatly exceeded design tolerances.)

As a result it was decided to proceed with the mine extraction trial. (With the necessary safeguards installed in place should the unexpected happen.)

FIELD TRIAL RESULTS

Field data retrieved from this study suggest that design tolerances were met, and that monitoring and coal extraction methods worked well. The main points to arise from this information are listed below.

i) Surface subsidence has been limited to 35mm, which is only marginally above measured seasonal fluctuations in ground level (Figure 9).

ii) Water infiltration into the mine was kept below 600m^3/day (apart from a three week period when water inflow reached 630m^3/day, Figure 10).

iii) The integrity of coal/shale aquitards of aquifers 4 and 5 above the mine workings was kept in tact - no discernible change in water level was detected in these aquifers.

iv) The impact of mining a roadway into the barrier/inter-panel pillar between sub-panels 4 and 5 was minimal.

v) There is insufficient evidence to conclude whether or not ground movements have ceased, however given the very small magnitudes of subsidence to date, this is of no concern.

vi) There was no significant increase in load transfer to working faces in latter sub-panels.

vii) All caving/shearing was kept within the first sandstone aquifer (within 35m of the mining horizon).

viii) There was no road deterioration resulting from mining subsidence.

ix) The dimensions of the interpanel pillars appear to be more than sufficient to maintain safe mining conditions. Evidence exists which suggests that the width of these pillars can be reduced. Further work in this area (using geotechnical centrifuge modelling) is currently being finalised.

Figure 9 Surface subsidence NWB3 panel WD6 at the completion of each "sub-panel"

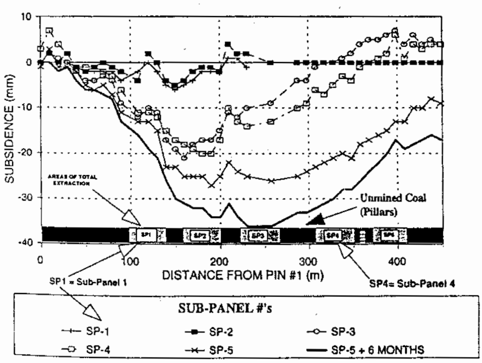
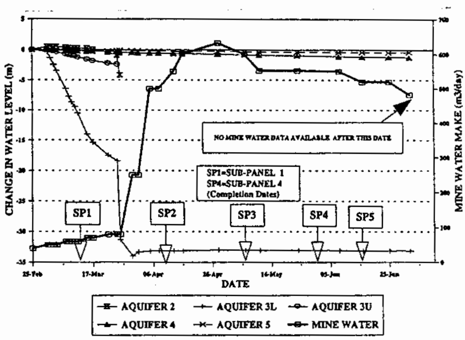


Figure 10 Change in SWL-piezometer W680/681 & mine water make-NWB3 panel WD6



CONCLUSIONS

Mining subsidence mechanisms and characteristics of the unique coal bearing sediments in the Collie Basin have been investigated and empirically based predictive subsidence "models" established for the continuous-trough-forms of subsidence in the Basin. During 1993, an opportunity to check the validity of these models arose, with the development of a Wongawilli total extraction panel in the Northwest B3 District of the WD6 mine.

A trial panel/pillar "total extraction" panel was designed for this area (based on these predictive models) to minimise:-

i) surface subsidence to protect a sealed haulroad, and

ii) subsurface subsidence to control groundwater inflow into the mine.

Physical modelling, using the geotechnical centrifuge at the University of Western Australia proved successful, giving supportive evidence for successful completion of the empirically derived trial panel design, and allowed the mining company (WCL) to plan the trial extraction panel with greater confidence.

Results from extensive subsidence and groundwater monitoring suggests that these relatively rudimentary predictive models are well suited to mining in the Collie Basin. The empirical modelling approach is seen to applicable to other mining regions.

ACKNOWLEDGEMENTS

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