SUBSIDENCE PREDICTION FROM THE BEGINNING -
COLLIE COAL BASIN (WESTERN AUSTRALIA)

By

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ABSTRACT

Surface subsidence resulting from "total extraction" of coal in the Collie Basin first occurred in 1967 when Western Collieries Ltd tried the Wongwilla mining method. Because very little quantitative subsidence data existed for the weak Permian sediments, a research program was set up prior to the extraction of the first panel. The objective of the study was to be able to predict subsidence characteristics and effects prior to mining future total extraction panels.

Attempts at predicting subsidence began using existing subsidence models from other coal mining regions, however, as more site information became available, it became clear that it was necessary to develop a separate, site specific predictive model for the Collie Coal Basin.

Analysis of extensive field monitoring data for both surface and subsurface subsidence has produced a series of empirical models which can predict the shape of surface subsidence troughs and corresponding lifts, and charts for rectangular panels and describe the sequences of ground movement from the mine roof through to the ground surface.

The fact that both subsurface and surface subsidence characteristics have held in well, gives greater confidence for predictions made from these models.

INTRODUCTION

Historical underground coal mining techniques in the Collie Basin were restricted to first workings due to the presence of overlying aquifers. Accordingly, surface subsidence in the Collie Coal Basin in the period from the first recorded case (at the Proprietary Colliery in 1902) to the mid 1960's, has been poorly documented and relatively uncommon.

Since then, increasing economic pressure for higher extraction rates has necessitated more efficient mining techniques (eg, the Wongwilla mining method) which promote large scale collapse of the immediate roof and often lead to surface subsidence.

With future extraction panels being located beneath important surface features, Western Collieries Ltd (WCL) recognised the need to be able to predict subsidence characteristics and effects prior to mining.

There are numerous publications on subsidence prediction, however, each study has been based on sit specific or regional empirical data. This can lead to large discrepancies between predictions from site to site.

Unless mining, geological and geomechanical conditions can be proven identical to other coal mining regions with well developed predictive models, it is probable that new mining areas will require their own, site specific subsidence model.

Consequently, it was decided to set up an extensive subsidence modeling program for the unique weak saturated Collie Basin sediments, (described in detail by Lord, 1952) to:

(a) Assess the applicability of the numerous subsidence modeling techniques used by many authors throughout the world, including Australia, and if required,

(b) set up a database to develop a unique modeling approach for the Collie Basin.

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REGIONAL GEOLOGY & HYDROLOGY

The Collie Basin sediments are mainly cyclic, high energy fluvialite sandstones with thin gravel and conglomerate lenses. Siltstones 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.

The whole Collie Basin can be thought of as an integrated groundwater system of Permian coal measures bounded by Archean basement, modified from Hamond, Masch & Boyd 1989.

Permeable aquifers comprise fine to granular quartzose sandstones with little to no fines content. Moderately permeable material consists of silty-cemented sandstones. Siltstones represent the low to moderately permeable aquifers; mudstone, shale and coal layers form the system aquitards.

All coal seams in the deep mines are bounded by aquifers. In some locations aquifers are situated directly above or below the seams, however, most areas have aquitard barriers of variable thickness separating the mining seam from neighbouring aquifers (Figure 1).

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, limestones). Each has a wide range of engineering properties, dependent 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>
<thead>
<tr>
<th>Lithology</th>
<th>UCS (MPa)</th>
<th>Elastic Modulus (GPa)</th>
<th>Cohesive Strength (MPa)</th>
<th>Friction Angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone</td>
<td>5.1-13.9</td>
<td>12.6-29.3</td>
<td>0.0-0.2</td>
<td>6-45</td>
</tr>
<tr>
<td>Shale</td>
<td>6.0-14.9</td>
<td>12.5-27.2</td>
<td>0.0-0.3</td>
<td>6-45</td>
</tr>
<tr>
<td>Limestone</td>
<td>5.5-15.3</td>
<td>15.0-35.0</td>
<td>0.0-0.5</td>
<td>7-34</td>
</tr>
<tr>
<td>Shale</td>
<td>6.0-14.9</td>
<td>12.5-27.2</td>
<td>0.0-0.8</td>
<td>6-45</td>
</tr>
<tr>
<td>Sandstone</td>
<td>7.0</td>
<td>15.0</td>
<td>3.0</td>
<td>6-37</td>
</tr>
<tr>
<td>Coal</td>
<td>7.1-16.6</td>
<td>40.0-120.0</td>
<td>0.0-2.0</td>
<td>6-45</td>
</tr>
</tbody>
</table>

Table 1

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 contact.

MONITORING APPROACH & METHODS

Due to the limited knowledge of subsidence characteristics in the Collie Basin it was decided to limit secondary extraction of coal to sections of the mine which did not have any significant surface features, and any fully saturated pressured aquifers which could impede mining.

Subsidence monitoring methods used were:

- Orthogonal subsidence grids of star pickets 1.5m long cemented into the ground surface. The chosen spacing was 5m for panels less than 100m deep and 10m for panels with depth of cover greater than 100m. Each picket was then surveyed at regular stages of panel development for vertical position to an accuracy of ±2mm.

The distances between each star picket (day lengths) were also measured (using a steel-reinforced fibreglass tape, again to an accuracy of ±2mm) in order to determine horizontal surface strains at each stage of mining.
o borehole extensometers in the centre of the panels with depth of cover greater than 60m.

These extensometers were open boreholes fitted with mechanical anchors, located at strategic horizons above the extraction panel. Each anchor had a stainless steel wire rope attached which was extended over a pulley at the surface and had a 10kg weight fixed to the other end.

Changes in the vertical position of these anchors were detected by:

(i) either manually measuring the distance between the hanging 10kg weight and a datum plate attached to the borehole casing, or automatically, using a data-logger to measure electrical output of potentiometers attached to the pulleys.

(ii) surveying the level of the surface at the extensometer site.

It was desired to monitor the subsurface subsidence for two reasons:

o to obtain quantitative data on aquifer movements above extraction panels, and

o to develop an understanding of what happens to the ground mass in sequence from the collapse of the immediate mine roof to final surface subsidence.

Prior to mining, an extensive literature search was undertaken for existing subsidence models and information from other mining regions. This was done to firstly obtain a rough estimate of the possible magnitudes of subsidence for the first extraction panels, and secondly, to assess the applicability of each method to Collie Basin conditions.

One further use of the existing subsidence models was to define the parameters WCL needed to measure during the monitoring program. Should existing subsidence models be found not applicable (as was expected to Collie Basin conditions), WCL would have sufficient data to formulate a model specifically for the region.

RESULTS OF SUBSIDENCE MONITORING

SURFACE SUBSIDENCE

Two generalised forms of subsidence were noted following extraction of coal during the study:

- Discontinuous subsidence, when the ground surface is ruptured in some form, and
- continuous subsidence, where the ground surface subsides in a gentle, continuous trough with few visible defects.

Discontinuous subsidence

The main forms of discontinuous subsidence observed were:

- Open cracks in the ground (millimetres to metres wide). These occur at the point of maximum tensile strain, usually above the edge of the extraction panel.
- Steps in the ground where the ground slides on inclined planes or falls away from the panel edge (millimetres to metres deep).
- Sink-holes (up to several metres wide and deep) where localised collapses in the mine workings extend to the surface. These features are steep sided and usually circular in form.

All forms of discontinuous surface subsidence have typically been limited to mine areas with less than 50m depth of cover where the strata is weak and provides little resistance to collapse.

Current mining practices limit high percentage extraction at shallow depths to panels superimposed by natural bushland (where the effect of surface subsidence is not important, and the surface area can be fenced off prior to rehabilitation.) When mining beneath sensitive surface features, the mine is worked to ensure the roof and pillars remain stable in order to prevent large scale collapse.

Mapping of discontinuous subsidence above the shallowest panel (35m depth) demonstrated that the sitting of discontinuous subsidence is mostly restricted to panel edges and toward the northern section of the panel. It was concluded that there was a definite correlation between sinkhole position and geology, as the near surface sediments in the northern section consist mainly of loose, weathered clays, with distinctive low vegetation cover and intermittent water bodies. The Southern section has lenticular outcrops, underlain by thick bands of fractured, plastic clays extending down to 15m beneath the surface which can absorb the strain energy and retard sinkhole development.

Furthermore, the depth of cover in the Southern area is up to 10m greater and the overburden may incorporate a stiffer clastic layer (which would be oxidized or weathered in shallow areas). This stiff layer can greatly retard vertical movements.

The probable explanation for the sink holes being located toward the panel edge is related to the fact that:

- this point represents the pivot point for a cantilevering of superincumbent strata across the panel edge towards the goaf.

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the perimeter of the panel is defined by a number of set-up roadways, which permit additional net of stabled material and reduces the bulking process.

However, although discontinuous subsidence can be related to site geology, the precise occurrence, frequency and magnitudes of this form of subsidence cannot be foretold.

Continuous subsidence
Continuous trough shaped subsidence occurred when the depth of cover exceeded 60m.

There is little visual evidence of this form of surface subsidence in natural bushland other than small tension cracks in the proximity of the panel edge.

The main characteristics of measured continuous subsidence troughs and their prediction are discussed in the following sections.

Maximum subsidence: The most subsidence measured to date is 1.4m above 2 South A Panel, WCI-6 mine. The precise positioning of maximum subsidence is usually toward the trailing edge (in the first group of lifts in the panel) and not in the centre of the panel.

The most common empirical relationship established for any mining area is the relationship between maximum subsidence (Smax) and effective mining height (T) and the panel width (W) and depth of cover (H) ratios. Where T is the product of the actual mining height and extraction ratio as used by Kapp, (1973). Attempts at adopting existing empirical curves to Collie Basin data were unsuccessful for all panel widths. (Figure 2).

Figure 3 below and an equation for the curve (derived using a modified hyperbolic tangent function, as used by Kaputskis for the Bowran Basin in central Queensland (personal correspondence), is also given in the diagram.

The Figure includes interim subsidence data from various stages of panel extraction. There is, therefore, some time related subsidence not accounted for, however, by taking the bounding envelope, this is minimized. The impact of time on these interim subsidence values is further reduced by the delay between mining cycles. (The time taken to form the next leading pillar by mining of the adjacent roadway.)

This empirical relationship is very useful for predicting other subsidence characteristics which are related to the magnitude of maximum subsidence, as discussed later.

Angle of draw: The angle of draw represents the angle from the vertical between the panel edge to a point on the surface where there is no measurable subsidence.

Due to seasonal fluctuations in moisture content of near surface clays, ground movement of 100mm have been measured prior to mining, and in areas well beyond the influence of mining. Consequently, 20mm has been used as the limiting subsidence value to determine the angle of draw.

In many cases, it is difficult to determine the exact angle of draw as it can be influenced by:

- seam dip,
- surface topography,
- pillar punching of set-up road pillars, chain pillars and mine splits adjacent to each panel, and
- natural/background movement of the surface.
- local geological variation and anomalies.

Where it was obvious that one of the above was
having a significant effect on the subsidence profile, the calculated draw angles at these points were ignored.

The mean value for angle of draw in all is 25°. The range of draw angles varied from 16° to 30°.

It would appear valid to assume a conservative angle of draw of 30° for Collie conditions (the maximum draw angle measured) when designing for very sensitive surface features. A limiting angle of 25° can be used for all other cases (assuming flat topography and seam dip).

**Inflection point**

The inflection point represents the position of maximum lift. Its location commonly coincides with the point of zero strain between maximum compressive and tensile strains near the panel edge. The location of the inflection point is often used in both nomogram and analytical methods to determine the shape of the subsidence profile. Holla, 1988, reported migration of the point of inflection according to the WHi ratio. Surface subsidence measurements in the Collie Basin, to date, suggest that the inflection point may be located at 0.17 x H from the panel edge for all panel widths and depths. This is noticeably nearer the panel edge than predicted by Holla for the Northern N.S.W. Coalfields, however, Southern Coalfield predictions compare closely for much of the curve.

**Prediction of subsidence profiles**

Prediction of the complete subsidence profile is necessary to be able to estimate subsidence effects at any point or surface feature along the subsidence trough.

The profile function was selected as the most appropriate technique for subsidence prediction because the inflection point was not located above the panel edge and lifts and curvature can be calculated directly from the curve-fit equation. Ground lifts can be calculated by differentiating the profile equation to obtain the change in vertical movement for a unit change of horizontal distance. Curvature at any point can be derived by differentiating the expression previously attained for lift (by double differentiation of the profile function). This expression effectively reflects the rate of change in slope (curvature) along the subsidence trough.

Furthermore, several researchers (eg, Karmis et al, 1985) state that horizontal strains can be predicted from curvature. Thus the profile function technique can be used for prediction of magnitude of relevant surface subsidence parameters at any point across the subsidence trough.

The approach used in defining a suitable profile function for the Collie Basin is similar to that of Karmis et al, 1985. Where necessary, they developed a new site-specific profile function for local conditions.

The process for selection of existing profile functions was to choose those which incorporate the major factors influencing the shape of subsidence profiles.

These factors, identified previously and given by research on subsidence in all other areas, have been incorporated. They are:

- depth of cover
- panel width
- effective mining height
- proximity to panel edge (specifically the inflection point)

Where existing profile functions did not explicitly relate to these parameters, (eg, the NGB curve) they were calculated for a standard width and depth (as in Whittaker and Reddish, 1989). All profiles were plotted against field data to assess their applicability to the Collie Basin. (Seam dip and topography effects have been discounted to simplify calculation).

After close scrutiny of the plots, it was clear that none of the existing profile functions accurately represented Collie Basin profiles for the entire length of the subsidence trough and that the unique Collie Basin sediments required a separate, site-specific profile function. The best fit to Collie Basin data was obtained using a hyperbolic tangent function as used by Karmis (1985) in the USA and Kapusniak (personal communication) in Central Queensland. The Collie equation is:

\[ S_{\text{m}} = \frac{1}{2}[\text{tanh}(2.5D/B)] \]

\[ S_{\text{m}} = \text{maximum subsidence derived from equation (1)} \]

\[ S_{\text{m}} = \text{subsidence at any point D (m)} \]

\[ D = \text{distance from inflection point, IP (m)} \]

\[ B = \text{distance between point of maximum subsidence and inflection point (m) (sometimes referred to as the critical subsidence radius)} \]

where the value 2.5 can be regarded as a coefficient for the curve fit, and

B can be expressed as a fraction of H,

\[ B = \frac{1}{2}(W-2P)/H \]

The coefficient 2.5 in this equation corresponds to values of 2.9 and 3.47 used by Karmis et al (1985), and Kapusniak respectively.

**Figure 4** illustrates the comparison between predicted and measured subsidence for 2 South A Panel in the WD6 mine.
Predicted Vs Measured Subsidence
South A Panel

It follows that by differentiation of the profile function equation above (with respect to $x$), ground tilt and curvature can be calculated simply from the following:

Ground Tilt $\frac{dx}{dt} = -\frac{3}{8} \mu \cos \theta \left( \frac{2 \sin \theta}{B} \right) \left( \frac{D(D/B)}{B} \right) (3)$

Ground Curvature $\frac{d^2 x}{dt^2} = \frac{6}{8} \mu \cos \theta \left( \frac{2 \sin \theta}{B} \right) \left( \frac{D(D/B)}{B} \right) (4)$

As mentioned previously, horizontal strain can then be calculated using the relationship of ground curvature and strain. Figure 5 illustrates the curvature-strain relationship for Collie conditions and is similar to that suggested for coal mining regions in the USA byгранинс (1985) and gives the equation used to calculate strain in the Collie Basin:

$\text{strain (mm/m)} = 7.2 \left( \frac{\text{curvature} \times 10^4}{\theta} \right)^2$

Relationship of Curvature with Horizontal Strain

This figure represents a plot of maximum measured strains against maximum curvatures for selected subsidence profiles. Consequently, calculated strains along subsidence profiles are artificially higher than field data. Work is continuing on developing a more representative predictive equation for horizontal strain.

It is interesting to note that although the properties of weak Collie Basin sediments differ greatly from the general characteristics of the coal measures in the Eastern Australian Coalfields, the form of the profile function is very similar to that used by Kapusnak (personal communication) for the Bowen Basin in central Queensland, as is the relationship of maximum subsidence with width to height ratio.

SUBSURFACE SUBLIENCE

A total of three extraction panels have been researched in detail for subsurface ground responses to 'total extraction' of coal by the Wengawan method. A fourth panel - 1 North B Panel also in the WC-8 mine is currently being monitored for surface and subsurface subsidence.

A summary of the Bule Panel borehole extensometer anchor movements (relative to the surface) at varying stages of panel development and heights above the extraction seam level is illustrated in Figure 6.

Extensometer Anchor Movement Relative to Datum Plate (Surface)

The main conclusions from subsurface data are:

- More subsidence occurs at deeper anchors
- The variation between subsurface and surface subsidence was greatest when the position of the anchor approximated the line defining the goaing angle (extracted from Figure 7 to be 23° from the vertical from the panel edge). As the goaing area becomes larger, (as WH ratios increase) the difference between surface and subsurface subsidence reduces.
- There appears to be bed separations at the base of each aquitard (determined from vertical strain peaks

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Results from other panels also indicate that there is an initial 'cone piece' collapse at the start of the panel. This collapse appears to be similar to the vertical collapse of mine roof strata once the self weight of the roof beam exceeds the beam strength. In the Wongawilli system, the strata tends to span across nearmaat steaks in the early stages of panel extraction. Only very localised roof collapse occurs at this stage, until the panel width is sufficient to totally collapse the upper strata. This is further supported by surface subsidence profiles where the maximum subsidence is commonly located towards the trailing edge. (No significant bulking would be expected with this type of collapse.)

After close scrutiny of these observed and measured trends, a chart was formulated which represents the sequencing of subsidence subsidence (Figure 8) as the panel edge passes beneath and moves beyond the position of the extensometer.

The horizontal axis, Goal edge-Extensometer Distance (GED) x Cotan (goal angle)\(^n\), represents the position of the anchor in relation to the line of goaling at any horizon above the seam (h), as illustrated in Figure 8. A ratio approaching one signifies that the anchor is in the vicinity of the angle of goaling leading away from the panel edge, and the subsurface movements are much greater than at the point on the surface directly above. The vertical axis represents the ratio of subsidence at h (S(h)) against surface subsidence (S(S)).

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 (tanner the seam), the ground movements are far greater than surface subsidence. As the h/H ratio approaches one (the anchor/aqueduct is near the surface) the ground mass obviously moves in similar magnitudes to the surface.

The structure of the curves in Figure 8 are such that subsurface subsidence magnitudes and profiles can be predicted at any stage of goaling development at any point above the mine (knowing the surface subsidence from equation (1) and (2)). 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 the support and aqueduct offsets may be evaluated from known material properties.

A tentative empirical procedure for estimating strains and aqueduct offsets in Cilico has already been established and reported (Mellick, Evans and Jones 1991). This paper gave a goaling angle of 17.2°, however, further information since suggests that this angle approximates 23° (as mentioned previously).

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One problem with this homogenisation is that for narrow panels (with \( W/H < 0.3 \)), subsurface subsidence may differ from ground movements measured adjacent to a significant extraction area (as has been the case with the positioning of the current extensometers). This question is being addressed at present, by setting an extensometer close to the panel edge.

**FUTURE RESEARCH**

The main line of future research will have the basic aim to further develop existing models in order to more accurately predict surface and subsurface subsidence and the effects on surface features and aquifer systems in the Collie Basin:

- for the range of mining depths and panel dimensions,
- with and without saturated, pressurised strata,
- using different mining techniques (eg. no stooks, larger mining height).

In particular, the caving processes at narrow panel widths will be assessed to define, more accurately, the effect of panel dimensions on aquifer systems.

Because extraction panels take quite some time to set up and mine, and monitoring conditions are never ideal, subsidence predictions for the complete range of mining conditions are often attempted to be solved analytically. Future research, currently underway, will combine mathematical (Minex System’s Subsoil) and physical modelling (using the University of Western Australia’s geotechnical centrifuge) along with additional detailed field monitoring to further refine existing models and knowledge on subsidence effects on surface features.

A recent geotechnical centrifuge model test, using inst Blue material worked well. The caving sequences, given by the lines of fracture are represented in Figure 9.

This figure illustrates:

- the first stage collapse, followed by cantilever goaling, as postulated above from field data,
- bed separation beneath the aquitard, also interpreted from field data,
- a goaling angle (at the trailing edge) of 23°,
- a low angle, curved goaling angle for the first four “lifts”

These features are better illustrated by photography at various stages of “panel extraction”. Some of the fractures at the front edge “skin” of the model do not entirely represent those further into the model.

Further quantitative assessments of this modelling method are currently underway.

**CONCLUSIONS**

Subsidence monitoring above “total extraction” panels in the Collie Coal Basin over the last five years has proven to be very successful. Field data obtained is of very good quality and demonstrated consistent trends after eight Wongawilli panels have been completed.

Two forms of surface subsidence have been identified during this program:

(a) discontinuous subsidence, and

(b) continuous subsidence.

Fracture Sequence above Extraction Panel in Geotechnical Centrifuge Model

**Figure 9**
Discontinuous subsidence, at first appearing to occur indiscriminately over shallow workings, can now
be shown to have a relationship with site geology.

Experimental and interpretive work indicate that existing predictive models are not totally applicable to
subsidence in the Collie Basin.

Following from this empirical data have been produced from which we can predict for the Collie Basin
continuous - trough - form of surface subsidence :-

- maximum subsidence
- the complete subsidence profile and associated til and strains.
- the manner in which subsidence is manifested through to the surface, as panels are developed
- indirectly the shape and magnitudes of subsurface subsidence profiles for uniform, continuous geological layers above extraction panels where WPH > 0.3.

Preliminary work on caving processes has demonstrated :-

- two types of collapse - firstly, a vertical, "roof beam" type, collapse which results in greater
  subsidence at the trailing edge of the panel, followed by a sequential cantilever, rotational
  type collapse.
- the sequence of fracturing above the extraction panel in the immediate roof aquifer.
- bed separations at the base of aquitards, as determined from bore measurements.

Work is continuing on more analytical models which may be used to predict subsidence for any
combination of conditions. Their validity will be checked against field data and empirical models established to date.

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