Subsidence prediction and management in the Collie coalfields (Western Australia)

IAN MISICH  
Department of Minerals and Energy Western Australia, East Perth, Western Australia 6004, Australia

ALBERT EVANS  
Collie Campus, Curtin University, Bentley, Western Australia, Australia

ODWYN JONES  
Brodie Hall Research and Consultancy Centre, Curtin University, Western Australia, Australia

Abstract: Extensive field monitoring from 1985 to 1994 has enabled the researchers to establish a sound database from which empirical models have been developed for predicting surface and subsurface subsidence in the Collie coalfields. These predictive procedures have been successfully used to efficiently design coal extraction panels and thereby manage ground subsidence with respect to subsidence tolerance of specific superimposed features both on the surface and subsurface.

INTRODUCTION

There are basically two forms of mining induced subsidence in the Collie basin:  
(a) Discontinuous or stepped surface subsidence (at typically <40 m cover) resulting from all forms of coal extraction. This form of subsidence has been discussed in detail by Misich et al. (1993) and is not discussed in this paper.

(b) Continuous trough-shaped subsidence (at typically >40 m cover), caused by extensive pillar collapse in board and pillar mining or one of many "total" extraction systems.

Continuous trough-shaped subsidence can be manifested in a number of ways (as illustrated in Fig. 1), and can have significant effects on superimposed features and can, in some cases, preclude the use of certain coal extraction techniques. It is therefore essential to be able to predict and manage ground subsidence for any mining scenario. This paper describes the prediction methods and mine design techniques used following research of the subsidence characteristics of the Collie coalfields sediments in Western Australia.

SUBSIDENCE MONITORING RESULTS AND EMPIRICAL MODELLING

As mentioned previously, an extensive subsidence monitoring programme has been underway since 1985 to establish a sound database for the development of empirical predictive subsidence models. The subsidence monitoring techniques involve the use of
Fig. 1 Illustration of the basic modes of mine subsidence development. (a) Elastic mine roof convergence. (b) Foundation-type bearing failure of roof or floor materials. Floor "punching" illustrated. (c) Mined pillar collapse resulting from excessive vertical/tributary load. (d) Superincumbent strata pillar collapse. Caving on either side of a mine pillar can form an irregular shaped column of material which is susceptible to failure from excessive loads. (e) Total extraction. Many mining methods can be grouped into this classification. Some methods can leave up to 20% of mineable resource unmined.
various survey methods to record the movement of specific survey stations; borehole extensometers (using mechanically installed wire-line anchors) for detecting subsurface subsidence; and borehole piezometers, V-notch weirs, and mine-water flow meters for monitoring groundwater movements.

These monitoring techniques were used successfully in all panels and enabled the development of empirical charts and procedures which could be used to predict the complete surface subsidence profile in the Collie basin for any range of mining width, height and depth. These predictive models, based on curve fitting equations for ease of calculation, are well described by Misich et al. (1993). These equations can be used to predict tilts, curvature and strains at any point along the subsidence trough (Misich et al., 1994). In turn, the predicted subsidence parameters can then be used to predict the likely damage to specific surface features. Some of the more accepted models for surface subsidence damage classification are listed in the National Coal Board (1975) publication, and by Peng (1992).

Subsurface subsidence at any height above the excavation can in turn be estimated using the nomogram illustrated in Fig. 2 which relates the surface subsidence to subsurface subsidence at aquitard layers, at any height above the mine workings. Subsurface subsidence profiles derived from this nomogram can then be used to predict the aquitard strains and the potential for aquitard rupture and likely groundwater inflow to the mine workings (Misich et al., 1991). This nomogram is only suitable for extraction panel widths (W) greater than 0.25 times cover depth (H). For narrower extraction panels (when \( W/H < 0.25 \)); where surface subsidence cannot be distinguished from survey error or natural ground movements, aquitard rupture/cracking begins when the "unsupported span" (as illustrated in Fig. 3) of the aquitard typically exceeds 5 m. The length of the unsupported span is calculated by plotting the angle of break from both

![Fig. 2 Subsurface subsidence prediction nomogram. (To be used for panel widths > 1/4 mining depth.)](image-url)
panel edges to the position of the aquitard and calculating the distance between the intercepts.

The effect of various "unsupported aquitard spans" on aquitard integrity depends on the geomechanical properties of, and large scale geological discontinuities in the superimposed strata and in particular the aquitard itself. For example:

(a) massive, strong sandstones can span very large distances (however it is likely that these lithologies will only significantly affect the subsidence profile near the caving zone) and minimize subsidence magnitudes and effects, and

(b) very soft, plastic strata — usually weak clays — can absorb large strain energy and have the capacity to "re-knit" with minimal confining pressure, thereby maintaining the integrity of the aquitard;

(c) weak overburden material forming the caved overhang which supports the base of bridging aquitards can crush; thereby increasing the unsupported span. In this case the panel width is limited by not allowing the projected caving angles to intersect at or above the position of the aquitard. The design width for panels located below these weaker sediments (as in Collie) is 10 m less than the maximum allowable width for stronger sediments.

Assuming that aquitards are usually composed of interbedded coals, shales, siltstones and sandstones it is reasonable to assume that some other mining areas will experience similar conditions to those prevailing in the Collie basin.

Concurrent with subsidence monitoring and modelling, the researchers investigated various mining and mine design methods for controlling subsidence and developed criteria for the design of extraction panels. This research is summarized below.
SUBSIDENCE MANAGEMENT — MINING METHODS

Subsidence damage to surface and subsurface features most commonly results from a change in ground curvature and corresponding strain. It therefore follows that if this curvature (and indirectly the maximum slope of the subsidence trough — Misich, 1996) can be controlled, then concomitant ground effects will also be managed. Two basic methods have been identified which can be used to reduce the curvature of subsidence troughs:

(a) reducing maximum subsidence ($S_{\text{max}}$) and/or
(b) softening the "sharp" subsidence profile above the edge of extraction panels (e.g. by leaving "yield" pillars immediately adjacent to the extraction panel, or in thick seams — by mining successive strips of coal with vertically and inwardly staggered edges).

The design and application of each of these techniques will vary according to the geological and geotechnical characteristics of the strata in each particular mining area. In the Collie basin, the most appropriate method for managing subsidence was to reduce the maximum subsidence with the adoption of the panel/pillar "Wongawilli" extraction method as illustrated in Fig. 4.

![Fig. 4 Panel/pillar mining concept (adapted from Brauner, 1973).](image)

**Fig. 4 Panel/pillar mining concept (adapted from Brauner, 1973).**

SUBSIDENCE MANAGEMENT

After identifying that panel/pillar mining was the best suited mining method for subsidence management, it was decided to set up a trial panel/pillar extraction panel in the NWB3 area of Western Collieries' WD6 mine. The following (successful) stepped approach illustrates the design methodology used for this panel.

(a) Establish the **maximum extraction width** according to superimposed features. The first task is to obtain all relevant information about the superincumbent strata and superimposed surface features and establish subsidence tolerance limits for anything needing to be safeguarded against subsidence damage. For example, the trial panel had a requirement to protect both a sealed open-pit haulroad sited 145 m directly above the panel and the aquitard immediately below aquifer 3 (35 m above the mine workings — see Fig. 5). (Aquifers 1 and 2 were largely depressurized by previous
mining activity around the panel.) Thus the first issue needing consideration was the safe upper limit of surface subsidence for the protection of the haulroad and its drainage features (selected to be 100 mm). Using the $S_{\text{max}}$ prediction "Growth Curve" as developed by Misich et al. (1994), the maximum panel width allowable to limit $S_{\text{max}}$ to less than 100 mm is 55 m.

The second issue of importance was the need to protect the mine workings from water inundation from aquifer 3 by restricting the panel width so that the unsupported span of the protective aquitard does not exceed a critical width. (Historical evidence indicated that an unsupported aquitard span in excess of 5 m began to develop open cracks along cleavage planes and that a 10 m span always led to failure of similar aquitards.)

Therefore, using the unsupported span/fracture angle concept (Fig. 3) described previously, the maximum allowable extraction panel width ($W_{\text{ext}}$) is calculated by:

$$W_{\text{ext}} = 2h \tan \alpha \pm 5 = 25 \text{ m}$$

(1)

where $\alpha$ = angle of fracture (23°), and $h$ = height of aquitard above the panel (35 m); +5 is used for strong interburden and −5 is used for weak interburden.

It follows therefore that the maximum width of extraction had to be designed in accordance with the need to protect the closest aquitard.

In the case study, the resultant panel design also had to take account of the imposed restrictions of previous mining in the area which effectively defined the shape and size of the extraction panel, and also the need to satisfy management’s production requirements which previously were dependant on mining 6 m wide "splits" and 7 m wide "fenders", lifted on either side each split. Consequently, the final panel layout incorporated 40 m (2 x 20 m) wide sub-panels, separated by 20 m wide intra-panel pillars and included drainage and sump facilities to accommodate the expected inflow of groundwater into the workings from aquifer 3.

(b) Establish the minimum intra-panel pillar widths to ensure (i) safe mining conditions for mine personnel and (ii) prevention of collapse of coal and/or superincumbent
strata which would result in an increase in final subsidence and, in turn, potentially damage superimposed surface and subsurface features and result in a major inflow of water into the mine. Similar increases in subsidence would result if the coal pillar abutment loads were to exceed the roof or floor bearing capacity causing the pillars to "punch" into the roof or floor strata. The intra-panel pillars must therefore be designed for long-term stability for the whole "pillar system".

Firstly, a suitable design Factor of Safety ($FOS_C$) had to be adopted for the design of the intra-panel coal pillars which ensures the required long term stability of the complete pillar support system. The $FOS_C$ of mine pillars being given by:

$$FOS_C = \frac{\text{pillar strength}}{\text{pillar load}}$$

This approach is supported by the comprehensive investigation into design coal pillars in the South African coalfields by Salamon & Oravecz (1967) which led to the conclusions that a design $FOS_C$ of 1.6 is acceptable in most situations but that a $FOS_C$ of 2.0 be adopted for pillars between development entries.

In the trial case study, because pillar width was preselected to be 20 m, it was necessary to check that the corresponding $FOS_C$ was of sufficient magnitude to take into account the potential collapse of the weak overlying sediments. Intra-panel coal pillar strength for the Collie basin was calculated using a modified Hustraldid/Salamon-Munro/Wagner (Bieniawski, 1982; Wagner, 1980) pillar strength design criteria as described by Misich & Humphreys (1988). The pillar strength ($PS$) and pillar load ($PL$) are calculated by:

$$PS = k \frac{(W_{eff}/W_o)^{0.46}}{(T/T_o)^{0.66}} \text{ (MPa)}$$  
$$PL = \frac{(A + B + C) \gamma \cdot 10^{-6}}{W_p} \text{ (MPa)}$$

where, $A + B + C$ are tributary load components per extraction widths (see Fig. 6); $\gamma$ = unit weight of superincumbent strata, MN; $W_o, T_o = 1$ m; $W_p$ = pillar width, m; $k =$ compressive strength of 1 m$^3$ of coal, which in Collie is estimated to be 6.5 MPa; $T =$ mining height/thickness, m

$W_{eff}$ (effective pillar width) = $4 \frac{A_p}{C_p}$ (Wagner, 1980), m

where, $A_p =$ pillar area, m; $C_p =$ pillar circumference, m.

Using this approach for the trial case study, the calculated $FOS_C$ for the 20 m wide intra-panel pillar with 40 m sub-panels on either side was 2.2 which was accepted as being adequate for preliminary design. For situations where the mine planner has more design options for intra-panel pillars, the coal pillar width for a designated $FOS_C$, suitable for local conditions, can therefore be calculated by:

$$FOS_C \gamma H + FOS_C \gamma H \frac{W_{ext}}{W_p} = \frac{k}{T^{0.66}} \left(4W_p \frac{L_p}{2W_p} + 2L_p\right)^{0.46}$$

where, $L_p =$ pillar length, and $W_{ext} =$ extraction width.
The proposed design $FOS_c$ for intra-panel coal pillars at Collie is discussed below. As mentioned previously, it is also necessary to design the coal pillar width to have sufficient bearing area so as to prevent failure of the roof and floor material. The design criteria adopted for the Collie basin sediments was a modified Terzaghi/Hansen formula (Scott, 1980; and Stacey & Page, 1986) with a design Factor of Safety against bearing failure ($FOS_B$) of 3.0. The $FOS_B$ is calculated by:

$$
\frac{Q_{ult}}{PL}
$$

(7)

where:

$$
Q_{ult} = cN_c + qO + \gamma 0.5WpN_q
$$

(8)

and $c$ = cohesive strength, kPa, and $N_c$, $N_q$, and $N_q$ are functions dependent on frictional properties of the roof or floor material.

In the case study, with floor material properties (being the weakest), of $c = 200$ kPa and phi = 30°, the resultant ($FOS_B$) for a 20 m wide intra-panel pillar is well in excess of the design limit of 3.0 for bearing failure; which further supported the use of 20 m wide intra-panel pillars.

**FURTHER STUDIES**

Due to the concern for rupture of the "undisturbed" weak column of sandstone above the designed coal pillars, it was decided to conduct two geotechnical centrifuge tests on scaled models of the extraction system to examine the potential for such an event occurring. Centrifuge modelling is an effective and versatile method of producing realistic small scale model tests 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 largely dependent on stress levels. In a conventional model test, performed in the earth's gravitational field, it is not possible to maintain similarity with prototype situations whilst ensuring 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. This makes it possible to better represent full scale stress levels and thus ground response in the small scale model, and in particular the goafed material which is an important part of the subsidence processes.

The first model (run immediately prior to extraction of the trial panel; to further test the proposed use of 20 m wide intra-panel pillars) was scaled directly to 1/300 of the dimensions of the prototype extraction panel given earlier. The results from this test largely supported previous design assumptions that relatively small strains occurred in all aquitards, with the exception of the first aquitard where horizontal strains approached the ultimate failure strain of these materials (1.6 → 2.0 mm m⁻¹ as established from laboratory testing). This centrifuge test also proved that no measurable subsidence developed, and that no interaction between the separate goafs on either side of the pillar occurred. This evidence gave the researchers greater confidence in the proposed design for the trial panel/pillar extraction panel.
The second geotechnical centrifuge test modelled a 13 m wide intra-panel pillar with two 40 m sub-panels on either side at 104 m depth of cover. The mining height adopted for this model was artificially high – 4.3 m. This model demonstrated emphatically that a large scale collapse of the "undisturbed" superincumbent sandstone column was possible and should be taken into account for coal pillar design. This collapse resulted in an increase in overall subsidence from very little to greater than 60% mining height at 50% cover depth above the intra-panel pillar. This test demonstrated that a major collapse occurred immediately after "extraction" of the first of the two 20 m wide "lifts" in the second of the 40 m wide sub-panels. It is thought that the timing of the collapse is critical to this event occurring and has been attributed to the point in time when minimal confinement is provided by first caving at the newly goafed edge of the intra-panel pillar. This lack of confinement thereby allows the superincumbent sandstone column to shear toward this, initially, unconsolidated goaf.

It is proposed that the stability of this "undisturbed" column is also influenced by the height of first caving and the rock mass strength of the superincumbent column of strata between the two areas of collapsed ground. However, at this stage, neither of these variables can be defined well enough to be used for design purposes in all mining conditions.

**TENTATIVE DESIGN $FOS_C$**

It has already been established that a design $FOS_C$ of 2.2 is adequate to maintain stability of the entire pillar support system between the two fully goafed 40 m wide sub-panels.

---

**Fig. 6 Illustration of shearing of triangular wedge at the goaf edge and tributary load. This momentarily results in a rectangular shaped pillar which is useful for calculation of required pillar dimensions.**
however the precise lower limit for the design $FOS_c$ has yet to be determined. In order to assist the definition of a design $FOS_c$ for the intra-panel coal pillars for narrower or wider panels, in ground conditions similar to those existing at Collie, the following points are listed:

(a) It has been demonstrated that major failure can occur with limited extraction on one side of the pillar and large scale extraction on the other. It follows therefore that the pillar design $FOS_c$ must be calculated for this worst case scenario.

(b) It is postulated that in cases where large goafed areas exist on both sides of intra-panel pillars — in this case 40 m or more each side — the constraining pressure provided to both the superincumbent sandstone column and coal pillar by the goaf material will increase the apparent strength of the pillar.

(c) Through back-analysis of the trial panel, the resultant $FOS_c$ with a fully collapsed goaf on one side and first caving on the other side of the pillar is 2.6. After back-analysis of the failure of the 13 m wide superincumbent sandstone column with a 4.2 m mining height, in the second centrifuge test (when failure occurred with a 40 m goaf on one side and a 20 m goaf on the other side of the intra-panel pillar — see Fig. 6); the resultant $FOS_c$ of the coal pillar was 1.2.

Therefore, taking these points into consideration, and in the absence of further testing, it is suggested that a design $FOS_c$ of 2.5 be used when designing for the long-term stability of intra-panel coal pillars below weak sediments of similar nature to those existing in the test panel.

CONCLUSIONS

Mining subsidence mechanisms and characteristics of the unique, weak and water saturated coal bearing sediments in the Collie basin have been investigated both in the field, and laboratory. Empirical predictive subsidence "models" have been established from these investigations and design criteria established which have been successfully used for subsidence management through panel/pillar mining. It has been established that in conjunction with the need to limit mining widths to control subsidence, it is also essential to maintain the permanent stability of the supporting column of strata between the sub-panels. Failure to keep this supportive strata intact will result in the large scale collapse of this material and therefore the development of significantly more subsidence than is desired.

Acknowledgements The authors wish to thank Western Collieries Ltd and the Minerals and Energy Research Institute of Western Australia for their support and encouragement for this project. The views expressed in this report represent those of the authors and are not necessarily the same as those of the Company.

REFERENCES


