Validation of a Subsidence Prediction Approach of Combined Modelling and Empirical Methods

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Summary

Subsidence prediction is often required outside the limits of empirical databases where we look to other methods to expand our understanding of overburden caving and subsidence effects. Computer modelling, through simulation of rock failure and overburden caving, provides a means to extrapolate beyond current experience and to investigate other aspects of caving processes that are becoming increasingly important; aspects such as multi-seam interactions, irregular overburden geologies and groundwater interactions.

This paper describes examples and a range of useful outcomes from modelling simulations of rock failure and overburden caving to illustrate how modelling is being used to extend understanding of multi-seam mining scenarios, irregular overburden geology, "greenfield" mining areas, increasing overburden depths and the requirement to understand overburden fracture formation and vertical hydraulic connectivity. A case study from the Bowen Basin is used as an example of the value of combining modelling and an empirical approach to improve subsidence prediction and provide validation and calibration of the prediction methodologies for future subsidence prediction.

1. Introduction

Subsidence prediction is increasingly required outside the limits of empirical databases and we often look to other methods to expand our understanding. With complex multi-seam mining scenarios, irregular overburden geology, increasing interest in "greenfield" mining areas, increasing overburden depths and the requirement to understand overburden fracture formation and connectivity, the empirical approaches are often limited in their application to these areas.

Computer modelling of rock failure provides a method of parametrically assessing subsidence and subsidence characteristics to provide subsidence predictions tailored to site-specific lithology and panel geometry.

2. How Computer Modelling Can Improve Subsidence Prediction

Computer modelling of the rock failure process can be used to simulate caving of the overburden due to longwall extraction. In this paper, the computer modelling is conducted in FLAC 2D, using rock failure code developed in house. The rock failure code is based on Mohr failure criteria and is a coupled fluid flow and mechanical model. Further detail of the modelling process, application and validation for Tahmoor Colliery in NSW, Australia, can be found in Gale and Sheppard (2011).

Modelling of the longwall caving behaviour has many advantages for understanding the caving process and resulting subsidence. A key advantage is that modelling allows parametric assessments to be conducted to understand the sensitivity of caving to key geotechnical parameters. This is especially useful in "greenfield" areas where significant data gaps may exist.

Key areas in which modelling provides important information for subsidence prediction include:

- Ability to conduct parametric assessments for sensitivity analyses.

- Assessment of the impact of variation in overburden lithology on overburden caving – weak strata or massive units.

- Assessment of multi-seam extraction to provide multi-seam subsidence profiles and interaction.

- Assessment of impact of seam dip on caving and surface subsidence.

- Assessment of increased mining depth to understand the more complex subcritical subsidence behaviour which is significantly influenced by pillar yield behaviour and panel geometry.

- "Greenfield" sites. Without an empirical database, modelling provides assessment of the caving behaviour and resulting subsidence for the overburden lithology and panel geometry.

- Assessment of mining induced fracture networks and overburden conductivity and connectivity.

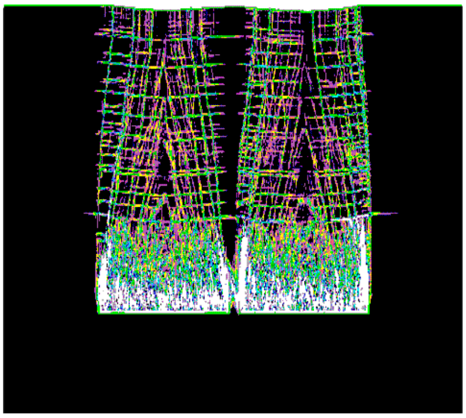
3. Varied Lithology

A key benefit of computer modelling is that the result is tailored to the mine area using site-specific stratigraphy, lithology and rock properties. Variations in caving behaviour and subsidence due to varying rock properties and lithologies can also be assessed.

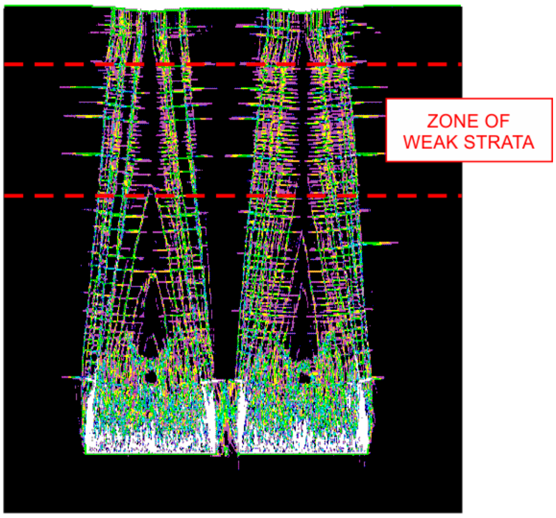
The nature of overburden caving depends on the composition of the strata. Caving due to longwall extraction produces a caved zone with a caving angle that is related to the geotechnical properties of the strata. Weak, laminated strata causes a reduced caving angle, where the sides of the caved zone are steeper and the height of caving increases. Likewise, massive strata can increase the caving angle and even bridge the strata, resulting in a reduction to the caving, depending on the location and nature of the massive strata above the longwall panel.

Modelling results for stratigraphy in one mining area in the Bowen Basin, QLD, Australia, are presented in this section to highlight the effect of lithology on caving and subsidence. Figure 1 shows the model results for Bowen Basin overburden strata where variations in lithology, including massive sandstone and weak lithology, were assessed. The panel width is 340m in all models.

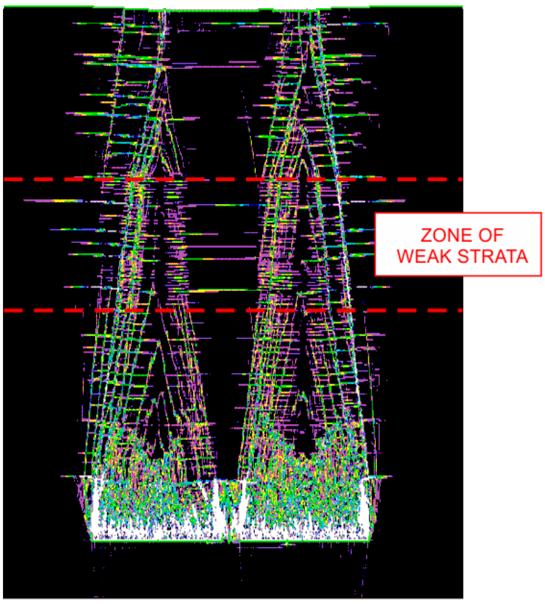
A summary of subsidence for the displayed models in Figure 1, plus an additional 400m model with typical lithology, is presented in Table 1.



a) 200m depth



b) 320m depth



c) 450m depth

Figure 1 Model of variation in overburden lithology

Table 1 Model subsidence results for varied overburden lithology Mine Subsidence

Model Seam Depth	Lithology	Modelled Max. Subsidence/ Extraction Height %
200m	Massive sandstone unit	55
320m	100m weak bedded unit	65
400m	Typical bedded lithology	55
450m	100m weak bedded unit	54

Figure 1a shows a 200m seam depth model section with a 30m thick massive sandstone unit. The maximum subsidence summary in Table 1 shows a reduced subsidence for the 200m depth due to the massive sandstone unit.

Figure 1b shows a caving model with a weak section of strata from 40m to 140m depth. Figure 1c shows a weak section of strata from 150m to 250m depth. The caving steepens in the weak bedded strata associated with increased bedding shear failure and a lower fiction angle.

The 320m and 450m models show a zone of reduced caving angle and more closely spaced bedding shears in the 100m section of interbedded coal, mudstone and tuff. The reduced caving angle in the bedded weak strata changed the nature of caving for this interval and increased the height of caving.

For a panel width of 340m and depth of 320m, it would be expected that the height of caving would just reach the surface, however, the model shows increased fracturing to the surface due to the presence of the weak strata. Likewise, for the 450m depth model, the 340m panel widths would not be expected to have significant fracturing to the surface, however, the weak zone has increased this fracturing height to the surface.

A summary of the maximum subsidence for the models is presented in Table 1. For the supercritical panels, the weak lithology model showed maximum subsidence of 65% extraction height, significantly higher than the massive sandstone model with 55%.

For the subcritical model depths, the typical overburden lithology at 400m depth gave a reduced maximum subsidence of 55% of extraction height due to its subcritical nature. The 450m overburden depth would be expected to reduce in maximum subsidence due to the reduced panel width to depth (W/H) ratio. However, the weak strata in the overburden increased the caving height and the resulting maximum subsidence to 54% of the extraction height.

It is beneficial to understand the nature of the overburden strata in order to understand any changes in subsidence that may result from the presence of weak and bedded or massive strata.

4. Multi-Seam Subsidence

Multi-seam subsidence is becoming increasingly topical with a few Australian mines currently extracting multi-seam operations and many more including multi-seam subsidence in their life-of-mine planning and environmental approvals.

There is a limited amount of literature available on multi-seam subsidence experience in Australia (Li *et al,* 2010; MSEC, 2007; Mills & Wilson, 2017), however, much of this experience is based on pillar extraction or oblique longwall panels. It is becoming better understood that paralleling multi-seam panels is beneficial for multi-seam stress interaction impacts, particularly at depth or with less interburden. Mills & Wilson (2017) provide subsidence survey data on parallel multi-seam panels at Ashton Mine in the Hunter Valley, NSW, for supercritical panel geometries.

Modelling of multi-seam extraction simulates the caving and interaction between seams, providing the mechanics of caving and resulting subsidence where empirical data is limited. Computer modelling of multi-seam mining scenarios also provides a means of assessing the interaction for site-specific lithology, panel geometries and interburden thickness.

Multi-seam subsidence is a combination of subsidence due the current seam extraction and remobilisation of the existing overlying goaf. For this reason, multi-seam subsidence profiles are often asymmetric in shape. This asymmetry is related to panel offset geometry and latent subsidence of strata adjacent to pillars due to remobilisation of the overlying goaf (Mills & Wilson, 2017). Additional key factors that influence multi-seam subsidence are interburden thickness between extracted seams, overburden depth and lithology.

An example of modelled multi-seam subsidence predictions is provided for a Bowen Basin Mine with multi-seam extraction of a parallel offset panel geometry. Figure 2a shows the modelled caving results for the approximate 300m to 400m depth model for the upper seam.

The vertical displacement contours for this model example are presented in Figure 2b and give insight into the mechanics of the interaction between the caving of the second seam with the first seam goaf and pillar system. The vertical displacement shows that with the extraction of the lower seam, the upper seam pillar system is mobilised and the strata that was supported by the upper seam pillar now caves with the extraction of the second seam. This creates a subsidence profile that is biased towards the extracted pillar (Figure 2d).

The cumulative subsidence profile in Figure 2c shows that the total maximum subsidence is not a simple addition of the maximum subsidence of each seam as the location of peak subsidence for each seam is different.

The maximum subsidence of the second seam, as a percentage of the second seam extraction height, is presented in Table 2. The results of a 200m to 300m model are also included to show the variation in subsidence with depth. The second seam subsidence percentage is greater than that of the first seam due to remobilisation of the existing goaf, particularly in the location of the upper seam pillars. The remobilisation of the previous goaf can also produce subsidence greater than 100% of second seam extraction height.

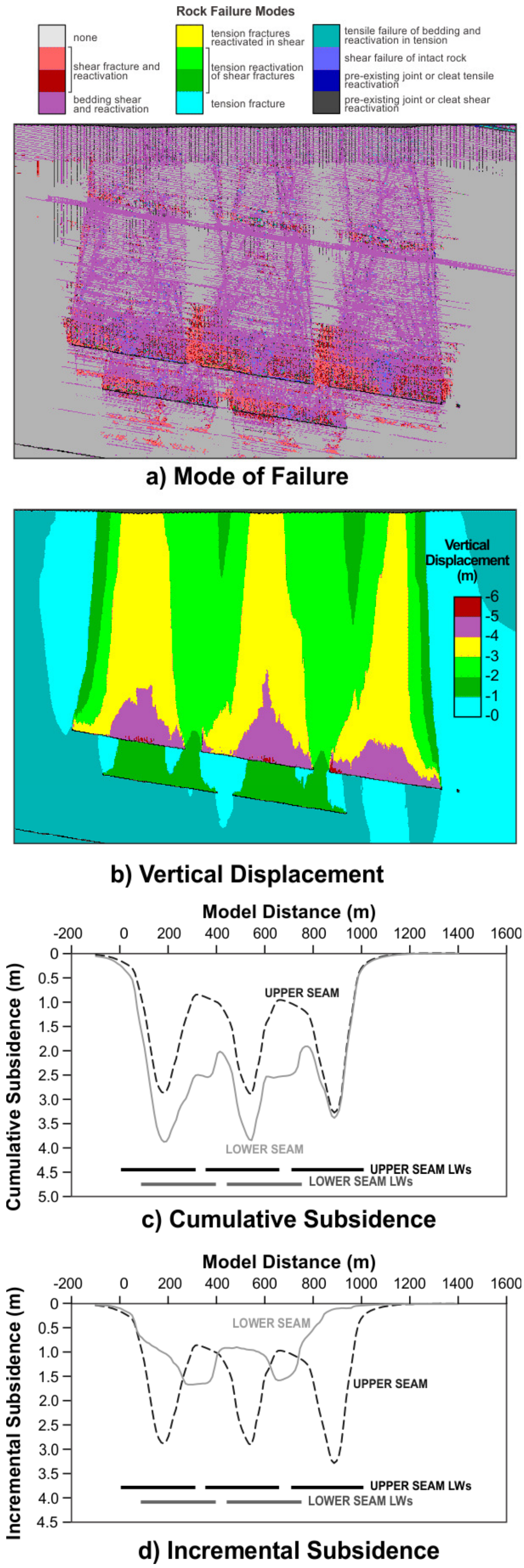


Figure 2 Model example of multi-seam subsidence

Table 2 Model subsidence results for multi-seam extraction

Depth (m)	Seam	Max. Subs. (m)	Modelled Max. Subsidence/ Extraction Height %
200-300	Upper	2.7	67.5
	Lower	2.6	104
300-400	Upper	2.9	72.5
	Lower	1.66	83

This multi-seam extraction example has a number of contributing factors that influence the subsidence profile shape. These include, but are not limited to, seam dip, tertiary alluvials, panel offset geometry, pillar strength and stiffness, overburden lithology and extraction height. Modelling provides the ability to assess interacting factors.

5. Chain Pillar Subsidence

Chain pillar subsidence is often described as a function of elastic strain of the pillar system due to abutment load. At shallow depths, where yielding of the pillar does not generally occur, the subsidence is typically due to elastic strain. However, at greater depths where the coal pillar and the strata above the coal pillar is indicated to yield by the modelling due to the high vertical stress, the pillar strain becomes more complex.

The yielded pillar system has a reduced stiffness due to the failed strata above the pillar. This less stiff strata increases the strain from the abutment load and contributes significantly to the pillar subsidence.

The following example is a model based on the stratigraphy for the Southern Coalfield in NSW, Australia. Figure 3 shows the rock failure due to caving of two 250m wide panels at 400m depth. The strata above the pillar shows shear failure of the intact rock due to vertical stress. A vertical displacement profile from the surface down through the pillar and into the floor strata shows the location of strain in the modelled pillar system. There is a high strain zone from the seam to 70m above, correlating with the yielded strata above the pillar.

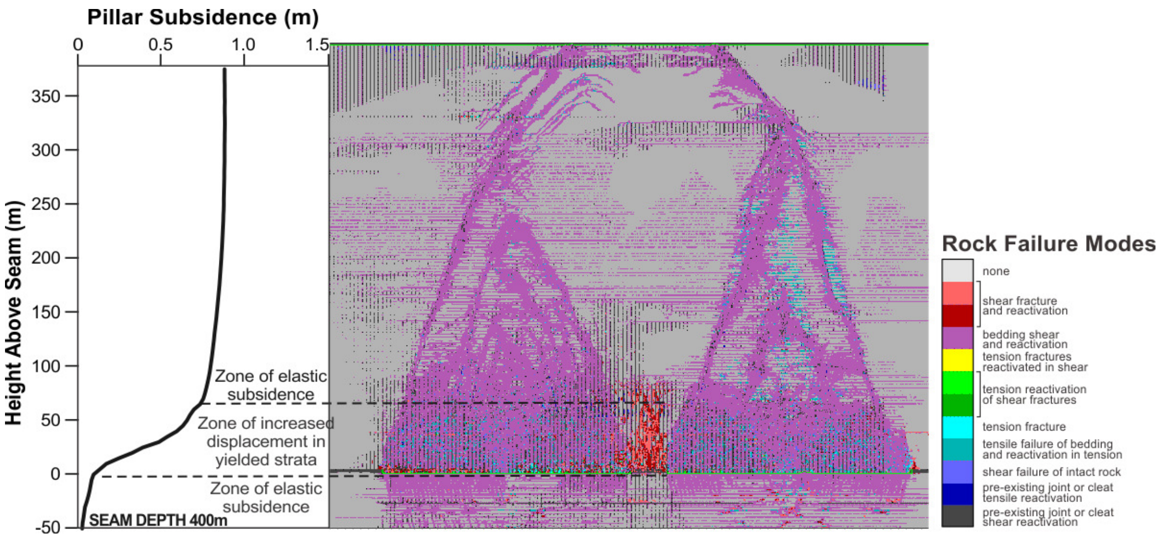


Figure 3 Model example of chain pillar subsidence

Variation in pillar geometry, extraction height, strata properties and abutment load can impact the pillar strength and the resulting chain pillar subsidence. All these parameters are modelled to provide a site-specific assessment of chain pillar subsidence. Additional panels can also be modelled to assess the increase in chain pillar subsidence for multiple panels.

6. Increased Overburden Depth

With an increase in overburden depth there is a transition from supercritical to subcritical panel geometries. The lower the panel width to depth ratio, the less sag subsidence is observed and the more the subsidence profile is influenced by pillar compression.

With subsequent panels mined adjacent to each other at large overburden depths, there is greater abutment load on the pillars, in turn increasing the subsidence. Computer models can effectively model the additional subsidence due to multiple panel extraction.

As discussed earlier in this paper, chain pillar compression can be due to elastic subsidence of an intact pillar or subsidence due to yielding of the pillar and overlying strata. Computer modelling simulates the rock failure process that drives the pillar compression and the resulting surface subsidence profile.

The model example for deep panel subsidence profiles is based on the stratigraphy of the Southern Coalfield in NSW, Australia. The seam depth in the model is 375m, the panel void widths are 300m with a 45m pillar width and the extraction height is 3m. The modelled subsidence profiles for this example are presented in Figure 4 where the effect of multiple panel extraction can be observed.

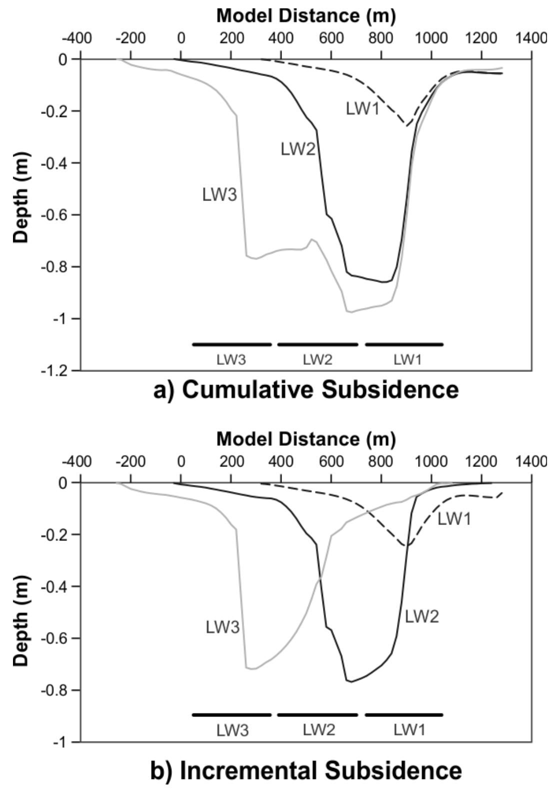


Figure 4 Modelled subsidence profiles for deep panels

In Figure 4a, LW1 is the 1st panel extracted and shows 0.25m of total subsidence. The subsequent extraction of LW2 shows 0.85m of total subsidence and LW3 extraction produces 1m of total subsidence. These cumulative profiles highlight the increase in subsidence over the previous pillars due the extraction of the current pillar.

The incremental subsidence for each extracted panel is presented in Figure 4b. The incremental subsidence profiles shows a skewed profile towards the current chain pillar. The previous chain pillar also experiences increased subsidence due to the increased load.

The advantage of the computer modelling for deep panels is that the rock failure in the pillar and overlying strata is dependent on the site-specific geology, pillar geometry and panel width. Therefore the modelled surface subsidence predictions are based on the representative site-specific parameters.

7. Overburden Hydraulic Conductivity

One of the most useful features of longwall caving modelling is the ability to estimate overburden hydraulic conductivity. The models simulate the caving process and the mining-induced fracture network for the site-specific geometry and geology. The hydraulic conductivity estimates are strain, stress and aperture based and provide both horizontal and vertical conductivity and secondary porosity.

Figure 5 shows an example of the vertical hydraulic conductivity for a model based on stratigraphy of the Southern Coalfield of NSW, Australia. The conductivity profile plot shows the average conductivity across the second extracted panel on the left. The average vertical conductivity across the panel is also provided as a cumulative average from the seam upwards and is presented as the cumulative profile line.

The model vertical conductivity output in Figure 5 shows a distinct high conductivity zone in the 60m above the seam, reducing two orders of magnitude to approximately $1x10^{-3}$m/s up to approximately 175m above the seam. Above this height are horizons of lower conductivity of about $1x10^{-6}$m/s and horizons of about $1x10^{-4}$m/s. The lower conductivity horizons reduce the average cumulative vertical conductivity, from seam to surface, to approximately $1x10^{-5}$m/s.

The overburden conductivity is specific to the overburden lithology, panel and pillar geometry and extraction height of the specific mine area.

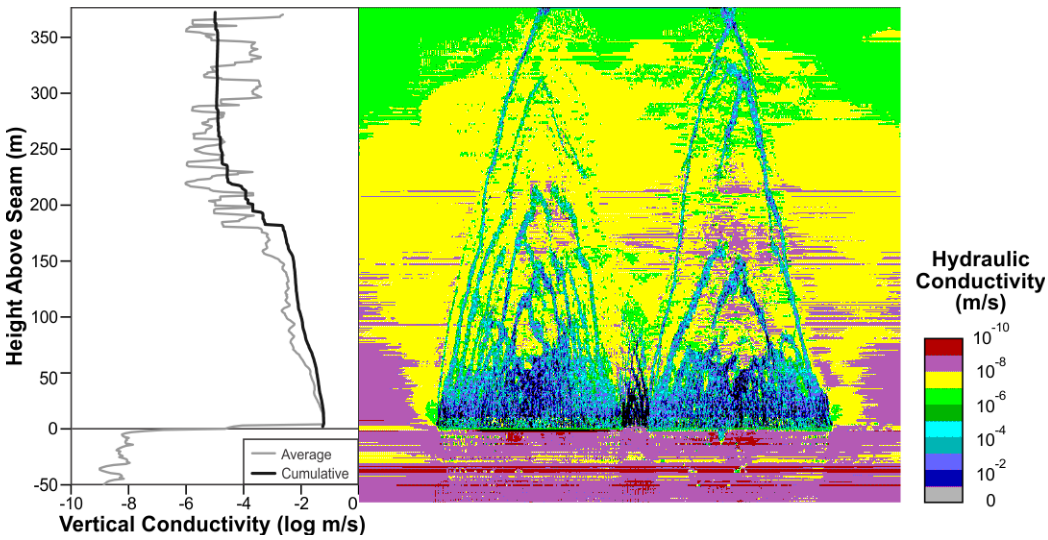


Figure 5 Example of modelled overburden hydraulic conductivity

8. Combining Model Results and Empirical Datasets

Modelling is a valuable tool for creating subsidence profiles for site-specific parameters, particularly for “greenfield” mining areas. If, however, an empirical database exists, the actual data is valuable in validating or calibrating the model before extending the model beyond the current experience.

Even more so, the models can help “fill in the gaps” of the empirical dataset, whether that be increased or reduced W/H ratios, change in mine geometry, increased extraction height, change in pillar geometry, change in depth or change in lithology.

The results of the caving models are also used to extend the dataset trends for individual subsidence characteristics such as chain pillar compression and maximum subsidence. This is valuable for the construction of subsidence prediction curves.

Strengths of the modelling in “Brownfield” mining areas are that the model is calibrated with site data before extending the model properties to beyond the current experience and empirical dataset of the mine site.

The confidence of applying the computer models to “greenfield” mining areas without site-specific data for validation is achieved through validation of the model rock failure process. The rock failure model discussed in this paper has been validated at numerous mine sites with discussion and validation of the model rock failure process published in a number of papers (Gale, 1998; Gale *et al*, 2004; Gale, 2005; Heritage *et al*, 2015) in addition to subsidence outputs validation (Gale & Sheppard, 2011).

9. Case Study – Bowen Basin

The Bowen Basin case study presented in this section provides an example of using a combination of computer modelling and empirical datasets to provide validated subsidence predictions.

The case study mine consists of earlier panels mined with conventional longwall extraction before changing to a longwall top coal caving (LTCC) operation. The overburden depth range for panels LW1-8 is 100m-250m depth with proposed panels to extend up to 350m depth. Panels LW1-7 were extracted at 4-4.25m then for the LTCC panels from LW8 onwards the extraction height is 3.9m with estimated 80% top coal recovery.

The progressive nature of mining, together with a number of approval processes, allowed the subsidence predictions to be updated, validated and calibrated as new survey data and experience was provided.

Empirical datasets for the case study mine initially only provided site based characteristics on the maximum subsidence for conventional longwall extraction.

At these early stages the mine did not have experience for LTCC and so modelling was conducted to provide subsidence profiles for two overburden depths of 150m and 250m. The extraction height was 5.5m and the model was based on site-specific lithology and geotechnical properties.

The results of the modelling for LTCC are presented in Figure 6 and show the modelled subsidence profiles for the two depths. The profiles show a maximum subsidence of 3.8m which equates to a maximum subsidence of 69% of extraction height. Chain pillar subsidence was also modelled at 0.2m for 150m depth and 0.5-0.67 for 250m depth.

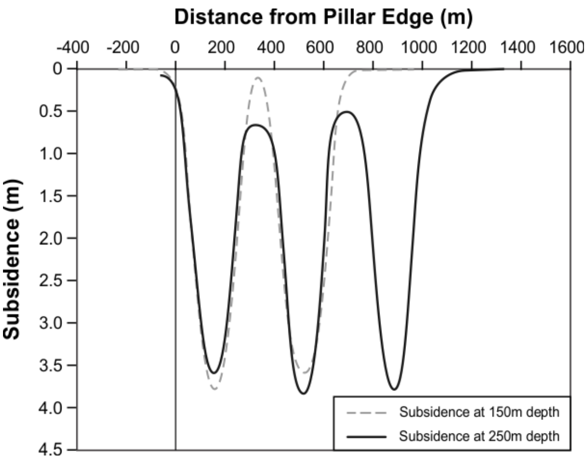


Figure 6 Modelled subsidence profiles for Bowen Basin case study mine

These model results were used for subsidence predictions for LTCC for the mine area. An important outcome of the model results was that the maximum subsidence to extraction height ratio for LTCC was consistent with the maximum subsidence ratio for conventional extraction.

Subsequent subsidence survey data for the case study is presented in Figure 7. A summary of the chain pillar predictions from the original model and survey data is presented in Table 3.

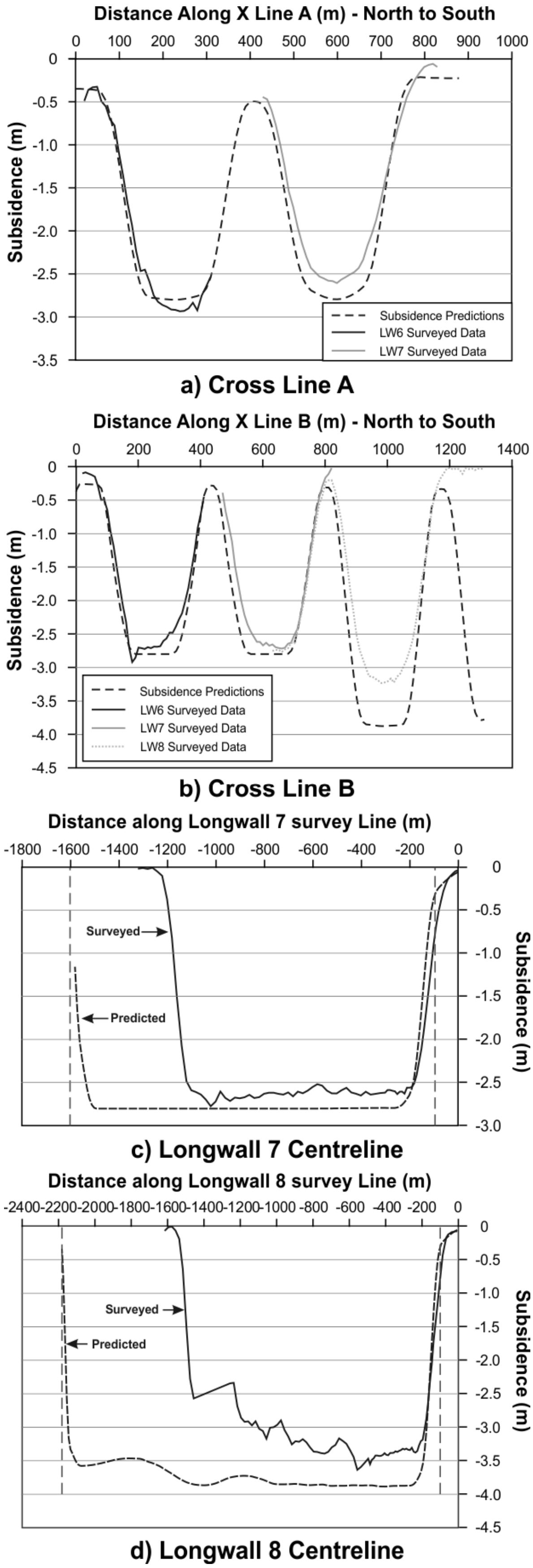


Figure 7 Surveyed subsidence for the case study mine

Table 3 Case study chain pillar survey data and model interpolations

Depth	Surveyed Chain Pillar Subsidence	Interpolated Model Chain Pillar Subsidence
220m	0.5m	0.53m
160m	0.25m	0.25m
175m	0.3m	0.32m

To expand the subsidence predictions to greater depths than previously experienced or modelled at the case study mine, a characterisation of Bowen Basin subsidence data and modelled scenarios was conducted. This initial maximum subsidence characterisation is presented in Figure 8a and shows the limited dataset at low W/H ratios. A model for the case study mine was conducted to produce a data point at the lower W/H required for the predictions. Models for a different Bowen Basin mine were used to fill in the roll over curve from subcritical to supercritical.

Subsequent mining and characterisation of survey data at the case study mine allowed for an in depth review of the maximum subsidence characterisation.

The updated maximum subsidence characterisation presented in Figure 8b shows the longwall start up centreline and crossline data for all panels to date. The updated dataset shows that the previous predictions based on both modelled and empirical data were consistent with the actual survey dataset where the maximum subsidence prediction trend line represents the maximum data within the dataset.

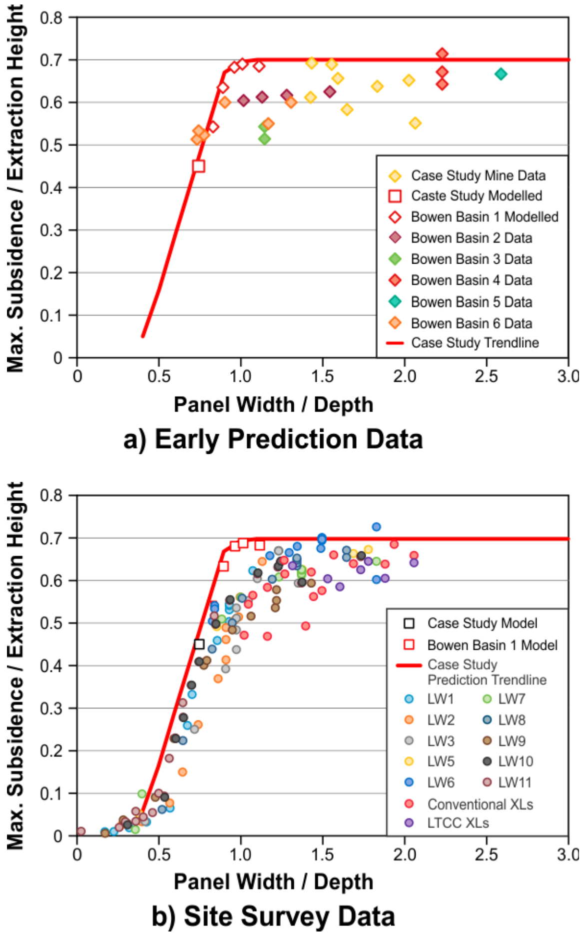


Figure 8 Case study maximum subsidence data

A disparity in the prediction curve and the data is the rollover curve that was based on modelling from a different Bowen Basin mine. This reinforces the requirement to conduct site-specific modelling. Although the case study prediction curve differed slightly at the rollover point, it produced a more conservative subsidence prediction. A new maximum subsidence curve would be recommended for future predictions to improve the predictions for the subcritical to supercritical transition.

The surveyed LTCC results observed in LW8 (Figure 7) were significantly less than the predictions, where the predictions were based on 80% recovery of the top coal caving. The extracted LTCC panels all showed significantly less subsidence ranging 50% to 60% of the predicted LTCC recovery height.

Figure 9 shows the comparison between the predicted coal recovery and actual tonnes as mined. The extraction height determined from the actual tonnes mined produced maximum subsidence range of 60% to 70% of actual extraction height. The characteristics of subsidence for LTCC were therefore as predicted in the earliest LTCC modelling.

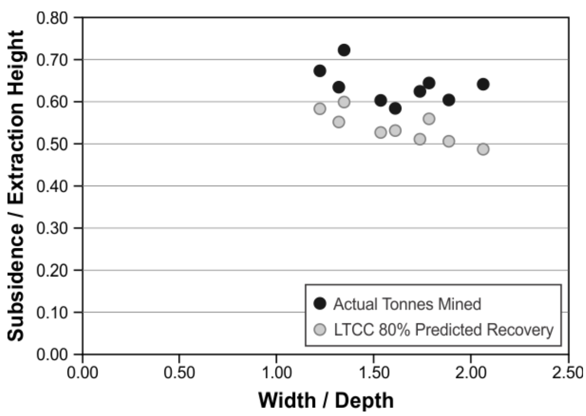


Figure 9 Maximum subsidence for LTCC predicted recovery and actual tonnes mined

Modelling also allowed assessment of overburden hydraulic conductivity for conventional and LTCC extraction for the overburden to the top of the Permian strata. This allowed assessment of the variation in conductivity with conventional and LTCC extraction heights. Figure 10 shows the overburden caving and fracturing to the top of the Permian strata with the associated modelled hydraulic conductivity of approximately 1×10^{-3}m/s to 1×10^{-4}m/s at the top of the Permian strata.

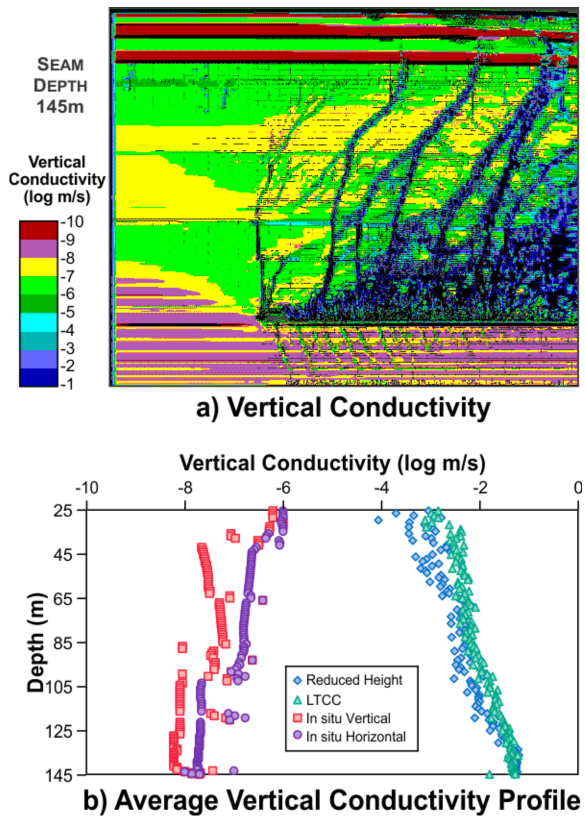


Figure 10 Case study overburden hydraulic conductivity model results

The progressive nature of mining and the multiple stages of approvals allowed for validation and recalibration of the subsidence predictions as site data became available. Computer modelling additionally provided detail on the mining-induced fracture network and hydraulic conductivity.

10. Conclusions

Computer modelling of rock failure to simulate overburden caving is a valuable tool in providing subsidence predictions in lieu of an empirical dataset for that site. Mining in its nature will more often extend beyond the limits of empirical databases where modelling can assist in bridging the knowledge gap.

Not only does computer modelling provide further assessment on subsidence prediction, it also provides understanding of the mechanics behind the subsidence process. Understanding the mechanics of overburden caving and pillar compression for individual mine geometries and lithologies, provides for further insight into subsidence variability and subsidence extrapolation about a mine plan.

Computer rock failure modelling is a valuable prediction tool that facilitates understanding beyond our current experience.

11. Acknowledgments

I would like to thank the case study mine for allowing publication of their data.

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