General Discussion on Systematic and Non Systematic Mine Subsidence Ground Movements

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CHAPTER 1. GENERAL DISCUSSION ON SYSTEMATIC AND NON SYSTEMATIC MINE SUB SIDENCE GROUND MOVEMENTS

1.1. The Prediction of Subsidence Parameters

1.1.1. Alternative Methods of Prediction

Several alternative methods have been used in the past to predict subsidence parameters, including:

- Graphical Methods, such as the National Coal Board Method used in the U.K.
- Profile Function Methods.
- Influence Function Methods.
- Numerical Modelling Methods.
- Empirical Methods.

Profile function methods seek to define the shape of the subsidence profile using a single mathematical formula. These are generally only applicable to single panels, since they assume the profiles to be symmetrical and fail to recognise the way in which subsidence profile shapes are modified over adjacent and previously longwall goaf areas.

Subsidence, tilt, horizontal displacement, curvature and strain are the subsidence parameters normally

Influence function methods predict subsidence profiles based on the theory of an area of influence around a point of extraction. These methods can be applied to a wide range of mining geometries, but are more difficult to calibrate and check than profile function methods.

Numerical modelling techniques have been developed in recent years using finite element and discrete element models such as FLAC, UDEC and FLOMEC. These are particularly useful tools for investigating strata mechanisms and hydrological impacts, but have not been found to produce sufficiently accurate predictions of mine subsidence parameters.

Empirical methods can be developed for the prediction of subsidence parameters whenever a large database of measured subsidence parameters is available. These methods can be advantageously employed over a wide range of mining geometries, taking into account local variations in strata lithology. Other modelling methods can also be successful where sufficient local data is available for model calibration. To be successful, all methods of prediction have to be checked against measured data and calibrated to reflect local geology.

An empirical approach has generally been adopted in the coalfields of New South Wales, and this has been expanded in recent years by the development of the Incremental Profile Method. The Standard Empirical methods and the Incremental Profile Method are described in the following sections. Further information on alternative methods of subsidence prediction can be found in Kratzsch (1983) and Whittaker and Reddish (1989).

1.1.2. Standard Empirical Methods

At collieries in New South Wales, the maximum subsidence of the surface has generally been predicted using empirical methods. In the past, subsidence predictions were based upon the methods outlined in the Subsidence Engineers Handbook, first published by the National Coal Board of the United Kingdom in 1965 and revised in 1975. This involved the use of a series of graphs derived from numerous field observations in British mines, which allowed the shapes of the subsidence, tilt and strain profiles to be predicted.

The method gave good results when applied to British mining situations, but when the method was adopted in Australia, it became clear that the field observations differed considerably from predicted values and were generally much less than theory would suggest.

This is because the strata that overlie the coal seams in British coalfields differ from those that occur in the coalfields of Australia and because the subsidence measurements in British coalfields were in some cases affected by multi-seam mining. The rocks in Britain are generally less competent and less able to bridge the extracted voids and, therefore, for a given seam thickness, the maximum subsidence is greater than it would normally be for the same mining geometry in Australian conditions.

An intensive research program was therefore undertaken by the then New South Wales Department of Mineral Resources (DMR) to develop a predictive model that was more appropriate for Australian conditions. It was noted that the subsidence behaviour varied significantly between the Southern Coalfield, the Newcastle Coalfield and the Western Coalfield of New South Wales. Subsidence data from collieries in New South Wales were therefore studied separately for the three coalfields. The work resulted in three publications which provide guidelines for the prediction of mine subsidence parameters in each coalfield. The handbook for the Southern Coalfield was completed in 1975 (Holla, 1975) and the handbooks for the Newcastle and Western Coalfields were completed in 1987 (Holla, 1987a) and 1991 (Holla, 1991a) respectively. It should be noted that the method of prediction given in the New South Wales handbooks is only applicable to single, isolated panels.

Additional research by Dr L. Holla of the DMR led to the publishing of a paper (Holla, 1988) which included a graph which can be used to predict the maximum subsidence above a series of longwall panels, for critical extraction conditions. This graph is reproduced as Fig. 1.1, where S_{max} is the maximum subsidence, T is the seam thickness and H is the depth of cover.

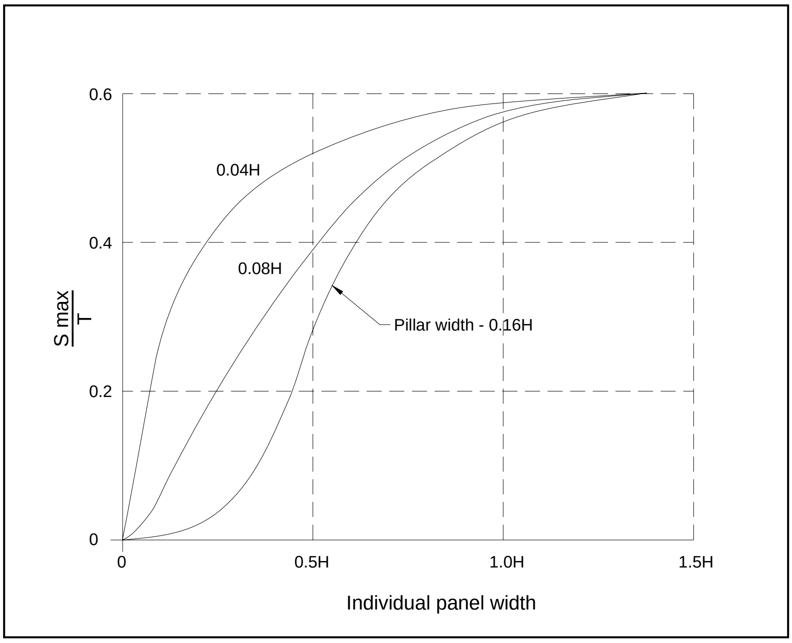


Fig. 1.1 **Graph for the Prediction of Maximum Subsidence over a Series of Panels for Critical Extraction Conditions (after Holla, 1988)**

Following further study, a revised handbook was produced by the DMR for the Southern Coalfield in 2000 (Holla and Barclay). This later handbook included graphs that allow prediction of the maximum subsidence over a series of longwall panels. The handbook can also be used to establish an approximate subsidence profile and to predict the maximum tilt, curvature and strain above a mined area, for single panels.

When the width of an extracted panel, the depth of cover, and the extracted seam thickness are known, the following parameters can be predicted:

The maximum subsidence value

- The location of the inflection point
- The average goaf edge subsidence
- The limit of subsidence

Once these parameters have been determined, an appropriate subsidence profile can be produced as a line of best fit between the points of maximum subsidence, inflection, goaf edge subsidence and limit of subsidence. This method thus allows the approximate shape of subsidence profile to be determined for a single isolated panel.

The predicted maximum tensile strain, compressive strain and tilt can be determined from the maximum subsidence and depth of cover, using, respectively, factors obtained from the graphs shown in Figs. 4.6, 4.7 and 4.10 of the DMR handbook (Holla and Barclay, 2000). The predicted maximum curvatures can be derived from the predicted maximum strains using the graph shown in Fig. 4.9 of the handbook.

The limit of subsidence is determined from the depth of cover and the angle of draw. The DMR recommends a practical angle of draw of 26.5° for general use in the Southern Coalfield, and hence the limit of subsidence would generally be positioned at half the depth of cover from the perimeter of the extracted area.

Whilst the DMR method normally provides reasonable predictions of the maximum subsidence above a series of longwall panels, it does not predict the subsidence profiles across a series of panels and does not allow the variations in tilt, curvature and strain to be determined across a series of longwalls. This method therefore could not be used to provide the detailed predictions required for this study. However, it was used to provide a check on the accuracy of the maximum predicted subsidence parameters which have been obtained using the Incremental Profile Method.

1.1.3. The Incremental Profile Method

The Incremental Profile Method was developed by Mr A.A. Waddington and Mr. D.R. Kay during the course of a study for BHP Collieries Division, the Water Board and AGL during the latter part of 1994 (Waddington and Kay, 1995). The purpose of the study was to develop an empirical method which could be used to predict the subsidence, tilts, curvatures and strains likely to be experienced as longwall mining occurred at Appin and Tower Collieries, and to assess the likely effects of mining on surface infrastructure.

The first step in the development of the model was to study detailed records of subsidence movements which had been observed over previous longwalls at Appin and Tower Collieries and over longwalls at neighbouring mines, including Tahmoor, West Cliff, Cordeaux and South Bulli Collieries. The measured subsidence data was plotted in a variety of ways to establish whether or not any regular patterns of ground behaviour could be found. The most significant patterns were illustrated in the shapes of the observed incremental subsidence profiles measured along survey lines located transversely across the longwalls.

The incremental subsidence profile for each longwall was derived by subtracting the initial subsidence profile (measured prior to mining the longwall) from the final subsidence profile (measured after mining the longwall). The incremental subsidence profile for a longwall therefore shows the change in the subsidence profile caused by the mining of the individual longwall.

The consistency in the shapes of the incremental subsidence profiles led to the development of the Incremental Profile Method. This consistency can be observed in the typical incremental subsidence profiles presented in Fig. 1.2.

The Incremental Profile Method of prediction is based upon predicting the incremental subsidence profile for each longwall in a series of longwalls and then adding the respective incremental profiles to show the cumulative subsidence profile at any stage in the development of a series of longwalls.

The incremental subsidence profiles are also used to derive incremental tilts, systematic curvatures and systematic strains which can be added to show the transient and final values of each parameter as a series of longwalls are mined.

Profiles can be predicted in both the transverse and longitudinal directions, thus allowing the subsidence, tilts, systematic curvatures and systematic strains to be predicted at any point on the surface above a series of longwalls. The method also explains the development of undulations that occur within the subsidence trough and allows the magnitude of both transient and residual tilts and curvatures within the trough to be determined.

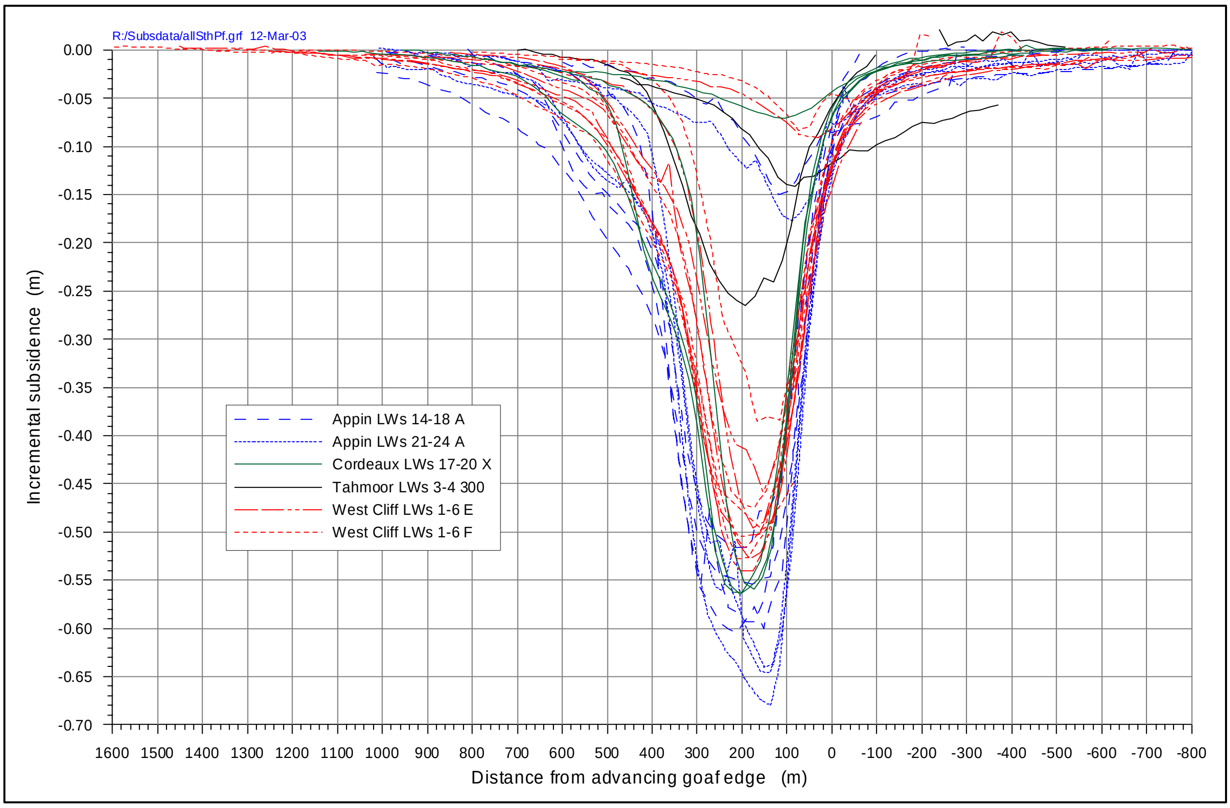


Fig. 1.2 Typical Incremental Subsidence Profiles – NSW Southern Coalfield

The model was initially tested by comparing the predicted values of subsidence, tilt, curvature and strain against the measured values for a number of longwalls at Appin, Cordeaux, Tahmoor and West Cliff Collieries. Following that study, the method was used to analyse and predict subsidence over other longwall panels at Appin, South Bulli, Bulli, Corrimal, Tahmoor, Teralba, North Cliff, Metropolitan, Tower and West Cliff Collieries. These studies found that the shapes of the measured incremental profiles conformed to the patterns and magnitudes observed during the initial 1994 study.

During 1996 and 1997, the method was extended for use in the Newcastle Coalfield. The shapes of incremental profiles over extracted longwall panels at Cooranbong, West Wallsend, Newstan, Teralba, and Wyee Collieries were studied and a subsidence model was developed for the Cooranbong Life Extension Project. These studies have shown that the shapes of the incremental profiles in the southern part of the Newcastle Coalfield conform to the patterns observed in the Southern Coalfield. Since that study, the method has been used to analyse and predict subsidence over other longwall panels at West Wallsend, Cooranbong, Wyong and South Bulga Collieries.

The collection of additional data has allowed further refinement of the method and the database now includes more than 475 measured examples. A wide range of longwall panel and pillar widths and depths of cover is included within the database and hence, the shapes of the observed incremental profiles in the database reflect the behaviour of typical strata over a broad spectrum.

Further research during the last few years has identified the shapes of the incremental profiles in a number of multi-seam situations. These profiles are generally greater in amplitude than the single seam profiles and differ in shape from the standard profiles over single seams.

The incremental profiles have been modelled in two halves, the point of maximum subsidence being the point at which the two halves of the profile meet. A library of mathematically defined profile shapes has been established, which allows the incremental profiles to be modelled, depending on the width to depth ratio of the longwall and the position of the longwall in the series.

The mathematical formulae that define the profile shapes are of the form given in Equation 1 below. The library of profile shapes simply comprises the values *a* to *k* in these formulae.

$$y = \frac{a + cx + ex^2 + gx^3 + ix^4 + kx^5}{1 + bx + dx^2 + fx^3 + hx^4 + jx^5} \qquad \text{Equation 1}$$

Different formulae apply, with unique *a* to *k* values, for first, second, third, fourth, and fifth or subsequent panels in a series, and for different width-to-depth ratios, within the range 0.3 to 5.0. For second, third, fourth and fifth or subsequent panels, the left and right hand sides of the profiles have different formulae.

The library of profile shapes thus contains a to k values for 693 different half-profile shapes for single-seam mining situations. In addition the library contains 236 different half-profile shapes for a range of multi-seam mining situations. A selection of model incremental subsidence profiles for various width-to-depth ratios is shown in Fig. 1.3, below.

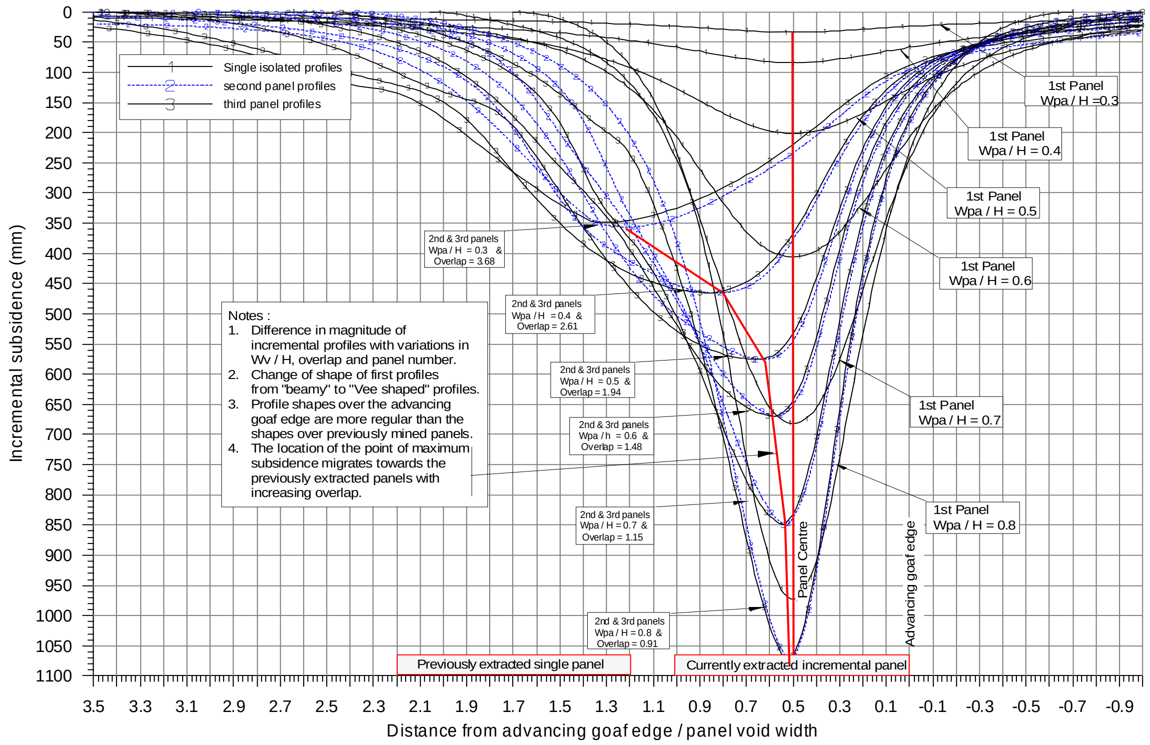


Fig. 1.3 Incremental Subsidence Profiles obtained using the Incremental Profile Method

The method has a tendency to over-predict the subsidence parameters because a conservative approach was adopted in preparing the graph that is used for predicting the maximum incremental subsidence. Fig. 1.4 shows the maximum incremental subsidence, expressed as a proportion of seam thickness, versus panel width-to-depth ratio.

Since this graph is used to determine the amplitude of the incremental subsidence profile, any over-prediction of the maximum subsidence value also leads to over-predictions of the tilt, curvature and strain values. Once the geometry of a longwall panel is known, the shapes of the two halves of the incremental subsidence profile of the panel can be determined from the appropriate formulae to provide a smooth non-dimensional subsidence profile across the longwall.

The actual incremental profile is obtained by multiplying vertical dimensions by the maximum incremental subsidence value and horizontal dimensions by the local depth of cover. Smooth tilt and curvature profiles are obtained by taking the first and second derivatives of the subsidence profile. Strain profiles are obtained directly from the curvature profiles.

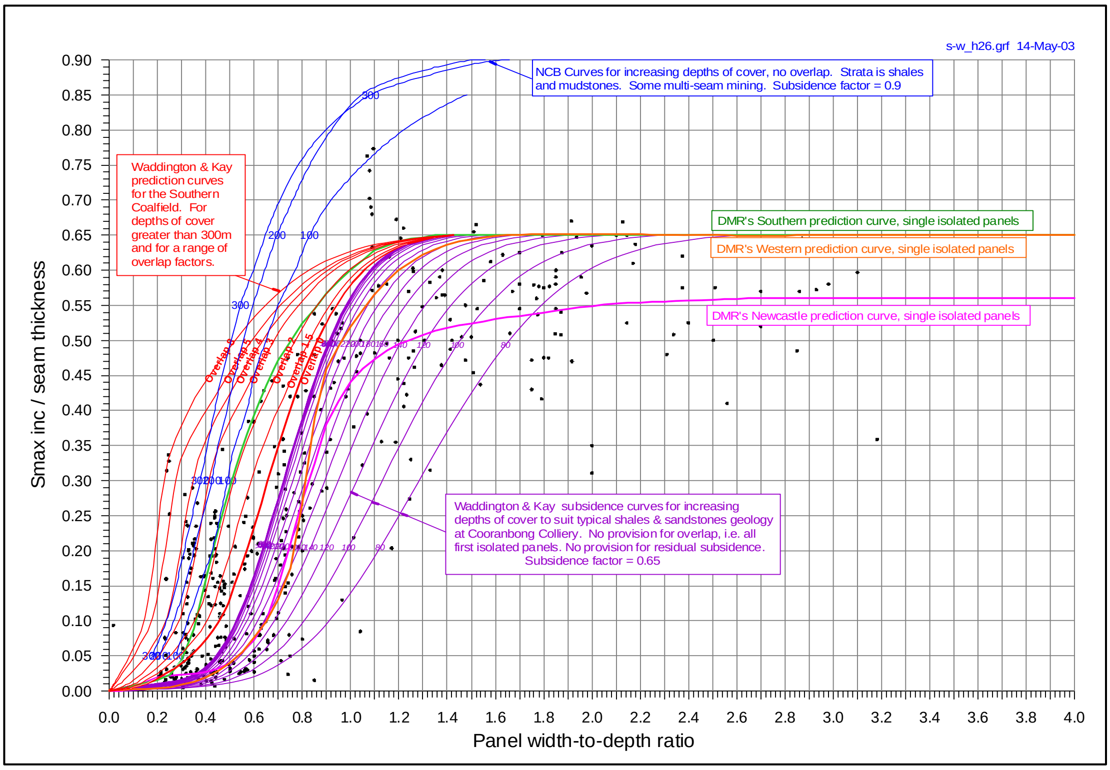


Fig. 1.4 Prediction Curves for Maximum Incremental Subsidence

It can be seen from Fig. 1.3 and Fig. 1.4 that, as panel width to depth ratio (W/H) decreases, the magnitude of the incremental subsidence profile is reduced and the position of the point of maximum subsidence moves closer to the previously extracted panels. It has been found that the amplitude and position of the incremental profile relative to the maingate of the longwall is determined by a factor known as the overlap factor. This overlap factor is derived empirically as a function of the panel width, pillar width and depth of cover.

In order to determine strain values from the curvature profiles, it is necessary to select an empirical relationship that will generally provide conservative results. The NCB Subsidence Engineers Handbook (1975) adopts a relationship in which the reciprocal radius of curvature, K, is equal to strain squared divided by 0.024.

This relationship does not provide a good fit when strains derived from predicted curvatures, are compared with measured values. However, if a linear relationship of strain = 15 × curvature is chosen, then a closer fit is achieved between predicted and observed data from the Southern Coalfield. This equates to the bending strain in a beam of 30 metres depth, bending about its centre line. The relationship of 15 × curvature is also reasonably close to the graph of radius of curvature versus maximum strain given in Fig. 4.9 of the DMR's handbook for the Southern Coalfield (Holla and Barclay, 2000), for depths of cover between 300 metres and 400 metres. It will, however, give lower values of strain for greater depths. A factor of 10 has been found to be more applicable in the Hunter and Newcastle Coalfields.

Predicted horizontal displacements in the direction of the prediction line (normal to the longwall), can be derived by accumulating the predicted strains multiplied by the bay lengths, after distributing any displacement closure errors over all bay lengths in proportion to the predicted strains. Alternatively, the predicted horizontal ground movement profiles can be derived by applying a proportionality factor to the predicted tilt profiles, which they resemble in both magnitude and direction.

Experience has shown that the subsidence and tilt profiles predicted using the Incremental Profile Method usually match the systematic observed profiles reasonably accurately. It is not possible to match the predicted and observed curvature and strain profiles to the same standard, due to the large amount of scatter generally found in the measured data. The range of systematic strains is, however, adequately predicted.

The scatter in the strains is caused by random variations in stratigraphy, rock strength, fracture characteristics and spacing of joints which dictate the way in which the near surface rocks will respond as subsidence occurs. The scatter sometimes results in anomalous peaks of strain, though in many cases these peaks can be predicted.

It should be remembered that the predicted strains obtained using the Incremental Profile Method are the systematic strains, which can, in some cases, be exceeded by local anomalous peaks of strain. In the Incremental Profile Method, such anomalous peaks of strain are dealt with statistically.

The Incremental Profile Method provides a greater understanding of the mechanism of subsidence over a series of panels and allows a detailed prediction of subsidence parameters to be made for any point on the subsidence profile.

Other benefits of the Incremental Profile Method are as follows:

The method can be used even where the seam thicknesses, pillar and panel widths and depths of cover vary from panel to panel across a series of longwalls. This is possible because the total subsidence predictions are an accumulation of incremental subsidence profiles for each longwall, based on their individual panel and pillar widths, the seam thickness and depth of cover and the position of each longwall within the series of longwalls.

- After superimposing the influence of the incremental subsidence profiles for each longwall it has been found, in the syntheses carried out to date, that the total subsidence profiles are predicted quite accurately.
- Because the total subsidence profiles are well represented, this method provides improved predictions of tilts, and general background or 'systematic' curvatures and strains.
- The method can be used to model the effects of alternative mine layouts with different pillar and panel configurations and to compare the impact of tilts, curvatures and strains for each alternative.
- By varying the proposed widths of panels and pillars, it is possible to show the variations in the predicted magnitude of the maximum total subsidence and the shape of the subsidence trough.

Because of the inherent advantages of the Incremental Profile Method, this method has been used to make the detailed subsidence predictions for this project.

1.1.4. Typical Subsidence Predictions

Typical predicted incremental and cumulative total subsidence, tilt and strain profiles over a series of longwalls are shown in Fig. 1.5. It can be seen that the subsidence parameters vary throughout the subsidence trough.

Subsidence profiles are generally prepared along a series of parallel prediction lines, orientated at right angles to the centrelines of the longwalls. The prediction lines are generally positioned 25 metres to 100 metres apart, depending on the depth of cover and generally cover the full area of the longwalls, extending outwards as far as the limit of subsidence.

When the predicted subsidence profiles have been developed along each of the prediction lines, the predicted subsidence data is used to develop a three-dimensional model of the subsidence trough, from which subsidence contours are derived.

A typical longwall layout showing predicted subsidence contours over a series of four longwalls is illustrated in Fig. 1.6. The variations in these contours reflect the changes in seam thickness and depths of cover from place to place over the area of the longwalls.

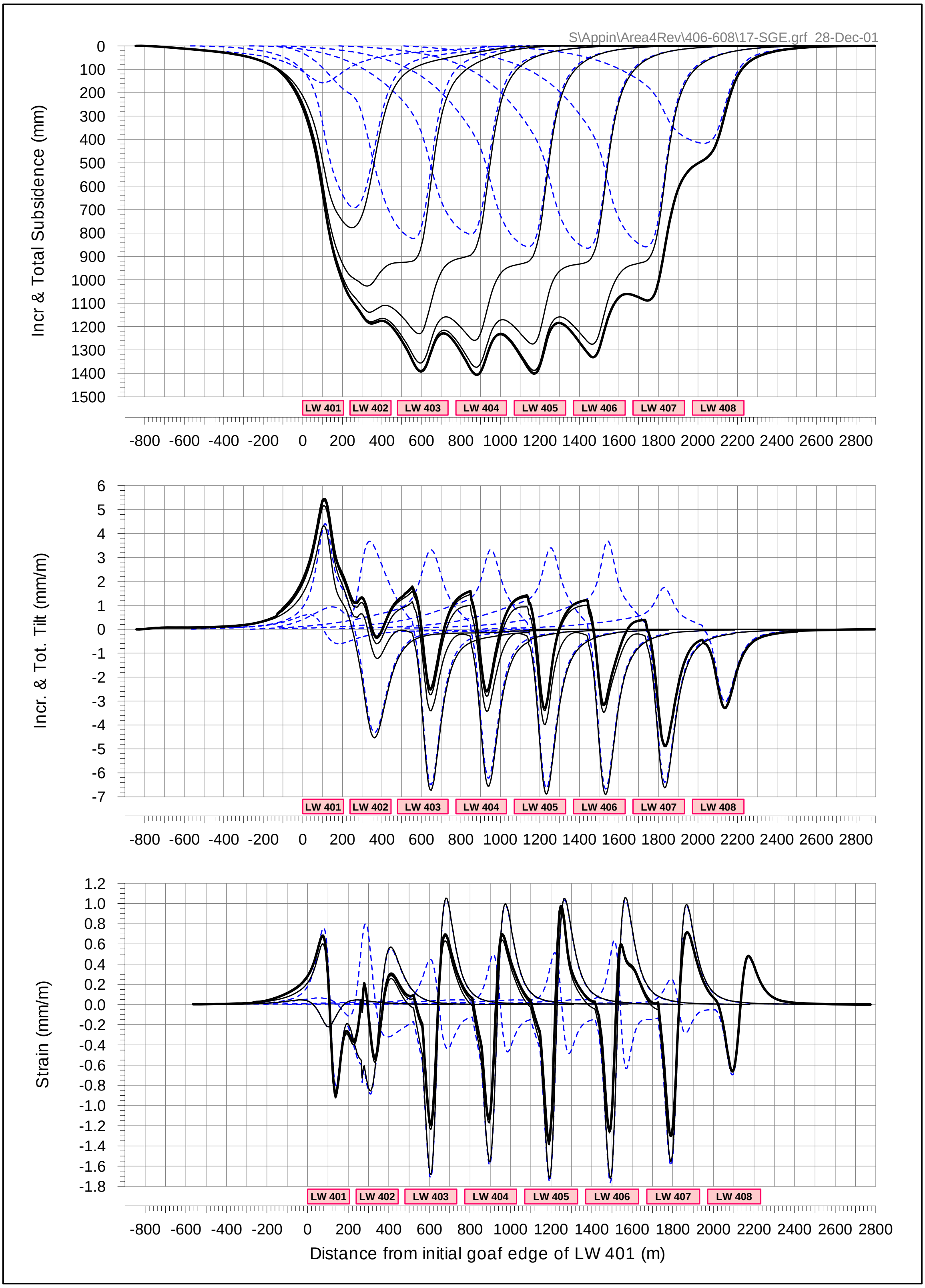


Fig. 1.5 Typical Predicted Incremental and Total Subsidence, Tilt and Strain Profiles

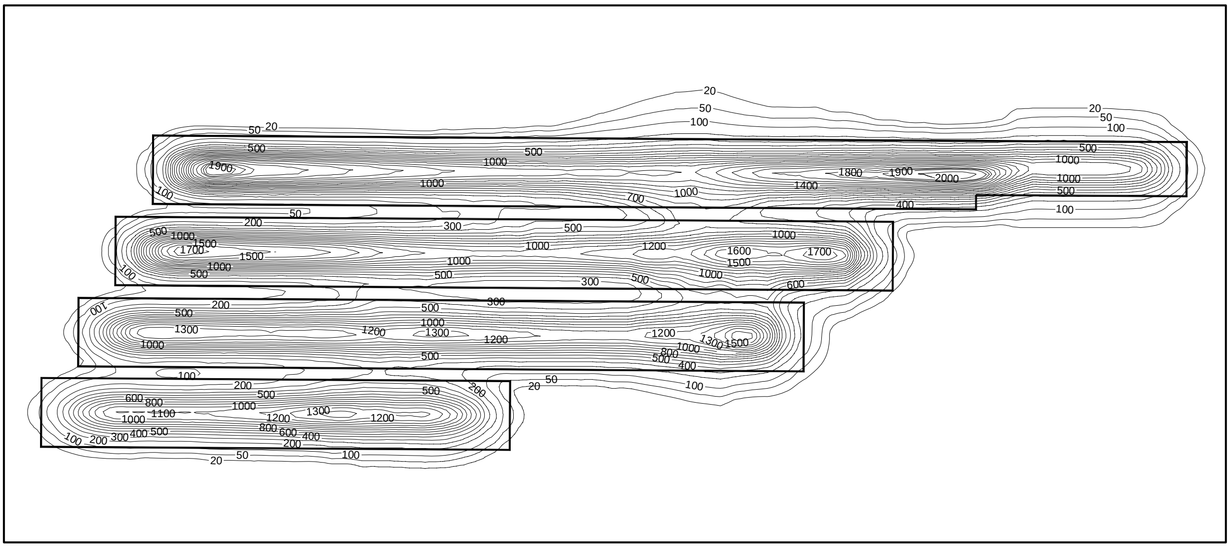


Fig. 1.6 Typical Predicted Subsidence Contours over a Series of Longwalls

1.2. Timing and Direction of Predicted Tilts and Strains

It is generally found that the maximum tilts and strains at any point within a mined area are aligned in the transverse direction across the longwalls and occur after the longwalls are extracted. However, there are cases when the maximum tilts and strains are not aligned in the transverse directions. There are also instances where the maximum tilts and strains at a particular point occur during the extraction of a particular longwall and are later reduced by extraction of subsequent longwalls. Treatment of these cases is discussed below.

1.2.1. Travelling, Transient and Final Subsidence Parameters

The Incremental Profile Method allows subsidence parameters to be predicted at any point on the surface when the longwall face is at any position in a panel, and hence for any:

- **travelling** scenario, *during* extraction of a longwall,
- **transient** scenario, *following* the extraction of *each* longwall, or
- **final scenario, following the extraction of all longwalls in a series.**

This is particularly relevant for assessing the impacts of curvature and strain on an item of surface infrastructure, which can be greater at a travelling stage than on completion of mining a particular longwall or all longwalls in a series.

A review of subsidence data from several collieries in the Southern Coalfields, in particular West Cliff Colliery, has indicated that the magnitude of the observed travelling strains in the longitudinal direction are generally smaller than the observed transient or final longitudinal strains over the ends of the longwalls. Using the Incremental Profile Method, the travelling strains at any point in the subsidence trough can be determined by taking into account the maximum predicted longitudinal strains over the ends of each longwall, the maximum predicted incremental subsidence value for the longwall and the predicted subsidence at the point of interest.

1.2.2. Tilts and Strains in the Transverse and Longitudinal Directions

The predicted maximum tilts and strains within the mined areas are, generally, those which are aligned in the transverse direction across the longwalls. However, at the ends of the longwalls, the maximum tilts and strains are at right angles to the subsidence contours, which can be aligned in various directions relative to the longwalls. Also, in some cases, the travelling wave that occurs during the extraction of each longwall can produce travelling longitudinal tilts and strains which can be greater than the transverse values. These cases typically occur at those points within the subsidence trough at which maximum subsidence is developed.

At points where it is found that longitudinal tilts and strains are greater than those in the transverse direction, it is extremely rare for these tilts and strains to be greater at a transient stage than on completion of mining. There may be isolated cases where the maximum tilts and strains are aligned in a diagonal direction to the orthogonal axes of the longwalls. In such cases, the magnitude of these tilts and strains will exceed the transverse and longitudinal values by a small proportion only and are unlikely to influence the final assessment of potential impact or development of management plans to mitigate this potential impact.

1.3. Statistical Analysis of Curvature and Strain

The peak values of curvature and strain that have frequently been noted along measured monitoring lines have generally been found to be localised effects associated with escarpments, river valleys, creek alignments or geological anomalies. Consequently, many of them are predictable.

Higher values of measured strain can also arise from buckling of near-surface strata at shallow depths of cover, from disturbance of survey pegs and from survey errors. There are, therefore, some anomalies that can not be predicted and it has to be accepted that there is a small risk of peak values of strain and curvature occurring, at some point, in addition to the predicted systematic background strains and the predictable local peaks. It is preferable to deal with such anomalies on a statistical basis and wherever measured records are available, frequency analyses should be prepared in order to determine the likely incidence of such occurrences.

A histogram of measured strains at South Bulga Colliery, where the depth of cover to the Whybrow Seam varies between 40 metres and 160 metres, is shown in Fig. 1.7. It can be seen that 90% of the measured strains were between 1.0 mm/m, tensile, and 2.5 mm/m, compressive. Approximately 9% of tensile strains were in the range 2.5 mm/m to 17 mm/m, whilst 9% of compressive strains were in the range 1.0 mm/m to 12.5 mm/m. Only 1% of strains exceeded 17 mm/m, compressive, or 12.5 mm/m, tensile.

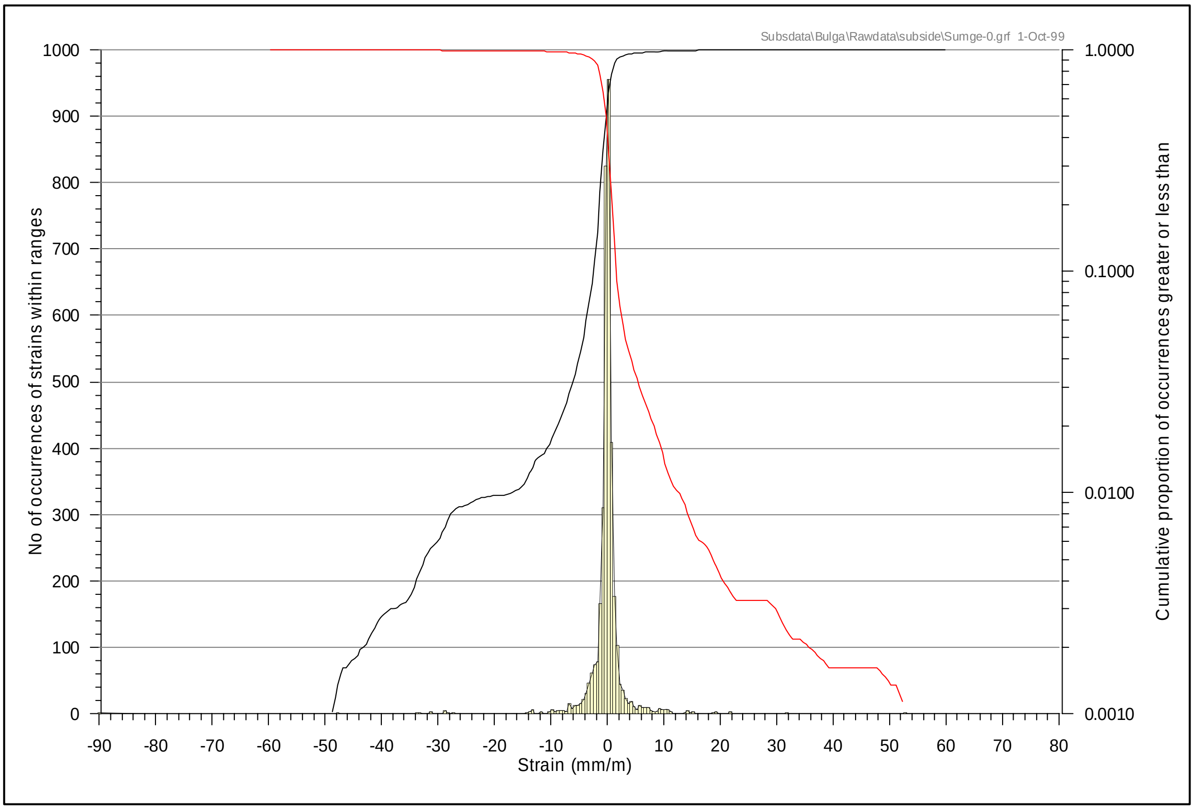


Fig. 1.7 Graph showing Histogram of Strain Occurrences at South Bulga Colliery

1.4. Adjustment of the Incremental Profile Method for Multi-Seam Mining Areas

1.4.1. Introduction

As discussed by Kratzsch (1983), a rock mass that has been undermined many times can be regarded as an accumulation of generally loose blocks of stone. The movement of the non-cohesive blocks within the rock mass are less dependent on the properties of those blocks, and more dependent on stochastic movement processes.

After extracting the longwalls in the Woodlands Hill and the Glen Munro Seams, the overlying strata will become more fragmented, particularly within and immediately above the longwall goaf regions, and higher stress conditions will be created in the strata above and below the remaining chain pillars in these seams. The subsidence movements, due to extraction of the longwalls in the Arrowfield, Bowfield and Piercefield Seams, will be affected by the changed strata conditions above the Woodlands Hill and Glen Munro Seams.

The difference in strata behaviour will depend on the:-

- Magnitude of the subsidence caused by mining the overlying seam,
- Degree of fragmentation or the proportion of voids left in the overlying strata, due to mining the overlying seam,
- State of stress in the remaining pillars,
- Relative positions of the overlying and underlying pillars, and
- Interburden thicknesses between the seams.

As a consequence of the changed strata conditions, the magnitudes and shapes of the subsidence profiles above the multi-seam extractions will differ from those over the single seam extractions.

1.4.2. Literature Review on Subsidence Impacts caused by Multi-Seam Mining

It is generally accepted that the magnitude of subsidence caused by multi-seam mining is greater than for single seam extractions of the same thickness, but, in addition, the shapes of the resulting subsidence profiles are flatter and wider. In order to calibrate the Incremental Profile Method for use in multi-seam mining cases, a detailed literature study was undertaken into available local and overseas subsidence prediction methods and monitoring data from multi-seam cases.

Most of the available literature was found in the United Kingdom and United States of America, and many of the published papers discussed ground control and mine safety issues resulting from the mining of longwalls both under and over previously extracted seams.

Considerable discussion was focussed on comparing the state of stress and stability of the pillars, the differences between stacking or staggering the pillars in overlying and underlying seams and the height of the collapsed zone above the extracted seam. Papers including observed subsidence survey data, in multi-seam mining cases, in Australia, have been written by Kapp, Holla and Holt, and these papers are discussed below.

Kapp (1985) advised that more subsidence would occur from mining a seam in multi-seam mining conditions than would occur under single-seam conditions. He reported that the subsidence measured after longwall mining at South Bulli Colliery was greater than the extracted seam thickness due to the additional effect of the collapse of pillar remnants in the overlying seam, which had been extracted by bord and pillar extraction methods. Similar observations were made at Wyee Colliery by Holla and Thompson (1988).

A more graphic example was given in the case of the longwalls at South Bulli Colliery of the Southern Coalfield as discussed by Kapp (1982). These longwalls were mined in the Balgownie Seam below pillar stooks which remained in old workings in the Bulli Seam, only 10 metres above the longwalls. The observed subsidence was in some cases greater than the thickness of the seam mined in the longwalls due to the additional effect of the collapse of pillar remnants in the Bulli Seam."

Holla and Thompson (1992) discussed the observed ground movements due to the extraction of two longwall panels at Newstan Colliery that were located on top of each other. Longwall 6 was extracted first in the Great Northern Seam and Longwall 8 was extracted one year later in the Fassifern Seam. Both panels were shallow, with depths of cover between 50 metres and 65 metres, and the panel width in both cases was more than three times the depth of cover. The tailgate of Longwall 8 was located directed below the tailgate of Longwall 6.

A maximum subsidence of 2 metres, which was 60 % of the extracted seam thickness, was observed after mining the Great Northern Seam. A maximum subsidence of 3.2 metres, which was 100 % of the extracted seam thickness, was observed after mining the Fassifern Seam. The interburden thickness was 15 metres, which the authors concluded was less than the height of the collapse zone above the extraction in the Fassifern Seam.

Holt (1996, 2001), on the other hand, advised that, based upon his observations in the Hunter Valley, an "additive" approach could be used and that multi-seam predictions could be made by treating each seam as a single seam and adding the results together.

Waddington Kay & Associates (2001), in its report to the Commission of Inquiry into the proposed Dendrobium Mine, provided monitored subsidence data from the mining of Longwalls 1 to 6 in the Wongawilli Seam at Kemira Colliery, which were 30 metres below bord and pillar workings in the Bulli Seam at Mount Kembla and Kemira Collieries.

The old mine workings in the Bulli Seam at Mount Kembla and Kemira Collieries were fully extracted except for a number of very small pillars, sometimes referred to as stooks, which were left in place to temporarily support the roof. It is reasonable to assume that these stooks would have collapsed as the longwalls in the Wongawilli Seam were extracted, allowing further settlement and consolidation of the strata above the Bulli Seam to occur. It is conjectured that the cracking or fragmentation of the strata above the Bulli Seam, due to the earlier mining, would also have resulted in greater subsidence as the Wongawilli Seam was mined, due to the reduction in the shearing capacity of the cracked strata.

The additional ground movement is dependent upon the thickness of the seam to be extracted, the thickness of the interburden between the seams, the methods of mining, the percentage of extraction in the previously mined seams, and the amount of subsidence caused by mining the previously mined seams as a proportion of the extracted seam thicknesses.

1.4.3. Available Multi-Seam Subsidence Monitoring Data from NSW Coalfields

Subsidence survey data were available from the following multi-seam mining cases:

- Newstan Colliery Longwall 8 in the Fassifern Seam - below LW6 in the Great Northern Seam
- Newstan Colliery Longwalls 1, 2, 3 and 4 - below extracted pillar workings
- Wyee Colliery Longwalls 1, 2, 3, 4, 7 and 9 - below extracted pillar workings
- John Darling Colliery Longwall 1 - below extracted pillar workings
- Teralba Colliery Longwalls 6, 7, 8 and 9 - below extracted pillar workings
- Kemira Colliery Longwalls 1 to 6 - below extracted pillar workings

This data has been analysed in order to develop a series of multiplying factors that can be applied to the predicted maximum incremental subsidence for a single seam to allow for the multi-seam effects of the overlying seams, which is discussed in Section 1.4.4. It has also been used to assist in developing a series of incremental subsidence profile shapes, which can be used to model incremental subsidence profiles in multi-seam mining cases, which is discussed in Section 1.4.5.

The maximum observed incremental subsidence in the available data from multi-seam longwall cases is shown in Fig. 1.8. It can be seen that the Newstan Colliery Longwall 8 case provided a significantly greater observed maximum incremental subsidence as a proportion of the extracted seam thickness, compared to the other cases, primarily due to its extremely shallow depth of cover and small interburden thickness. The South Bulli - Balgownie Seam case, however, reported by Kapp (1985), may also have experienced a similar ratio of maximum observed incremental subsidence to extracted seam thickness.

It can be noted from Fig. 1.8 that the magnitudes of the maximum incremental subsidence from multi-seam mining cases are generally greater than single seam cases. For each case, a prediction was made using the standard Incremental Profile Method for single seams and the observed multi-seam subsidence values were, on average, 10% higher than the predicted single seam cases.

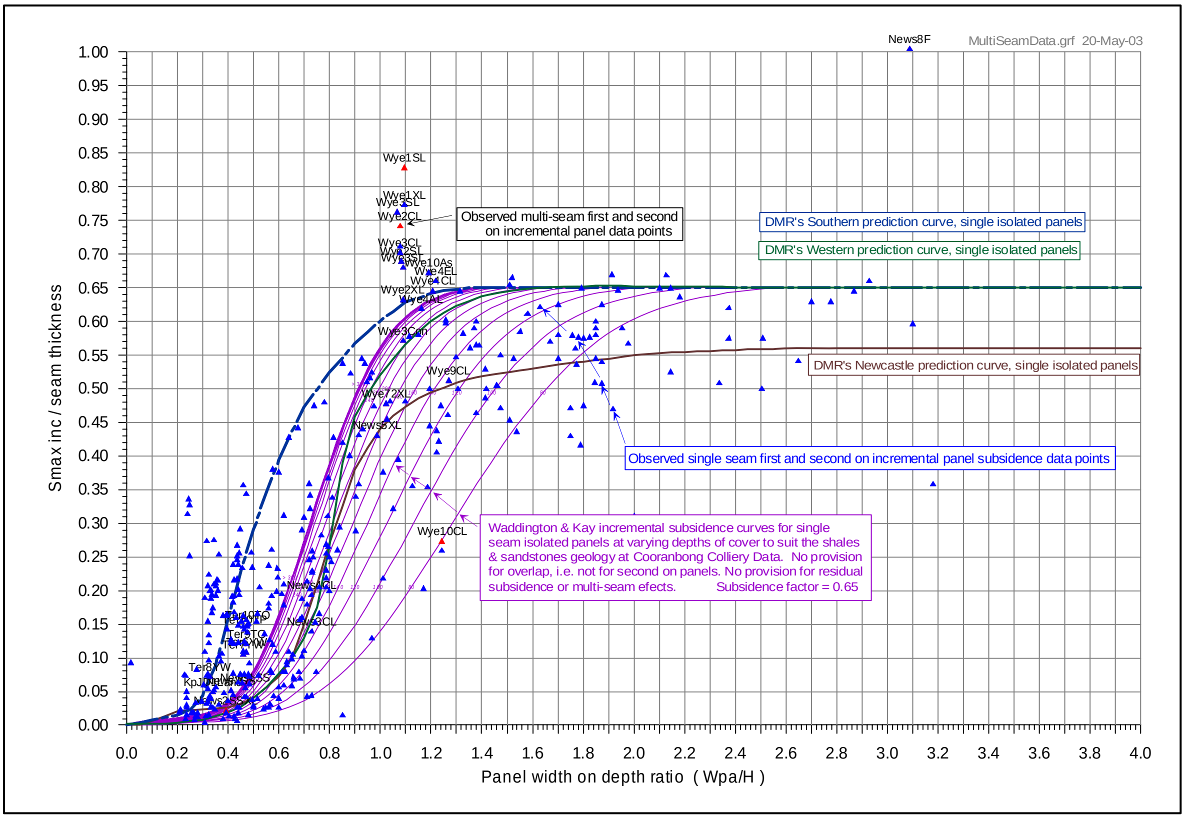


Fig. 1.8 Review of Maximum Incremental Subsidence from Multi-Seam Cases

1.4.4. Method of Multi-Seam Subsidence Predictions

Based upon an extensive review of multi-seam mining literature, subsidence predictions and measured subsidence levels, MSEC has developed multiplying factors that can be applied to the predicted maximum incremental subsidence for a single seam to allow for the multi-seam effects of the overlying seams.

A summary of the multi-seam prediction factors for an interburden thickness between 30 and 50 metres is shown in Table 1.1. A summary of the multi-seam prediction factors for an interburden thickness between 80 and 110 metres is shown in Table 1.2.

Table 1.1 Multi-Seam Prediction Factors for Interburden Thickness between 20 and 50 metres

Predicted Subsidence Factor for single seam (*Smax/T*) (%)	Overlying pillared areas (stable)		
	Extra Subs Factor (%)	Total Subs Factor (%)	Multiplying Factor
5	5	10	2.00
10	5	15	1.50
15	5	20	1.33
20	5	25	1.25
25	5	30	1.20
30	5	35	1.17
35	5	40	1.14
40	5	45	1.13
45	5	50	1.11
50	5	55	1.10
55	5	60	1.09
60	5	65	1.08
65	5	70	1.08

Table 1.2 Multi-Seam Prediction Factors for Interburden Thickness between 80 and 110 metres

Predicted Subsidence Factor for single seam (*Smax/T*) (%)	Overlying pillared areas (stable)		
	Extra Subs Factor (%)	Total Subs Factor (%)	Multiplying Factor
5	2.5	7.5	1.50
10	2.5	12.5	1.26
15	2.5	17.5	1.17
20	2.5	22.5	1.12
25	2.5	27.5	1.10
30	2.5	32.5	1.08
35	2.5	37.5	1.07
40	2.5	42.5	1.06
45	2.5	47.5	1.06
50	2.5	52.5	1.05
55	2.5	57.5	1.05
60	2.5	62.5	1.04
65	2.5	67.5	1.04

It can be seen from these tables that the multi-seam prediction factors are smaller for the higher depth of interburden. The interburden thickness between the proposed longwalls in successive seams varies between 50 metres and 110 metres, typically being around 70 metres. The multi-seam factors will, therefore, vary between those shown in Table 1.1 and Table 1.2.

The multi-seam prediction factors are based upon a limited amount of measured data and do not necessarily represent an upper-bound case. It is, therefore, possible that observed subsidence parameters may be greater than those predicted, although it is unlikely that the predictions will be substantially exceeded. It is also possible that the observed subsidence parameters could be less than predicted. It is recommended that monitoring be undertaken during the mining of longwalls so that the multi-seam prediction factors can be reviewed and revised to reflect the local conditions.

1.4.5. Review of Incremental Subsidence Profile Shapes for Multi-Seam Mining

A review of incremental subsidence profile shapes in multi-seam mining situations was carried out for this project and Fig. 1.9 shows a comparison between the observed multi-seam incremental profiles and the predicted single-seam incremental profiles for the same longwalls. This exercise confirmed that multi-seam incremental profile shapes were wider and flatter than single-seam incremental profile shapes for the same panel width-to-depth ratio. Study of the multi-seam profiles enabled the development of a method for the prediction of the incremental subsidence profiles in the multi-seam areas of this project.

Fig. 1.9 shows the observed multi-seam incremental subsidence profiles plotted in a normalised form, that is, subsidence values divided by the maximum observed subsidence value, versus the distance from the maingate of the incremental panel divided by the panel width.

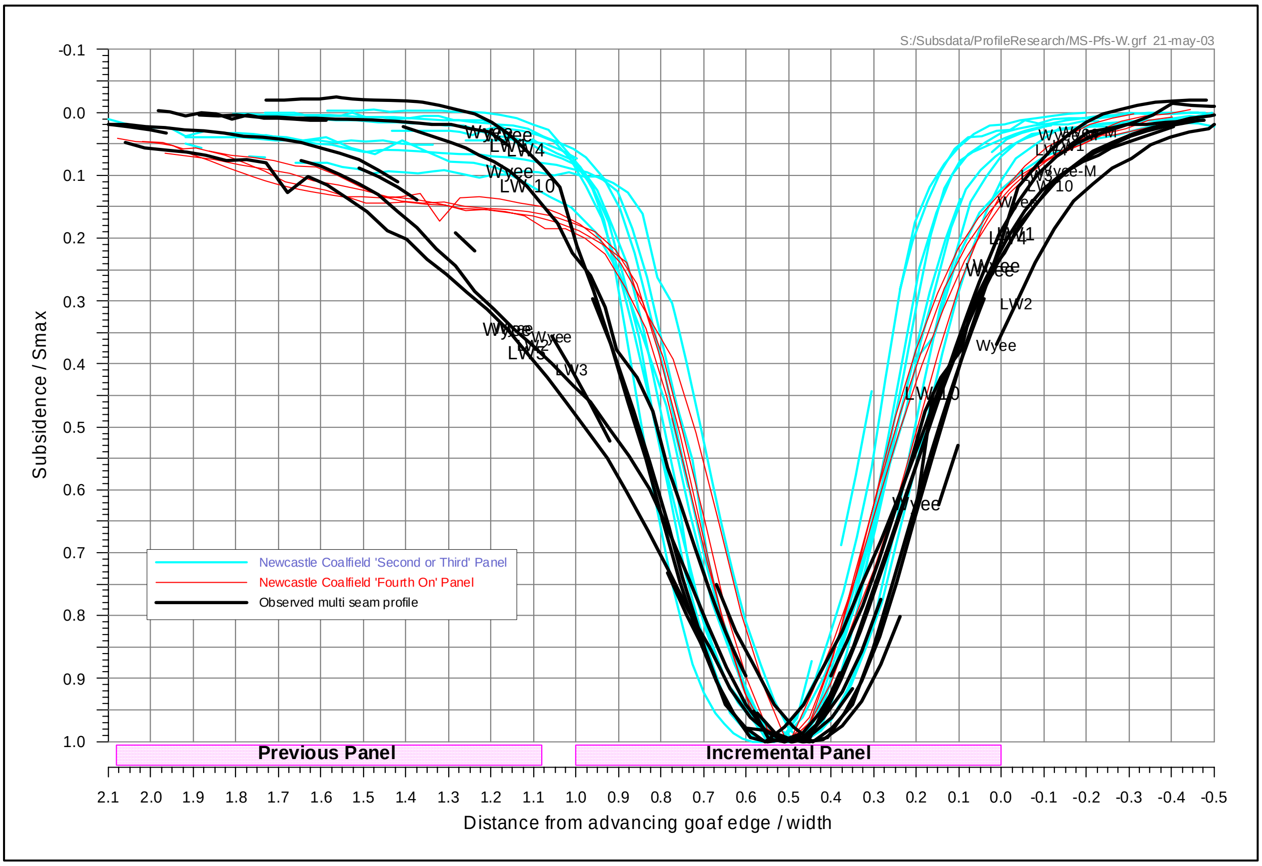


Fig. 1.9 Comparison between Single and Multi-Seam Incremental Subsidence Profiles

Fig. 1.10 shows the model multi-seam incremental profiles for a range of panel width-to-depth ratios that have been fitted over the available observed multi-seam incremental subsidence profiles, and these profile shapes have been used when predicting subsidence profiles for the multi-seam areas of this project.

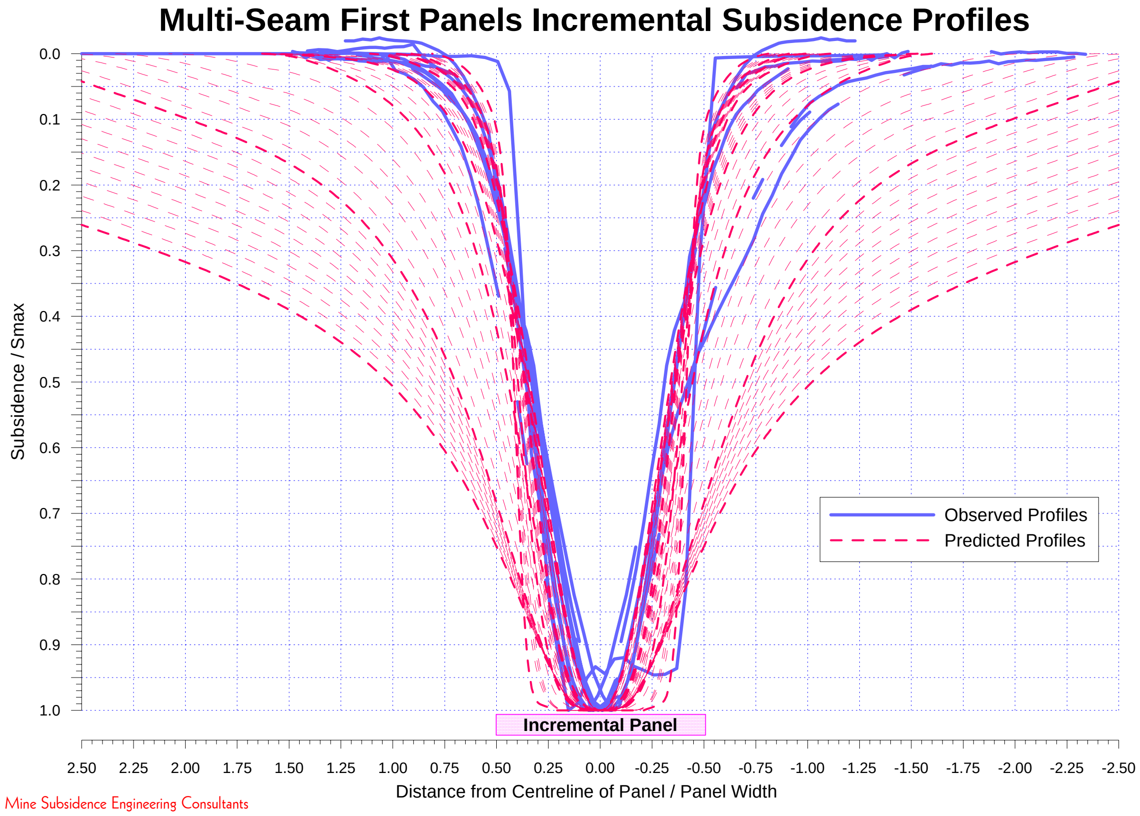


Fig. 1.10 Observed and Predicted Multi-Seam Incremental Profiles

The multi-seam incremental profiles in Fig. 1.10 are representative of the data currently available for observed multi-seam mining cases in Australia, which are relevant for this project. As this data set is limited, a reasonably conservative approach has been taken in developing the model. It is, however, possible that observed subsidence profiles may vary from those predicted in this report, although it is unlikely that the actual profiles will be substantially different from those that have been predicted.

1.5. Increased Predicted Ground Movements due to the Settlement of Overburden Spoil Heaps

The Incremental Profile Method is used to predicted subsidence at the natural surface level, and does not include additional settlement which may occur in spoil heaps located above extracted longwalls. The settlement of an unconsolidated spoil heap is additional to the predicted subsidence contours obtained provided in this report. In addition to this, the stability of an unconfined spoil heap may be affected by the subsidence and settlement which occurs when it is undermined.

A literature review was carried out in order to determine whether any empirical data might be available on the settlement of spoil heaps as they are undermined. Research in the United Kingdom has revealed that:-

- The subsidence profile that develops on a spoil heap is wider and deeper than both the predicted profile and the profile that develops on adjacent natural ground, due to additional settlement or consolidation of the spoil heap material,
- The magnitude of this settlement depends upon the extent, dimensions and rate of mine working, upon the geology of the site and upon the initial density of the spoil,
- The magnitude of the settlement is greatest over the worked-out area of the coal,
- The modified subsidence profile results in strain and tilt profiles that differ correspondingly from those predicted, and
- The initiation of ground movement due to an approaching longwall mine working is detected sooner on a spoil heap than on the adjacent natural ground.

In summary, mine subsidence can affect the stability of spoil heaps by:-

- Altering the shear strength of the spoil,
- Altering the internal and surface drainage of both the spoil heap and its foundation,
- Causing an increase in pore pressures in both the spoil heap and its foundation,
- Modifying the geometry of the spoil heap slope, and
- Inducing movement along old planes of failure.

Research work on spoil heap settlement was also referred to by Whittaker and Reddish (1989):

"Several other field investigations were carried out in the U.K. coalfields in order to monitor the general character of surface deformational behaviour of spoil heaps subjected to the effects of mining subsidence. The purpose of these studies was to compare the response of spoil heaps to undermining and relate these to anticipated movements as predicted by standard subsidence calculation procedures, Forrester and Whittaker (1976). Standard subsidence measuring methods were applied to collate data on the deformational behaviour of the spoil heaps.

The following general conclusions were drawn by Forrester and Whittaker (1976) on undermining spoil heaps:-

1. Spoil heap subsidence was observed to be greater than predicted in both magnitude and extent; maximum subsidence was observed to be as much as 67% greater than that for natural ground. Predicted magnitudes were generally low estimates.
2. Spoil heaps responded earlier to the effects of subsidence than the natural ground.
3. Observed maximum surface strains were greater for spoil heap structures than for natural ground.
4. The incidence of surface cracking was not covered by the standard prediction procedures; cracks on the surface of the tip were observed to occur when the observed tensile ground strain exceeded 3 mm/m. Compression humps became apparent on the spoil heap at compressive strain magnitudes of the order of 10 mm/m.
5. The presence of a mine spoil heap resulted in the area of influence of mining subsidence increasing, with angles of draw of up to 45^{o} being more representative than the 26½^{o} value for natural ground.
6. Mine spoil heaps were observed to respond gradually with uniform development of ground movement during the period of mining subsidence.
7. Typical displacement features observed, were those of excess settlement at the crest and heave at the toe of a mine spoil heap under the influence of mining subsidence.

A tentative linear relationship is indicated by these results and this is shown in Fig. 1.11. The results suggest that there is a relationship between excess settlement per unit spoil heap height and the *S/H* ratio. The relationship shown in this figure has been used to predict the settlement of any overburden spoil heaps for this project.

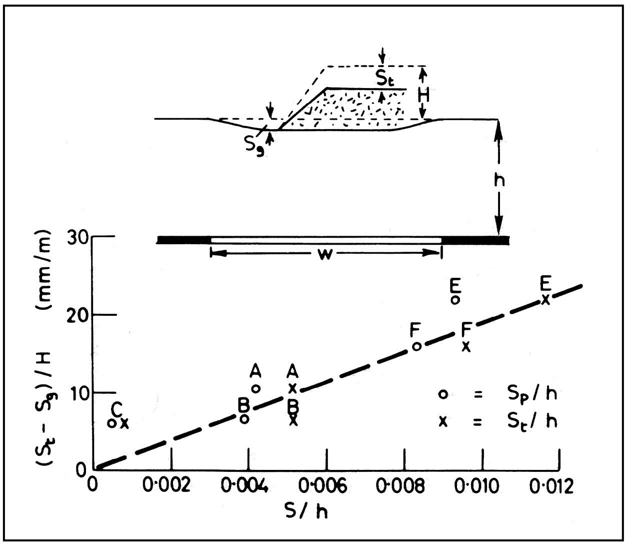


Fig. 1.11 Relationship between Excess Settlement of Mine Spoil Heap and the S/H Ratio. (From Whittaker and Reddish, 1989)

1.6. Surface Cracking

As subsidence occurs, cracks will generally appear in the tensile zone, i.e. within 0.1 to 0.4 times the depth of cover from the longwall perimeter. It is also possible that cracking could occur in other locations at right angles to the longitudinal centreline of the longwall as the longwall is mined and the subsidence trough develops. However, this cracking is likely to be transient, since the tensile phase, which results in the cracks opening up, is generally followed by a compressive phase that closes them.

Surface tensile fracturing in exposed sandstone is likely to occur coincident with the maximum tensile strains, but fracturing could also occur due to buckling of surface beds that are subject to compressive strains. Fracture widths tend to increase as the depth of cover reduces and significant cracking would normally be expected where the depth of cover is less than 250 metres.

Noticeable cracks are less likely to occur at low levels of strain, i.e. where the strains are less than 2 mm/m. Kratzsch (1983) indicated that tension cracks had been recorded in Germany, at strains of 3 mm/m to 7 mm/m. Whittaker and Reddish (1989) indicated, however, that noticeable cracking had been recorded in the United Kingdom, in Triassic Sandstone, at strains less than 2 mm/m.

Fig. 1.12 shows the relationship between the depth of cover and the width of surface cracks, based upon measured data in the NSW Coalfields and observations over mines in the United Kingdom. The upper blue line on the graph represents the upper-bound limit of the data in Australia and the lower red line represents the upper-bound limit of the data measured at South Bulga Colliery. It can be seen that the crack width increases as the depth of cover reduces and that significant crack widths can develop at lower depths of cover.

As subsidence movements were monitored over Longwalls 1 to 4 at South Bulga Colliery, it was noted that cracking had occurred generally over the area of the longwalls. The depth of cover over the longwalls varied between 40 metres and 157 metres and the seam thickness varied between 2.25 metres and 2.6 metres. The strata above the seam in this location were generally sandstones or fine-grained sedimentary rocks.

The maximum subsidence was approximately 1400 mm. Tilts reached maximum values of approximately 55 mm/m, transversely across the longwalls, and 250 mm/m, along the longwalls, due to buckling of the strata at shallow depths of cover. Measured strains varied between 54 mm/m, tensile, and 110 mm/m, compressive.

As expected, the extent of cracking and the widths of the cracks were both greater at the shallower depths of cover. Cracks up to 30 mm wide were recorded where the depth of cover was 155 metres and cracks up to 150 mm wide were recorded where the depth of cover was only 40 metres. Some compressive buckling was also noted at the shallower depth of cover.

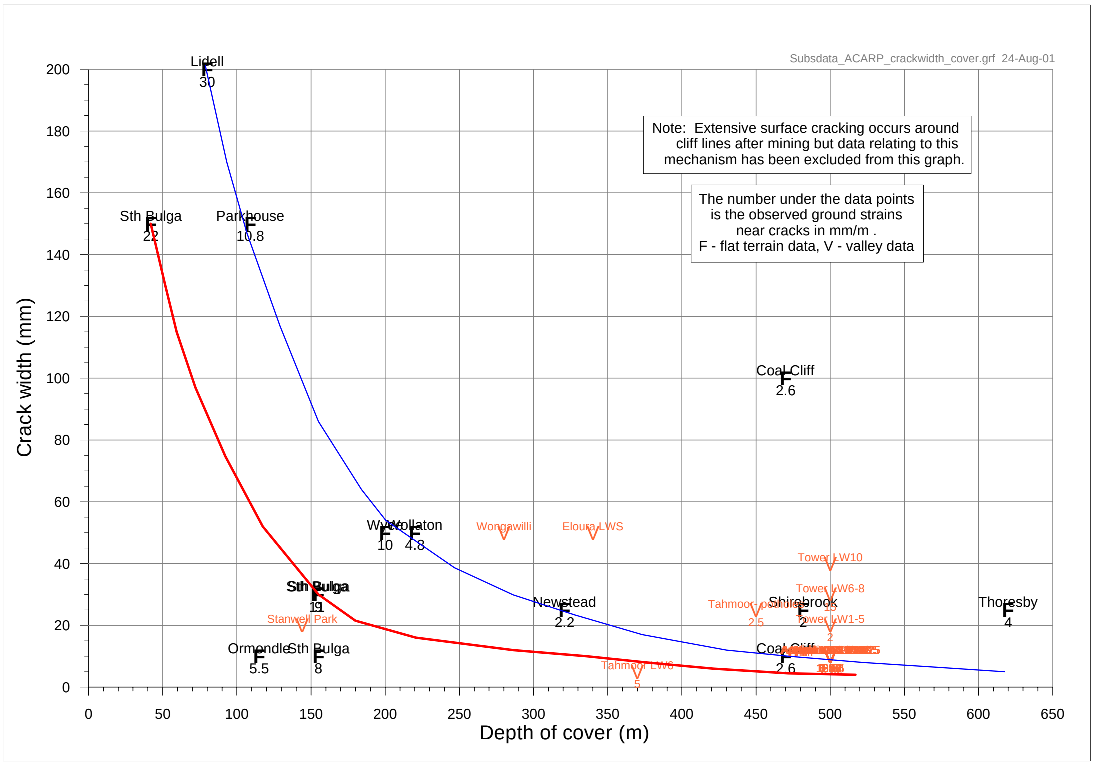


Fig. 1.12 Relationship between Crack Width and Depth of Cover

1.7. Additional Mining-Induced Ground Movements caused by Topographic or Geological Factors

1.7.1. Analysis of Ground Displacements from Measured Survey Data

When longwalls are extracted beneath steeply incised terrain, the ground movements that occur around the longwalls are very complex, particularly within a high stress regime, and these complex movements result from a number of distinct mechanisms. During research by MSEC, previously known as Waddington Kay & Associates, it was found that measured movements were often a combination of some or all of the following components:

Normal mining-induced horizontal movements of points on the surface, around an extracted panel, as subsidence occurs, which are generally directed towards the centre of the extracted goaf area.

- Upsidence and closure of creeks, gullies, river valleys and gorges due to valley bulging, which results from the redistribution of pre-existing in-situ stresses, as mine subsidence occurs.
- Predominantly horizontal displacements of surface strata due to release and redistribution of pre-existing regional in-situ stresses as the extracted goaf areas increase in size within a local mining area.
- Mass slippage movements in a downhill direction due to topographic factors.
- Differential movements of the strata on opposite sides of a fault line.
- Continental drift, which is known to change the positions of points on the Australian Plate by moving them approximately 70 mm each year towards the northeast.

Study of data collected over longwalls in the Southern Coalfield during the last twenty years has led to the development of methods that can now be used for the prediction of some of these components which are discussed in this section. Valley related movements are less obvious in the Hunter and Newcastle Coalfields and are usually more difficult to resolve from observed monitoring data. The reason for this is that the systematic movements in the Hunter and Newcastle Coalfields are generally much larger than those in the Southern Coalfield, and these movements tend to overshadow any valley related movements which may occur, especially in smaller, less incised valleys.

In developing predictive methods, it is advantageous if the measured data can be broken down into its various components prior to analysis. This is not an easy task, however, because in most cases the measured survey movements are relative movements rather than absolute movements and in all cases they are total movements. When analysing the closures that have been measured in creeks and river valleys due to valley bulging, however, it appears that many of the other components have little or no effect on the closure measurements.

Mass slippage down steep slopes, due to mining is a relatively rare occurrence and is due to the instability of surface soils in particular locations. Where steep slopes exist and can be affected by mining it is prudent to study the geology of the site and the nature of the surface soils so that any unstable areas can be identified. It is possible that some of the data studied by MSEC could have been affected by this mechanism, but if so it will have led to overstatement of closure movements.

Differential movements on opposite sides of a fault line are equally rare occurrences and there are only a few known major faults in the Study Areas. There is no evidence to indicate that any of the measured data used in developing the predictive methods have been affected by differential movements at faults.

In analysing the valley closure data, no allowance was made for differential movements caused by regional horizontal stress redistribution or continental drift, because the differential movements in the two sides of a valley, as a result of these mechanisms, would be negligible.

In the steep-sided Cataract and Nepean River Gorges it was found that the closures in the sides of the gorges were almost mass movements with little differential shear displacement between different horizons in the strata. Almost all of the closure, therefore, occurred in the bases of the gorges. Because the gorge bases are relatively narrow, the differential mining-induced horizontal movement, due to differential tilting in the sides of the gorges, was relatively small in comparison with the closure movements.

In the vee-shaped valleys, a large proportion of the closure occurred in the bases of the valleys, coupled with localised concentration of compressive strain, but in some cases, part of the closure was noted to occur at horizons above the bases of the valleys.

This observation from measured data was supported by numerical modelling work by CSIRO, which indicates that in vee-shaped valleys some of the shearing occurs along weaker horizons in the valley sides. The closure movements are, therefore, spread over a greater width than those measured in the gorges.

It is possible that some of the measured closure data from vee-shaped valleys could have been affected by differential systematic mining-induced horizontal movements in the valley sides. In some cases these differential movements could have caused the sides of the valley to open and the measured closure, being the sum of the two movements, could, therefore, be less than the actual closure caused by valley bulging.

The extent to which the data might have been affected in this way is difficult to determine. This is because many of the surveys that were carried out in the past did not measure the absolute movements of the ground in three dimensions. In these cases the closures have been calculated from the strains.

The method that has been developed for the prediction of closure is, therefore, based upon the overall closure of the valley recognising that, in the case of vee-shaped valleys, some of the movement will occur in the valley sides.

When predicting closures in vee-shaped valleys it would be prudent to ignore the impacts of differential mining-induced horizontal movements in the valley sides, if those movements result in a reduction in the predicted closures.

1.7.2. Normal Mining Induced Horizontal Ground Movements

The 'normal' horizontal component of subsidence, sometimes referred to as horizontal displacement, can be predicted, in flat terrain, i.e. where steep slopes or surface incisions do not influence ground movement patterns. As discussed in Section 1.3, the magnitude and direction of horizontal displacements can be determined, approximately, from the predicted tilt profiles, by applying the strain-curvature factor. These subsidence induced horizontal displacements are generally directed towards the centre of the mined longwall panel as shown in Fig. 1.13.

As also discussed in Section 1.3, the appropriate strain-curvature factor for the Hunter Coalfield is 10. If the predicted tilt at a point is 2 mm/m, for example, then the predicted horizontal ground displacement will be approximately 20 mm, directed towards the centre of the mined goaf.

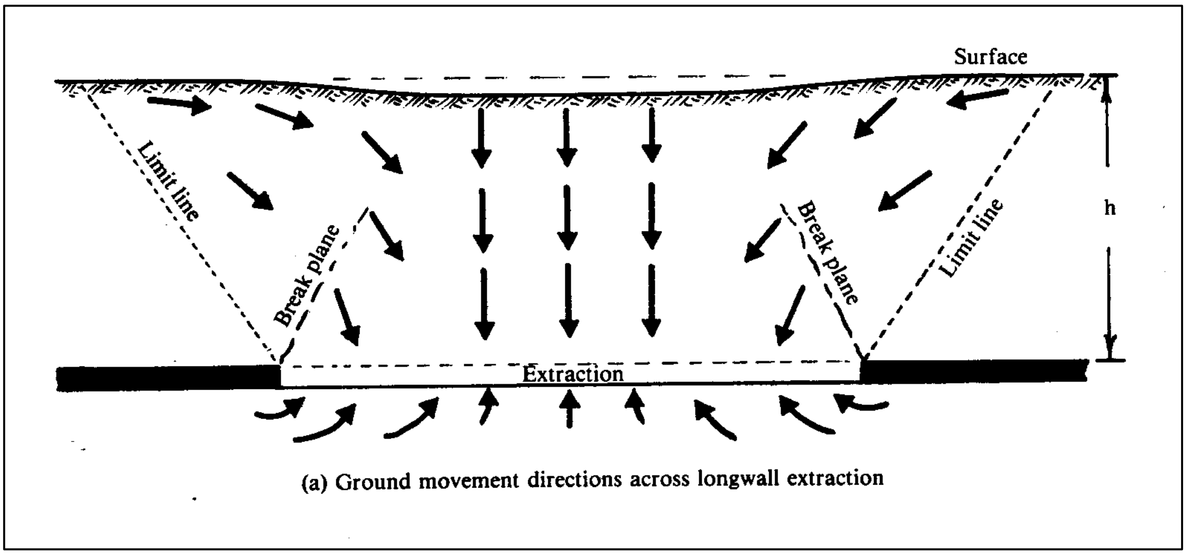


Fig. 1.13 Normal Mining Induced Movements above an Extracted Area (after Whittaker, Reddish and Fitzpatrick, 1985)

This method is only approximate and, whilst it tends to be conservative where the tilts are high, it tends to underestimate the horizontal movements where the tilts are low. Where the tilt is low, however, the 'normal' horizontal displacement is generally very small, even though it could be many times greater than the vertical subsidence at the same point. The tilts reduce with increasing distance from the goaf edge of the longwall, and at the edge of the subsidence trough, where the tilts approach zero, any small horizontal displacement at that point could be infinitely greater than the tilt. When large horizontal displacements are measured outside the goaf area, they are more likely to be a result of far-field movements, as discussed in Section 1.7.9.

1.7.3. Upsidence and Closure due to Mining beneath Gorges, River Valleys and Creeks

When creeks and river valleys are affected by mine subsidence, the observed subsidence in the base of the creek or river is generally less than the level that would normally be expected in flat terrain. This reduced subsidence is due to the floor of the valley buckling upwards. This phenomenon is referred to as valley bulging and results from the redistribution of, and increase in, the horizontal stresses in the strata immediately below the base of the valley as mining occurs. Valley bulging is a natural phenomenon, resulting from the formation and ongoing development of the valley, as indicated in Fig. 1.14, but the process is accelerated by mine subsidence. The phenomenon appears to be triggered, to varying degrees, whenever mining occurs beneath or adjacent to escarpments, gorges, river valleys, creeks or other surface incisions.

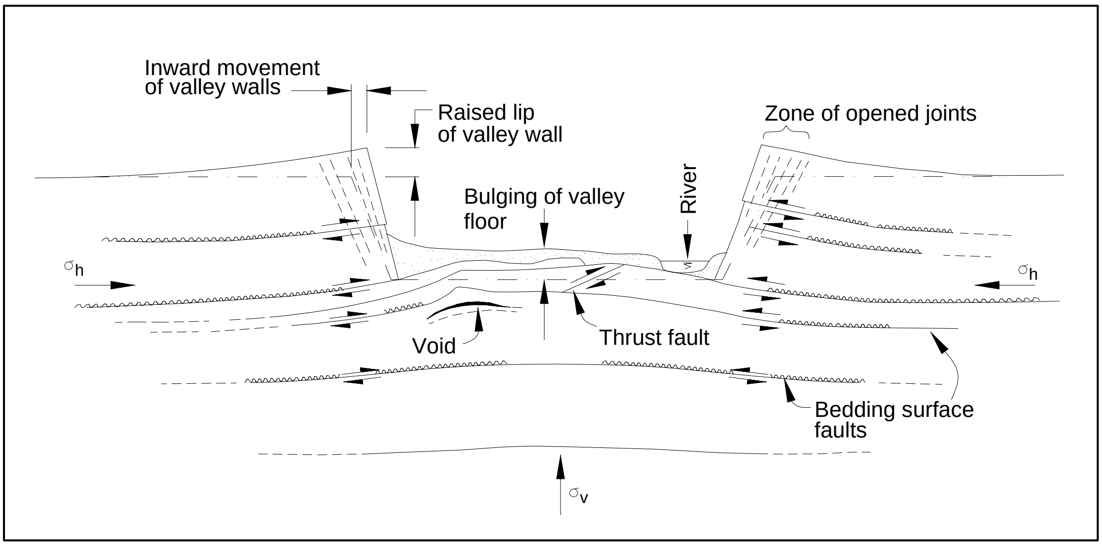


Fig. 1.14 Valley Formation in Flat-Lying Sedimentary Rocks (after Patton and Hendren 1972)

The local reduction in subsidence, which is referred to as ‘upsidence’, is generally accompanied by localised changes in tilt and curvature leading to high compressive strain in the centre of the valley and horizontal closure of the valley sides. In the case of escarpments and wide river gorges the movements may be limited to the cliffs that are closest to the extracted area.

The phenomenon is clearly seen when subsidence profiles are plotted to an exaggerated vertical scale, when the upsidence can be seen as a localised upwards spike in an otherwise smooth subsidence profile, coincident with a creek alignment. A typical example is illustrated in Fig. 1.15, which shows the measured subsidence profiles over Longwalls 1 to 6 at West Cliff Colliery, along a survey line known as the E-Line. The upsidence spike in the subsidence profile, between Longwalls 2 and 3, can be seen to coincide with the alignment of a local creek, leading to a reduced subsidence of approximately 200 mm coupled with a local concentration of compressive strain.

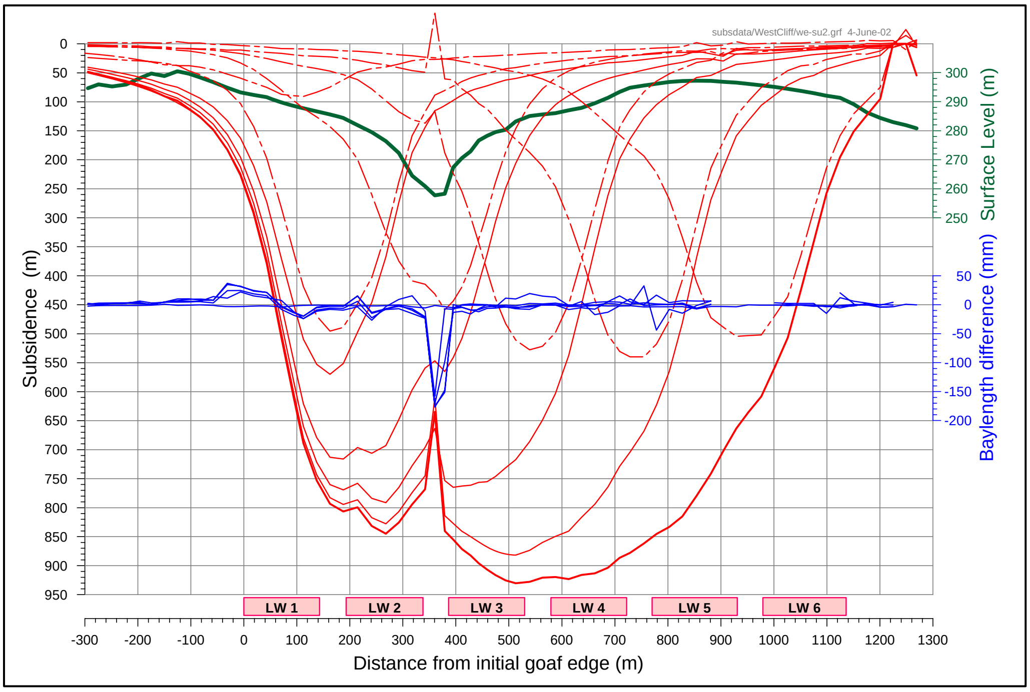


Fig. 1.15 Measured Subsidence Profiles over Longwalls 1 to 6 at West Cliff Colliery

In most cases studied, the upsidence effects extend outside the valley and include the immediate cliff lines and the ground beyond them. For example, monitoring within the Cataract Gorge, at Tower Colliery, as Longwalls 8 and 10 were mined, revealed that the upsidence extended up to 300 metres from the centre of the Gorge, on both sides of the Gorge. In that case, the magnitude of the upsidence was greater than the subsidence leading to an overall uplift in the base of the Gorge, consequently leaving it above its original pre-mining level.

In other cases, within creek alignments, upsidence has been observed well outside an extracted panel, apparently due to a beam within the near-surface strata rotating and pivoting as a seesaw, as one end of it rises and the other subsides. However, in these cases, the measured upsidence and strains were less than would be expected to arise from the compressive buckling mechanism described above.

Based upon the empirical evidence, upsidence and closure movements can be expected in cliffs and in the sides of valleys, whenever longwalls are mined beneath or adjacent to them. Such movements, however, tend to be smaller outside the goaf areas and tend to reduce with increasing distance outside the goaf edge. The movements are incremental and increase as each longwall is mined in sequence, and consequently the movements resulting from the mining of one longwall can be spread over several longwalls.

Methods of prediction have been developed for closure and upsidence, as detailed in the ACARP *Management Information Handbook on the Undermining of Cliffs, Gorges and River Systems* (Waddington Kay and Associates, 2002).

The methods used to determine the predicted upsidence and closure for gorges, creek and river valleys were developed using empirical data from the Southern Coalfield. The data was mainly taken from the Nepean and Cataract River Valleys, which are large and steeply incised when compared to many of the valleys within the Hunter and Newcastle Coalfields. It is expected, therefore, that the methods used to determine predicted upsidence and closure movements will provide conservative results for smaller, less incised creek and river valleys within the Hunter and Newcastle Coalfields.

1.7.4. The Prediction of Closure in Creeks and River Valleys

A method has been developed for prediction of closure across creeks and river valleys which is based upon measured data over a wide range of cases, with valley depths varying from 27 metres to 74 metres. This data was mainly collected from collieries in the Southern Coalfield where the valleys are incised into flat lying sedimentary deposits and where the in-situ horizontal stresses are high. However, valley closure has also been observed in other locations and with lower valley depths.

The method is expected to give superior results in areas with geology and stress regimes similar to those from which it was derived. The method is based upon upper-bound measured values and it is anticipated that the method will over-predict in most cases, especially in areas of lower stress. Further research is required to determine how pre-existing in-situ horizontal stress and variations of local geology specifically influence the closure movements.

The method of valley closure prediction was first fully described in the report tilted "Report on ACARP Research Project No C9067 Research into the Impacts of Mine Subsidence on the Strata and Hydrology of River Valleys and Development of Management Guidelines for Undermining Cliffs, Gorges and River Systems" that was published by Waddington Kay & Associates in 2002. Since then new observations of closure have permitted minor improvements to the method of prediction that allow for the detailed prediction of distribution of closure movement profiles across a valley and allow more realistic upper bound predictions when predicting closure and upsidence at large distances from the lateral and longitudinal edges of longwall panels. The minor modifications in the prediction curves are shown on the following figures.

The method for the prediction of closure is based upon a series of graphs that show the interrelationships between closure and a number of contributory factors. The interrelationships between the factors are illustrated in the following figures.

Fig. 1.16 shows a graph of closure plotted against the transverse distance from a point in the bottom of the valley to the maingate of the longwall divided by the width of the panel plus the width of the pillar.

Fig. 1.17 shows a longitudinal distance adjustment factor plotted against the longitudinal distance from a point in the bottom of the valley to the nearest end of the longwall in metres.

Fig. 1.18 shows a valley depth adjustment factor plotted against valley depth.

Fig. 1.19 shows an incremental subsidence adjustment factor plotted against the maximum incremental subsidence of the panel.

The graphs provide the original and the revised upper bound prediction curves, which are predominantly based upon closure data from the Cataract and Nepean Gorges, where the maximum incremental subsidence was approximately 410 mm and the depth of gorge was approximately 68 metres. The observed raw data values were "normalised" to account for variations in positions of the monitored creeks with respect to the panel edges and for variations in the magnitude of the maximum incremental subsidence over the mined panel and for variations in the valley depths. Large adjustment factors had to be applied to some of the raw observed data points and, where the raw data point is smaller than the survey tolerance, this magnification is also applied to the survey errors. Accordingly judgement was required to determine where to fit the new prediction curves, which are found to be above 90% of the adjusted observed closure data.

The closure is initially predicted from the graph shown in Fig. 1.16 and the value so obtained is adjusted with reference to the graphs shown in Fig. 1.17 to Fig. 1.19, depending on the position of the bottom of the valley relative to the end of the longwall, the valley depth and the maximum incremental subsidence of the longwall.

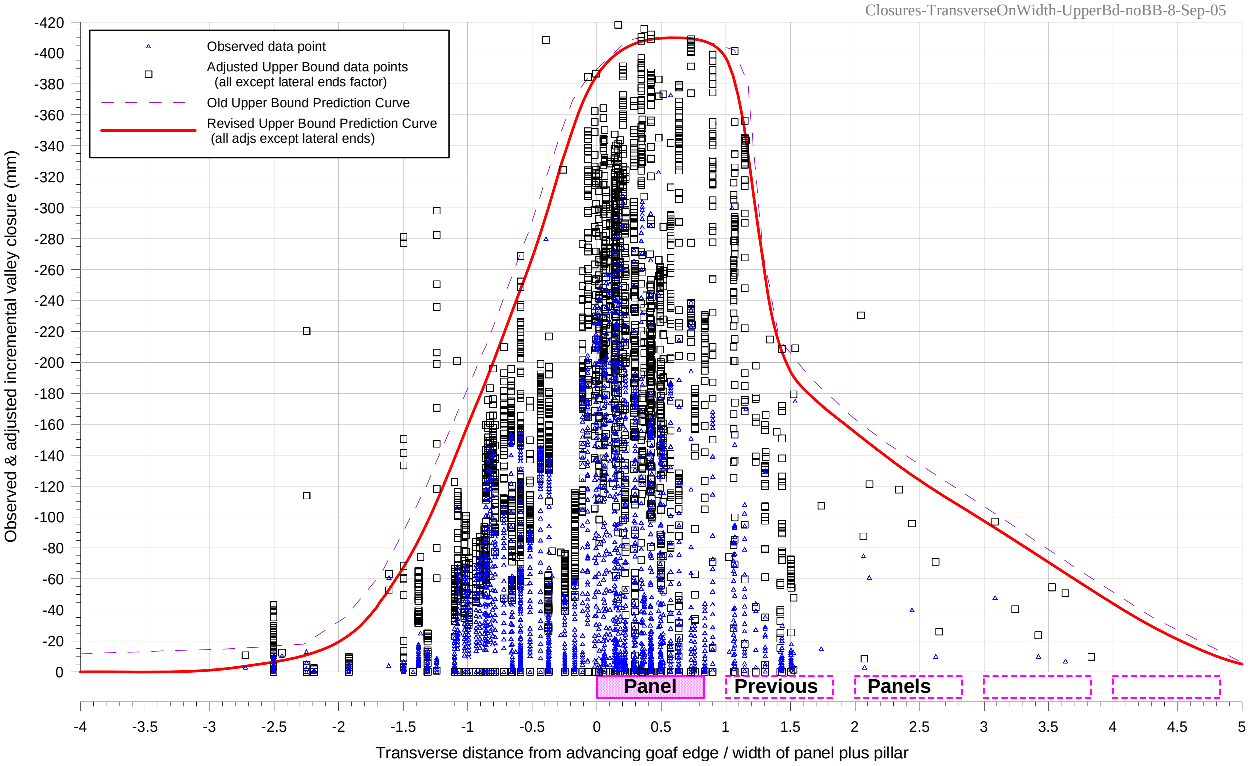


Fig. 1.16 Valley Closure versus Distance from the Maingate of the Longwall relative to the Width of the Panel plus the Width of the Pillar

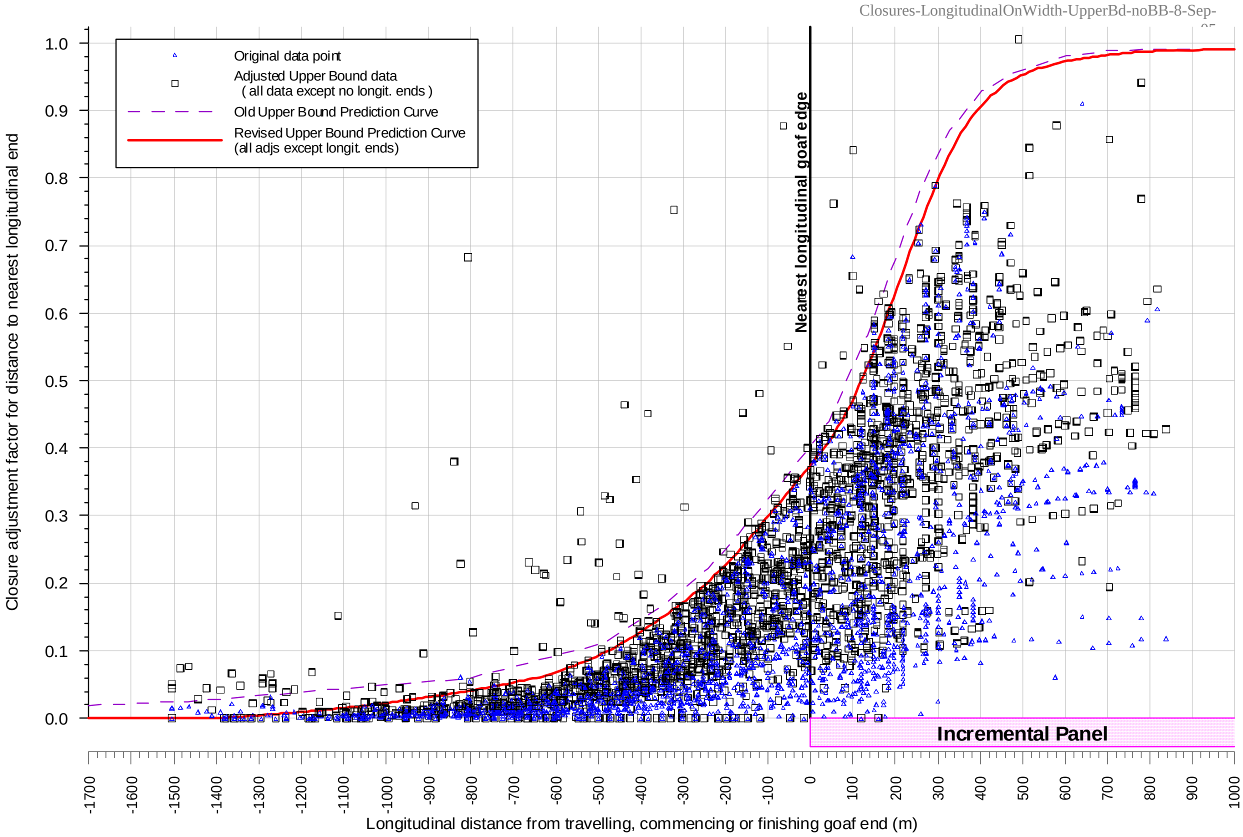


Fig. 1.17 Valley Closure Adjustment Factor versus Longitudinal Distance

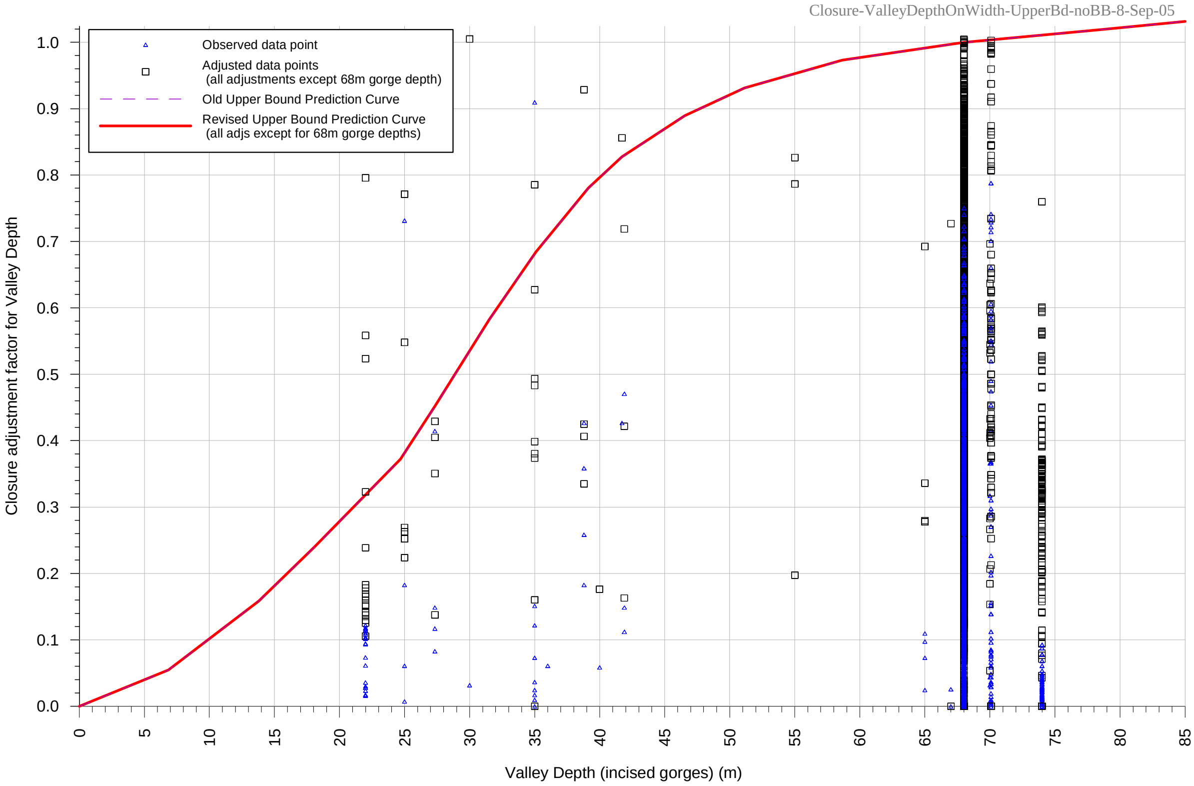


Fig. 1.18 Valley Closure Adjustment Factor versus Valley Depth

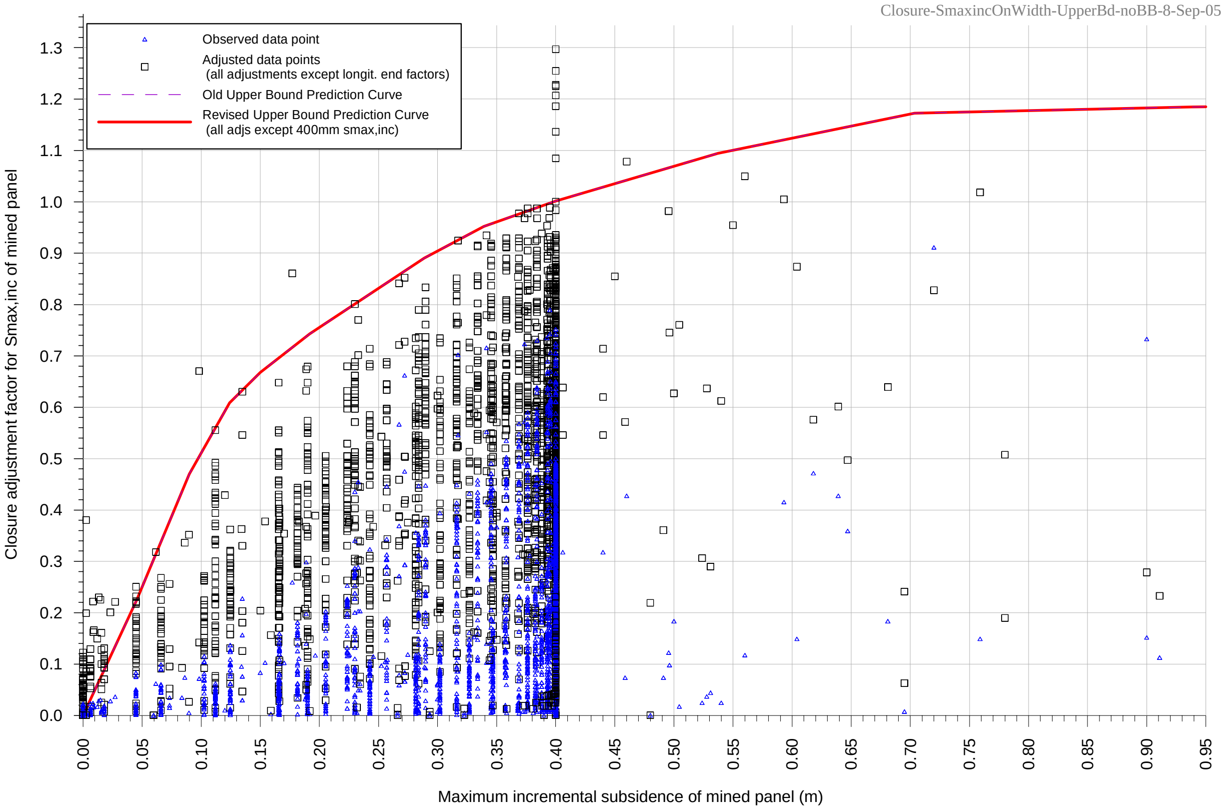


Fig. 1.19 Valley Closure Adjustment Factor versus Maximum Incremental Subsidence

Fig. 1.20 shows the distance measurement convention used to define the location of the point in the creek for which closure and upsidence predictions are required.

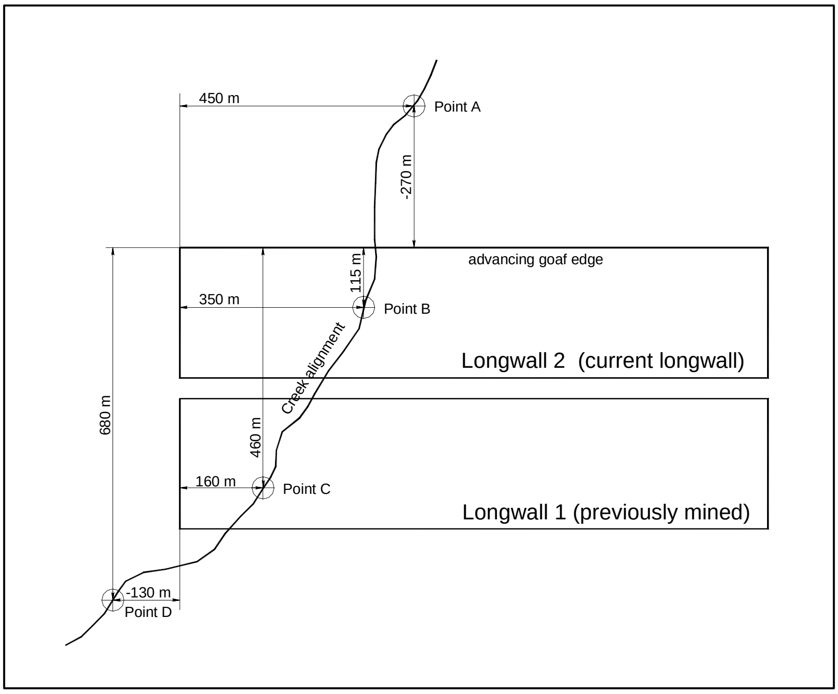


Fig. 1.20 Distance Measurement Convention for Closure and Upsidence Predictions

The transverse distances plotted in Fig. 1.16 are the distances measured at right angles to the maingate of the longwall expressed as a proportion of the width of the panel plus the width of the pillar. The transverse distances for points A, B, C and D in Fig. 1.20 are -270 metres, 115 metres, 460 metres and 680 metres, respectively, distances outside the goaf being negative.

The longitudinal distances plotted in Fig. 1.17 are the distances from the nearest end of the longwall, measured parallel to the longitudinal centreline of the longwall. These distances for points A, B, C and D in Fig. 1.20 are 450 metres, 350 metres, 160 metres and -130 metres, respectively, distances outside the goaf again being negative.

To make a prediction of closure at a point in the base of a creek or river valley, it is necessary to know the distance of the point from the advancing edge of the longwall, the longitudinal distance from the nearest end of the longwall, the valley depth, the maximum incremental subsidence of the panel that is being mined and the panel and pillar widths.

1.7.5. The Prediction of Upsidence in Creeks and River Valleys

The method developed for the prediction of upsidence in creeks and river valleys is similar to that described above for the prediction of closure. The method is based upon measured data over a wide range of cases, with valley depths varying from 8 metres to 87 metres. The data was mainly collected from collieries in the Southern Coalfield where the valleys are incised into flat lying sedimentary deposits and where the in-situ horizontal stresses are high.

The method of prediction would therefore be expected to give superior results in areas with similar geology and similar stress regimes. The method has also been modified based on new data received since the ACARP report was published in 2002. The method is based upon upper-bound measured values and it is anticipated that the method will over-predict in most cases, especially in areas of lower stress. Again, further research is required to determine how pre-existing in-situ horizontal stress and local variations in geology specifically influence the upsidence movements.

The prediction of upsidence is based upon a series of graphs that show the interrelationships between upsidence and a number of contributory factors. The interrelationships between the factors are illustrated in the following figures.

Fig. 1.21 shows the graph of upsidence plotted against the transverse distance from a point in the bottom of the valley to the maingate of the longwall divided by the width of the panel plus the width of the pillar.

Fig. 1.22 shows a longitudinal distance adjustment factor plotted against the longitudinal distance from a point in the bottom of the valley to the nearest end of the longwall in metres.

Fig. 1.23 shows a valley depth adjustment factor plotted against valley depth.

Fig. 1.24 shows an incremental subsidence adjustment factor plotted against the maximum incremental subsidence of the panel.

The graphs provide the original and the revised upper bound values, which are mainly based upon upsidence data from the Cataract Gorge, where the maximum incremental subsidence was approximately 350 mm and the depth of gorge was approximately 70 metres.

The transverse distances plotted in Fig. 1.21 are the distances measured at right angles to the maingate of the longwall, expressed as a proportion of the width of the panel plus the width of the pillar. Fig. 1.20 shows the distance measurement convention used to define the location of the point in the creek for which closure and upsidence predictions are required.

To make a prediction of upsidence at a point in the base of a creek or river valley, it is necessary to know the distance of the point from the advancing edge of the longwall, the longitudinal distance from the nearest end of the longwall, the valley depth, the maximum incremental subsidence of the panel that is being mined and the panel and pillar widths.

The initial prediction of upsidence is made using the upper-bound curve in Fig. 1.21, for the relevant transverse distance divided by panel plus pillar width. The value of upsidence is then adjusted by multiplying it by the factors obtained from the upper-bound graphs from Fig. 1.22 to Fig. 1.24.

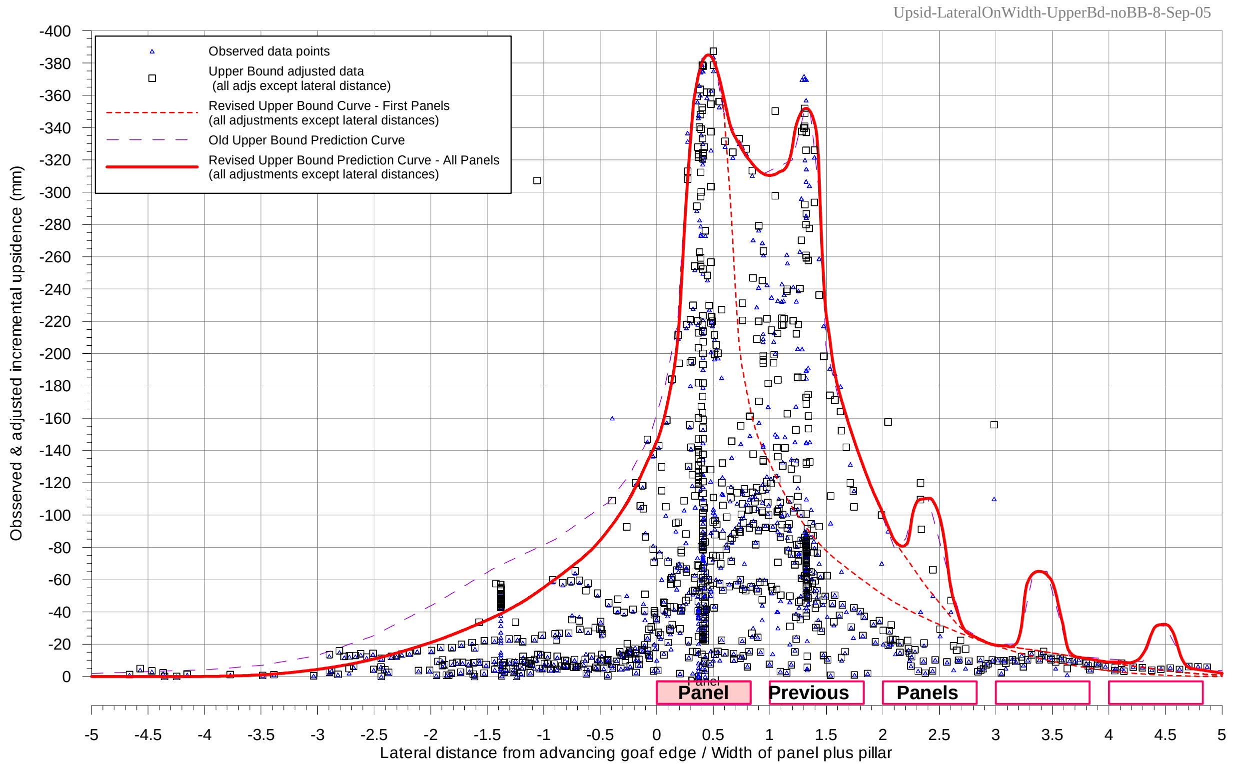


Fig. 1.21 Upsidence versus Distance from the Maingate of the Longwall relative to the Width of the Panel plus the Width of the Pillar

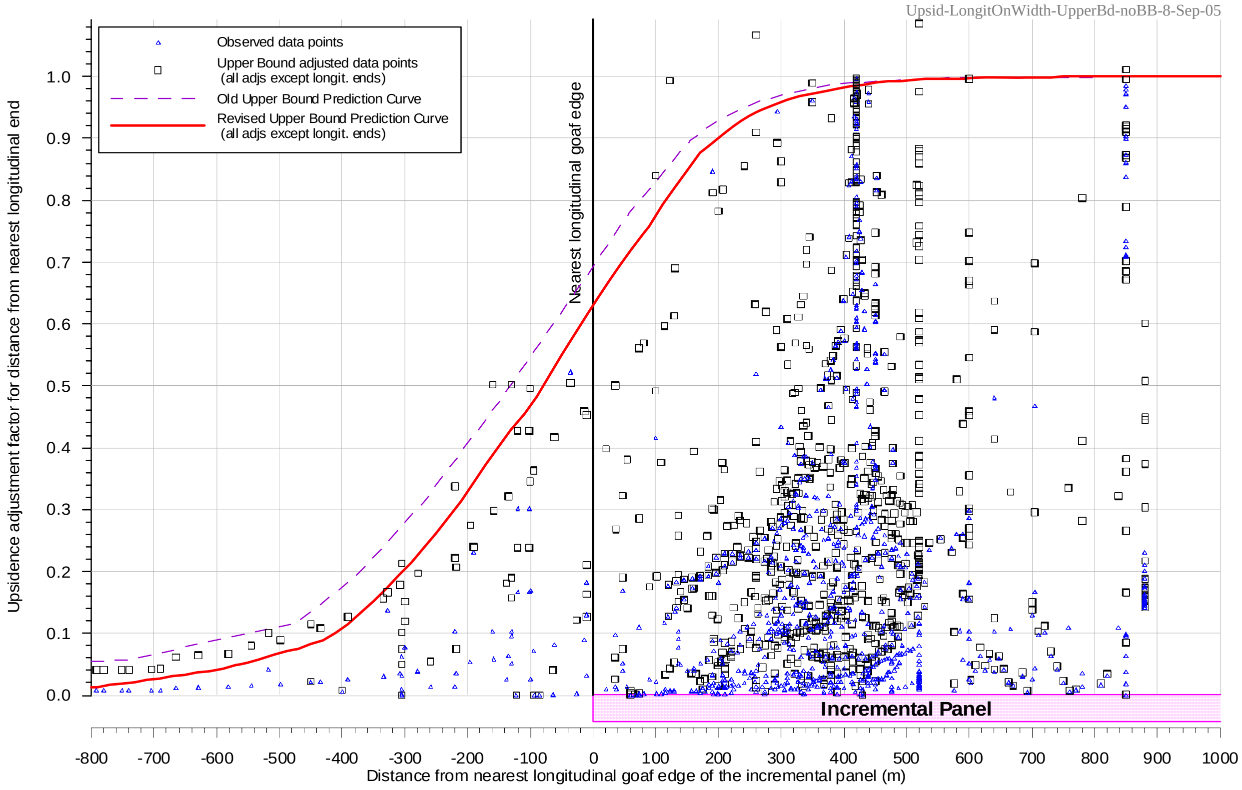


Fig. 1.22 Upsidence Adjustment Factor versus Longitudinal Distance

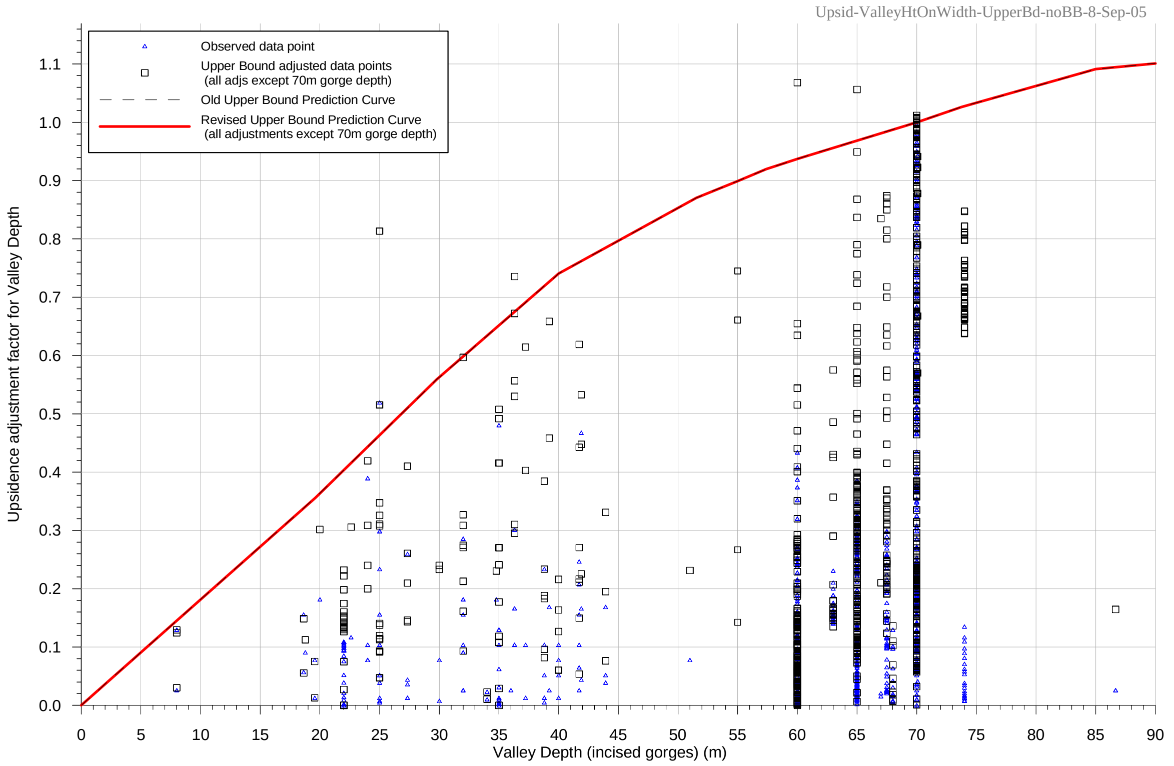


Fig. 1.23 Upsidence Adjustment Factor versus Valley Depth

Upsid-SmaxincOnWidth-UpperBd-noBB-8-Sep-05

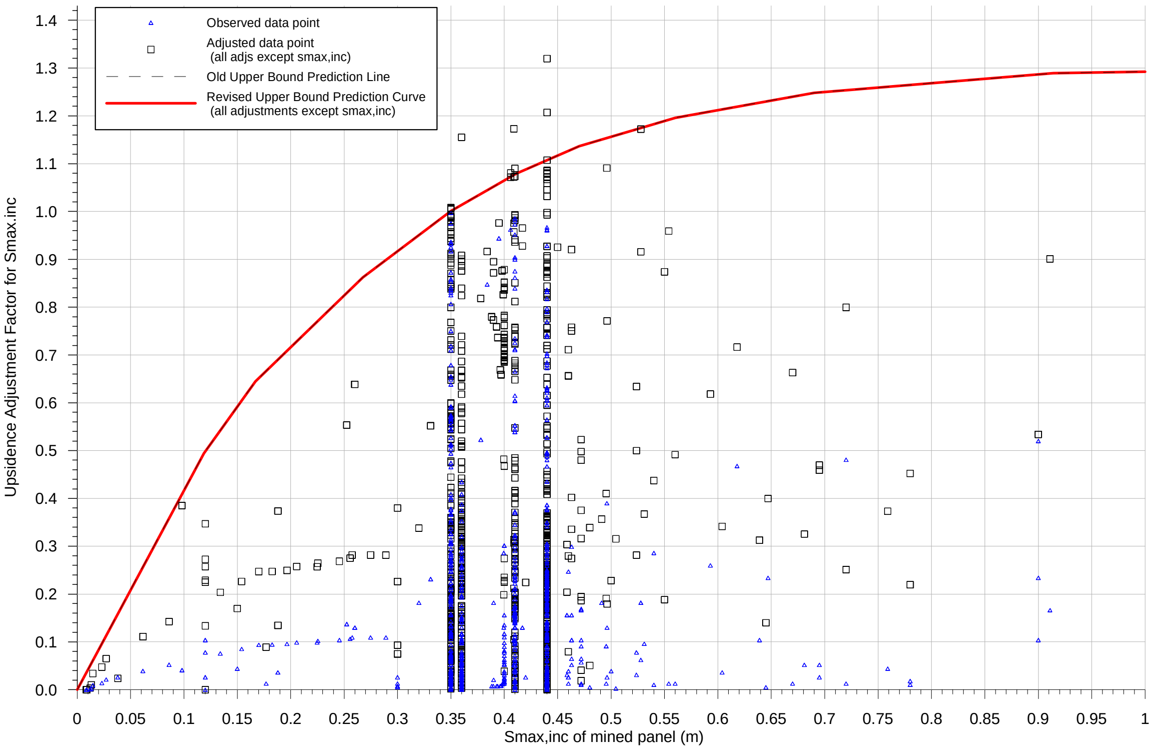


Fig. 1.24 Upsidence Adjustment Factor versus Maximum Incremental Subsidence

1.7.6. The Lateral Distribution of Upsidence

Upsidence is the result of two separate mechanisms, namely, valley bulging and buckling of the strata in the base of the valley. The maximum upsidence occurs in the base of a creek or river valley, where the strata buckling occurs, but the upsidence effect spreads outwards under the sides of the valley for a considerable distance due to valley bulging.

For example, in the Cataract Gorge above Longwall 8 at Tower Colliery, whilst the upsidence in the base of the gorge was 350 mm, the upsidence in the cliffs was around 100 mm and the upsidence effect extended for a distance of 300 metres on each side of the gorge.

Fig. 1.25 shows idealised profiles of upsidence across the Cataract gorge, both along the goaf edge of a longwall and along the centreline of the longwall. It can be seen that the lateral spread of the upsidence was greater where the amplitude of the upsidence was greater. Further research is required in order to develop a more definitive method for the prediction of upsidence profiles, but in the meantime it seems reasonable to model the profiles on the upper measured profile shown in Fig. 1.25. An approximate profile can be obtained by scaling both the width and amplitude of the profile in proportion to the predicted upsidence value. It should be noted, however, that the predicted profile can only be approximated since the actual buckling will depend upon local geology and might not be centrally positioned in the bottom of the valley or gorge.

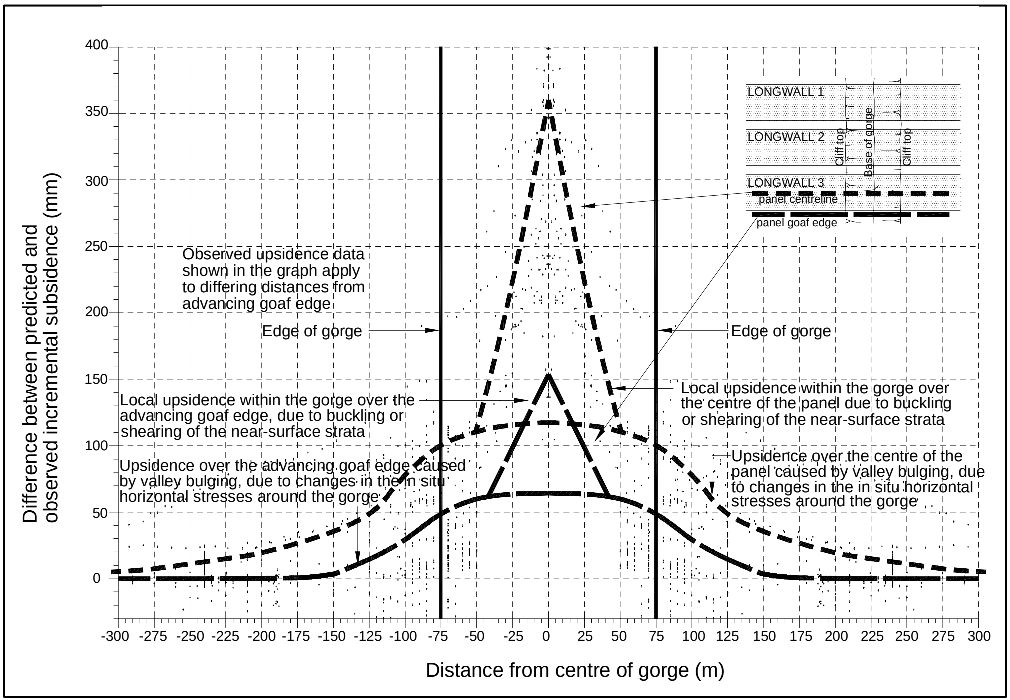


Fig. 1.25 Idealised Upsidence Profiles across the Cataract Gorge

1.7.7. The Prediction of Compressive Strains in Creeks and River Valleys

The method of prediction for compressive strain due to closure was developed as part of the ACARP study (2002). The method provides an indication of the maximum compressive strains that might be experienced as a result of mining by adopting an upper bound relationship between observed closure and maximum compressive strain. This relationship is shown in Fig. 1.26. The predicted closure, obtained using the method described in Section 1.7.4, is the overall closure across the valley.

The predicted strain is the average strain over a bay length of 20 metres and is assumed to occur within the lowest part of the valley. The closure of this bay can, therefore, be determined from the predicted strain. The closure over this bay length can be greater than the overall closure of the valley, due to expansion in the valley sides as the horizontal stresses are relieved.

It is believed that the closure and strain are both driven by the in-situ horizontal stress and it is reasonable to assume that the compressive strains will reduce as the in-situ stress reduces. Since the graph in Fig. 1.26 has been based on data that is primarily from observations at Tower Colliery, where the in-situ stress is particularly high, it is expected that the graph will generally be conservative and could over-predict strains by 100% in some cases, particularly where the predicted levels of strain are low. The data spread in the graph shows the variations that have occurred in practice and provides a guide to the potential range of strains that might occur in a particular case.

Since the completion of the ACARP study, an examination of observed ground movements suggest that the predictive method is mainly applicable for creeks and valleys that are located directly above extracted longwalls. However, it has been found that observed maximum compressive strains are substantially less in locations that are not directly above extracted longwalls. An upper bound relationship between compressive strain and lateral and longitudinal distance from longwalls is provided in Fig. 1.27 and Fig. 1.28. It is hoped that further analysis of observed ground movements will be conducted in the future, so that the method for predicting maximum compressive strains can be improved.

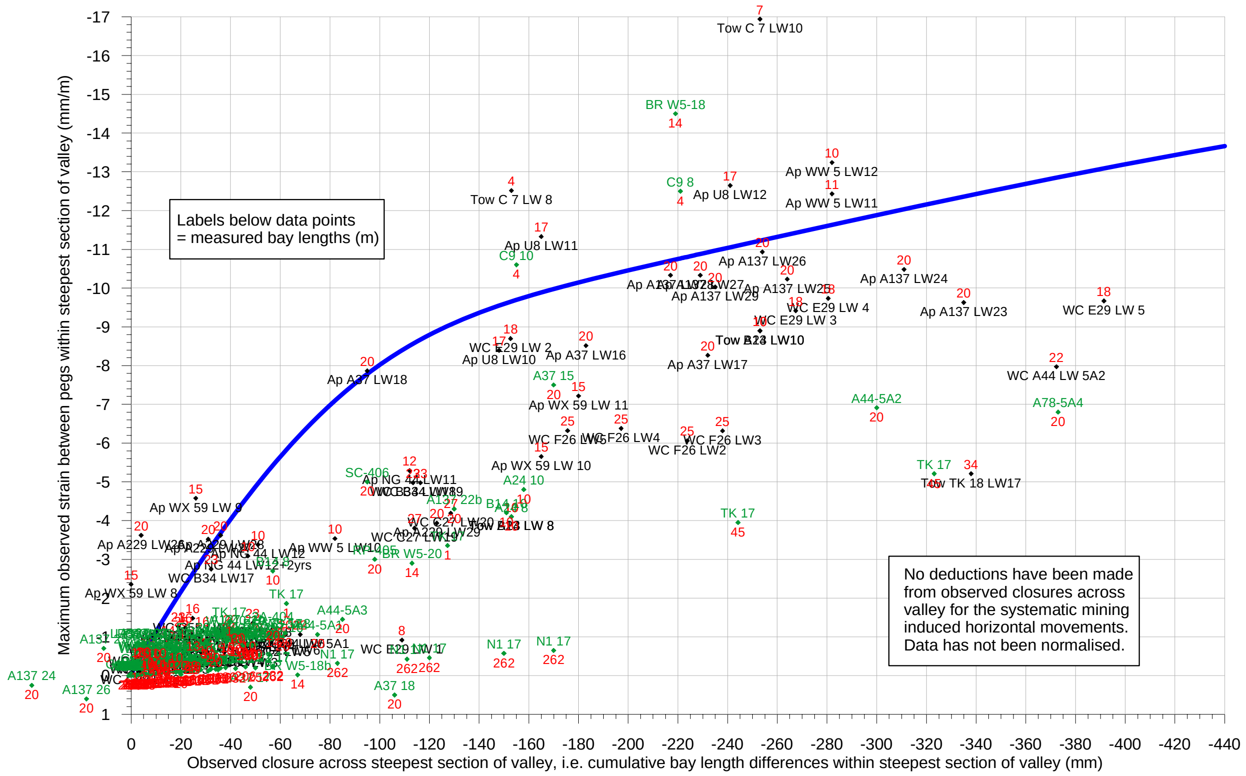


Fig. 1.26 Graph of Maximum Compressive Strain versus Valley Closure

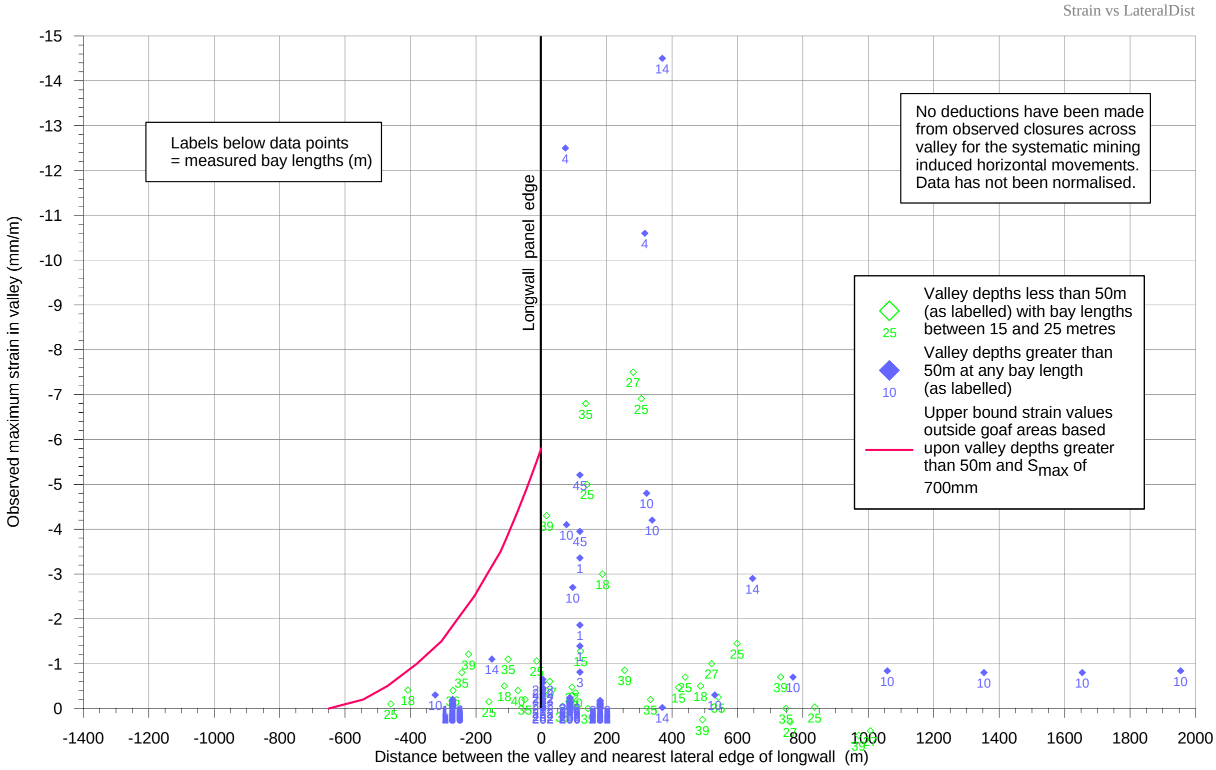


Fig. 1.27 Graph of Maximum Compressive Strain versus Lateral Distance

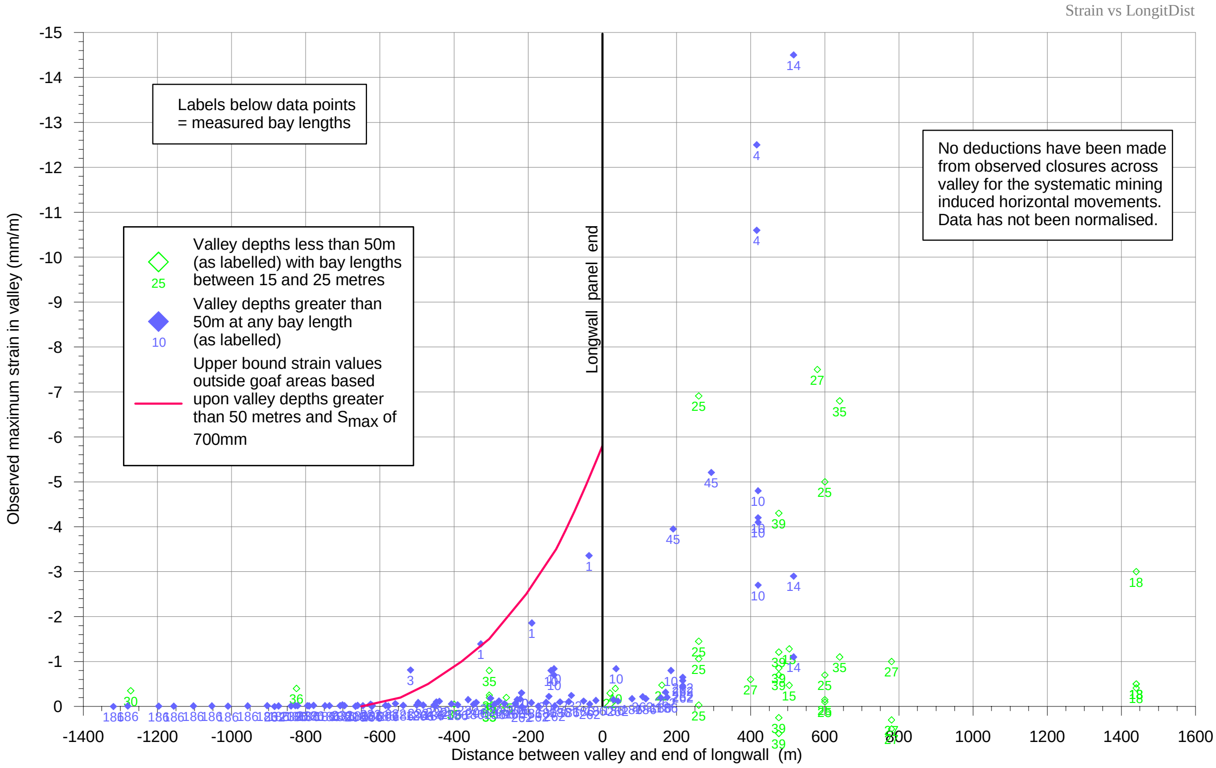


Fig. 1.28 Graph of Maximum Compressive Strain versus Longitudinal Distance

1.7.8. Irregular Subsidence Profiles

1.7.8.1. Definition of an Anomaly

An anomaly is defined as a significant irregular or non-systematic ground movement, which was not expected to occur. Small fluctuations in survey lines are not categorised as anomalies as these rarely affect surface features and are often within survey tolerance.

Systematic subsidence movements due to longwall extraction are particularly easy to identify as longwalls are regular in shape and the extracted coal seams are relatively uniform in thickness. Systematic subsidence profiles are typically smooth in shape and can be explained by the expected caving mechanisms associated with overlying strata collapsing into a void.

As a general rule, the smoothness of the profile is governed by the depth of cover and lithology of the overburden. Where the depth of cover is greater than 400 metres, such as in the Southern Coalfield, the subsidence profiles along monitoring lines are generally smooth. Where the depth of cover is less than 100 metres, such as in the Hunter and Newcastle Coalfields, the subsidence profiles along monitoring lines are not generally smooth.

Even where the subsidence profiles are smooth, at locations with a high depth of cover, however, localised non-systematic ground movements have been observed along monitoring lines on some occasions. The causes behind the majority of these movements can be interpreted and are outlined in Section 1.7.8.2. These include valley upsidence and closure, the influence of geological structures and issues related to the installation or surveying of monitoring lines.

Even though it is possible to attribute a reason behind most non-systematic ground movements, there remain some movements that still cannot be explained. These are termed “anomalies”, and their presence can sometimes impact surface features. Suggested reasons for some of these movements are discussed later in the report. In summary, it is believed that these anomalies are a result of the reaction of near-surface strata to increased horizontal compressive stress due to mine subsidence.

While the causes of anomalies are not yet fully understood, it is hoped that they will be better understood as the development of mine subsidence knowledge progresses. This may then allow these movements to be predicted, so that surface features can be better protected in the future.

1.7.8.2. Method of Identification of Anomalies along Monitoring Lines

Anomalies have been identified from observed subsidence profiles by a process of elimination. If a cause behind an irregularity in a subsidence, tilt or strain profile cannot be determined, the irregularity is recorded as an anomaly. All significant irregularities in the subsidence, tilt and strain profiles have been identified along each monitoring line, and the cause of each irregularity has been described and recorded. The most common causes of irregular or non-systematic movements are listed below.

- Valley upsidence and closure
- Geological Structures
- Change in direction of monitoring line
- Bumped pegs
- Damaged pegs
- Survey Line Discontinuities
- Survey Errors

1.7.8.3. Potential Causes of Anomalies

There are a number of possible causes of anomalies, the majority of which are due to local near-surface geology.

Upsidence and closure in unknown "hidden" creeks which have been filled in by geological processes or by infrastructure development. This cause could be eliminated by examination of topography and lithology records.

- The possible presence of an unknown fault, dyke or other geological structure.
- Buckling due to increased horizontal stress concentrations, similar to those experienced in valleys.
- Buckling due to cross bedding or blocky behaviour of the near surface strata.
- Rotation of near-surface strata over the goaf edge.
- The presence of a stronger stratum capable of forming a natural corbel at the goaf edge.

It is observed that the major observed anomalies have behaved in a similar manner. The anomalies show an upwards bulge, or upsidence in the subsidence profile, coupled with a local concentration of compressive strain. In some cases, a localised surface "wrinkle" has formed at the point of maximum compression.

It is generally considered that the ground within the subsidence trough is in tension close to the edge of the longwall and in compression close to the centre of the longwall. This, however, is only true for the immediate surface of the bedrock. The strata behaves as a series of distinct beds of varying strengths that separate due to shearing along planes of weakness as subsidence occurs. The strata can therefore be looked upon as a series of relatively thin slabs laying one upon the other.

The underside of the uppermost stratum, following subsidence, is in compression close to the goaf edge and in tension close to the centre of the longwall, contrary to what the upper surface of the stratum is experiencing. It is these changes in stress between the upper surface of one layer and the lower surface of the layer above it that results in the shearing between the beds and the resulting bed separation.

In the Hunter and Newcastle Coalfields, the in-situ horizontal stresses in the strata can be greater than the vertical stresses, even close to the surface. The strata are being compressed on all sides, with the exception of the surface, which is not vertically constrained. As subsidence occurs and the normal collapse mechanisms initiate, the strata above and close to the longwall move inwards to fill the void. This allows the strata outside the subsidence trough to expand towards the goaf area.

At the same time, the horizontal stresses in the strata are redistributed above and below the seam causing increases in stress above the collapse zone, which results in elastic shortening, horizontally, and elastic expansion, vertically. The strata on each side of the collapse zone expands towards the goaf and are partially stress relieved resulting in vertical shortening of the strata and increased subsidence movements well outside the angle of draw.

This redistribution of horizontal stress extends for a considerable distance outside the goaf area, with measurable displacements almost three kilometres away. It is believed that this expansion towards the longwall goaf areas, due to the relaxation of in-situ horizontal stress in the strata is the cause both of the far-field horizontal displacements and the unusually high vertical subsidence displacements that sometimes occur beyond the angle of draw.

All of the subsidence mechanisms are driven by in-situ stresses and gravitational forces, which are compressive. None of the driving forces behind the subsidence-induced movements are tensile. Generally, when the strata are vertically confined, they behave systematically. The irregularities that occur in subsidence profiles are therefore a surface phenomenon that is driven by compressive forces.

The surface strata can be likened to an ice flow, in which the individual blocks of ice are displaced due to the pressures exerted on them by their neighbours and by the underlying currents in the water beneath them. The blocks can buckle upwards or one block can shear and ride over the top of its neighbour. In some cases the blocks can be forced upwards to form arches or ridges. Not all movements are in the vertical plane and in some circumstances horizontal shearing can occur as one block slides past another, being propelled by a greater force and facing less resistance than its neighbour.

It is conjectured that the major anomalies that have been recorded were due to arching and buckling of near-surface strata as mining resulted in bed separation. It is also possible that shearing in underlying cross-bedded strata could initiate the anomaly, but there has been no stepping in the surface, which suggests that the near-surface strata have buckled rather than sheared.

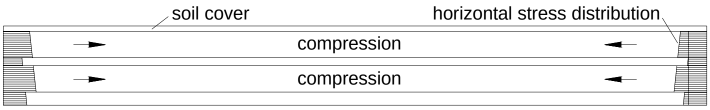
It is interesting to note that the most likely place for compressive buckling to occur at the surface is where the surface is convex, or hogging. This is because the tendency in that situation is for the rocks to buckle upwards when compressed horizontally and to fail in bending tension or in shear. Where the strata are concave, or sagging, the underlying strata restrain the buckling and, generally, failure would occur only when the applied horizontal stresses exceeded the compressive strength of the strata, which is much greater than its tensile or shear resistance.

The in-situ horizontal stress increases in intensity with depth, but the stresses still exist close to the surface. The stresses are distributed throughout the strata according to the stiffness of each unit and the weaker strata attract a smaller proportion of the stress than the stronger strata. The way in which the surface strata will behave is, therefore, dependent upon the nature of the surface and near-surface rocks.

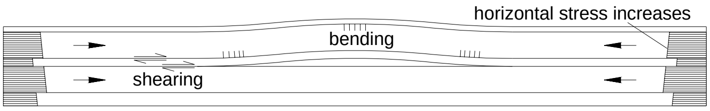
As mining occurs, subsidence and redistribution of in-situ horizontal stress results in bed separation and each stratum, particularly those at the surface, which are less confined by the weight of the rocks above them, becomes an independent and relatively slender compression member.

In this situation, very little eccentricity of loading or curvature of the member is required to initiate arching, followed by buckling. The initial buckling is a result of the in-situ horizontal stress and the movement is exacerbated as subsequent longwalls are mined and the longwalls get closer to the anomaly.

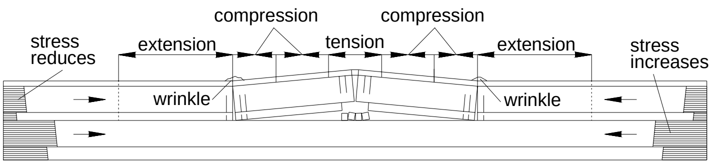
The increased subsidence over the goaf was initially difficult to understand, because it was anticipated that subsidence would be reduced in the high stress regime. A possible explanation, for the increased subsidence, is that the strata in the collapse zone had already been partially stress relieved by the adjacent goaf areas and thus offered less horizontal confinement, therefore allowing greater subsidence to occur.



1. Strata are subjected to in situ horizontal stress



2. The in situ horizontal stress increases causing shearing and bending



3. The strata fail in compression and buckle

Fig. 1.29 Strata Buckling Mechanism due to In-situ Horizontal Stress

The way in which buckling develops is illustrated in Fig. 1.29. The phenomenon starts as bed separation occurs in the near-surface strata, due to shearing between beds as the in-situ stresses in the strata are redistributed. The stress in a particular stratum results in bending occurring, either due to eccentricity of loading or curvature of the stratum and the stratum arches upwards.

As the subsidence impact increases, the stratum starts to crack on its convex surfaces as the rock fails in bending tension. If the mining-induced stress continues to increase and the tensile fractures continue to develop to the full depth of the stratum, the stratum eventually fails in compression and buckles upwards. The buckling releases the horizontal confining stress in the stratum on both sides of the buckle and allows the stratum to expand horizontally and locally relieve the compressive stress. The stress relief in the surface stratum transfers additional stress into the strata below it and this can result in progressive failure and buckling through a number of strata, until the buckling of a stratum is prevented by the weight of the rocks above it.

When buckling occurs, the resultant strains measured at the surface can vary considerably from the predicted systematic strains and can alternate between compressive and tensile, even though the strata are consistently being compressed. It is this erratic behaviour of the surface strata that results in the scatter in measured strain profiles. The measurement of strain does not differentiate between a real extension of an unstressed stratum under applied bending stress and the expansion of a stratum due to compressive stress relief. The measured strains can therefore give a false impression of the state of stress in the surface strata.

It is probable that the most substantial impact to building structures in the Southern Coalfield is due to the buckling of surface strata under the influence of in-situ horizontal stress. Generally the underlying systematic levels of tensile and compressive strain are too low to result in significant impact and the worst impact has been associated with anomalous behaviour of the strata, where curvatures, strains and tilts have been increased.

1.7.9. The Prediction of Incremental Far-Field Horizontal Movements

In addition to the ‘normal’ and topographically related movements, far-field (ie: regional) movements have also been recorded in a number of cases, at considerable distances from the longwall goaf areas. Such movements have often been several times higher than the vertical subsidence movements measured at the same locations.

It has been conjectured that these far-field movements are caused by redistribution of the stresses in the strata between the seam and the surface due to the regional mining activity. The direction of such movements would tend to be towards the active mining, but the direction of movement could also be dependent upon the scale and proximity of adjacent goaf areas.

It has been suggested by some authors that the far-field movements are generally aligned with the principal horizontal in-situ stress direction. However, it seems more reasonable to suggest that the movements will be directed from areas of high stress towards areas where the confining stresses have been reduced by mining activity, thus allowing expansion of the strata to occur. The stresses within the strata are generally compressive in all directions and until mining occurs the stresses are in equilibrium, the balance being controlled by the shear resistance within and between strata units. As mining occurs, the equilibrium is disturbed and the stresses have to achieve a new balance by shearing through the weaker strata units and by expanding into areas of greatest dilation, i.e. towards the goaf areas, where the confining stresses have been relieved.

An empirical database of observed far-field horizontal movements has been compiled using monitoring data primarily from the Southern Coalfield of New South Wales in Australia. The monitoring data was collected from Collieries including Appin, Bellambi, Dendrobium, Tower and West Cliff. The far-field horizontal movements resulting from longwall mining were generally observed to be orientated towards the extracted longwall. At low levels of far-field horizontal movements, however, there was a high scatter in the orientation of the observed movements.

Fig. 1.30 shows the observed incremental far-field horizontal movements, resulting from the extraction of a single longwall, relative to the distance from the longwall. It can be seen from this figure that incremental far-field horizontal movements of up to 20 mm have been observed at distances of 2000 metres from extracted longwalls.

Fig. 1.31 shows the observed incremental far-field horizontal movements, resulting from the extraction of a single longwall, relative to the distance from the longwall, for cases where there was solid coal between the longwall and the monitoring points. It can be seen by comparing Fig. 1.30 and Fig. 1.31, that the magnitudes of observed incremental far-field horizontal movements are generally less where there is solid coal between the longwalls and monitoring points.

The maximum movements tend to occur when the second and third longwalls are mined in a series, and tends to decline as subsequent longwalls are mined. This is possibly due to the fact that once the strata has been stress relieved by the first few longwalls, the potential for further movement is reduced.

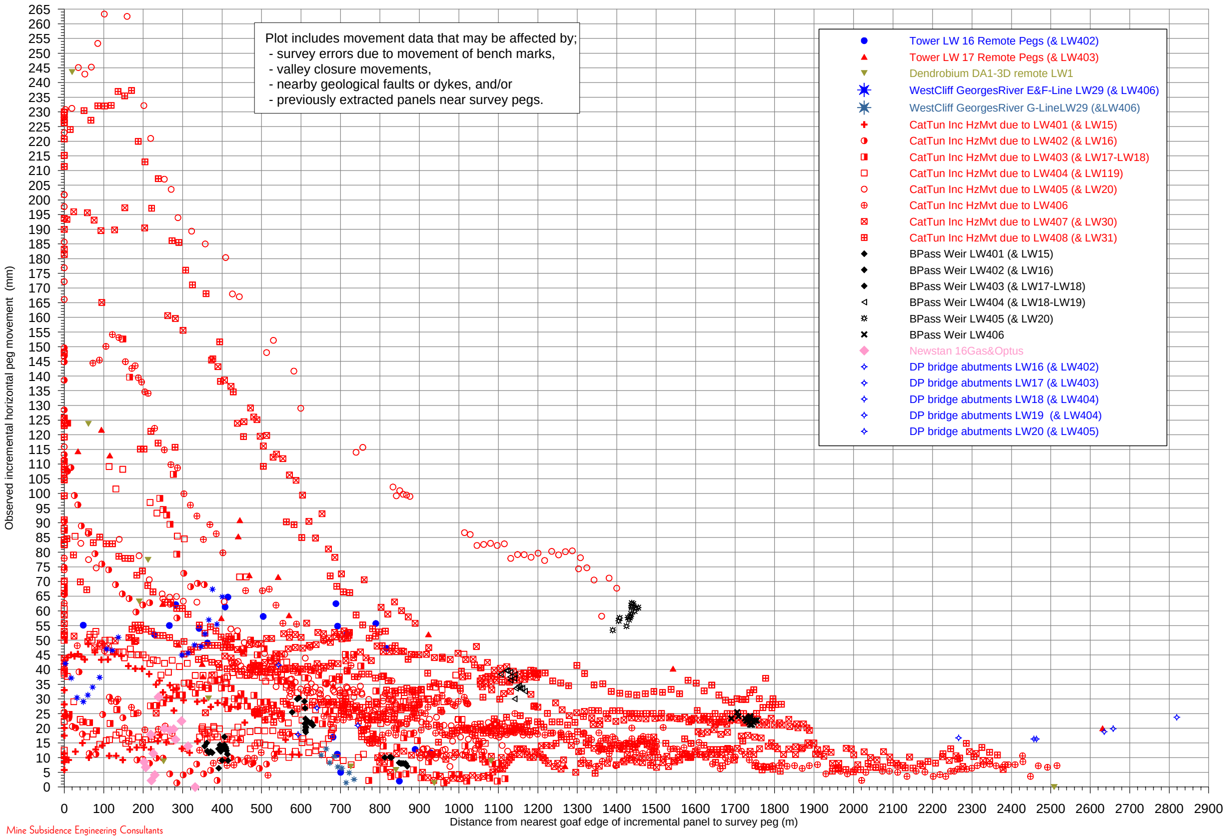


Fig. 1.30 Observed Incremental Far-Field Horizontal Movements

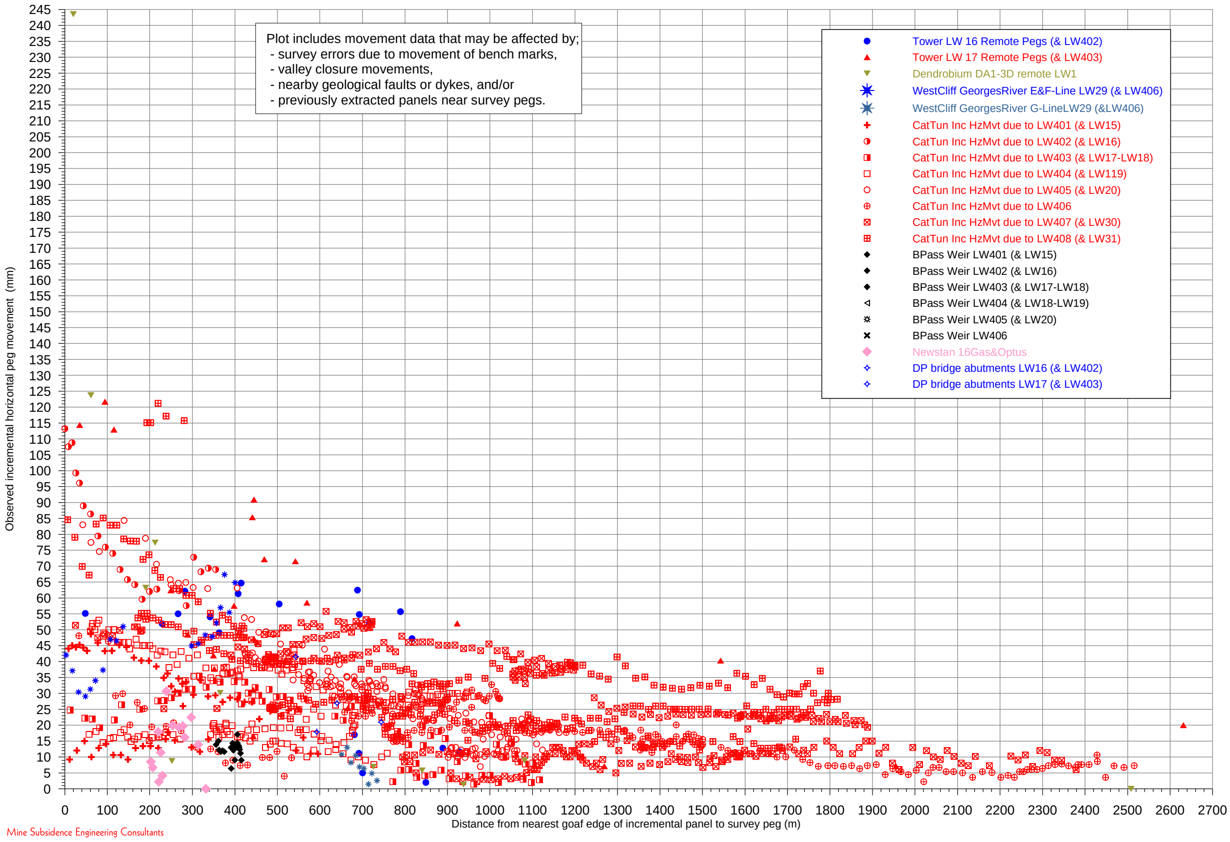


Fig. 1.31 Observed Incremental Far-Field Horizontal Movements with Solid Coal between the Monitoring Points and Mined Longwall

1.8. Sub-Surface Strata Movements above Extracted Panels of Coal

1.8.1. Collapse Mechanisms

Before the strata above an underground excavation are disturbed, all points beneath the surface are under compression from the weight of the overburden, and from pre-existing in-situ horizontal stresses, and are in a state of equilibrium. The extraction of panels of coal, by continuous miner or longwall mining operations, creates voids, which upset the balance of forces in the strata, causing displacements to occur until a new state of equilibrium is reached.

The overall force field in the strata, outside and around the extracted void, remains unchanged and the stresses have to readjust locally around the void to achieve this new state of equilibrium. The void provides the compressed rock with a space into which it can expand, and in so doing relieve the stresses that initiated the movement.

Because the extracted voids are generally much wider than the height of the seam, the initial movements tend to be vertical displacements of the roof and floor of the void, movements of the roof being assisted to a greater extent by gravity. Once the vertical movement occurs, generally by failure of the immediate roof strata, the strata outside the void, which are no longer constrained by the roof strata can relieve some of their stress by expanding horizontally into the goaf area. A state of equilibrium is achieved when the desire of the strata to expand is balanced by the frictional shear forces, developed by the weight of the overburden, which tend to resist the expansion.

The collapse of the immediate roof strata will generally be followed by the collapse of the rocks above them, unless the remaining overburden strata are sufficiently strong and homogeneous to span over the width of the void. Failure generally occurs due to the separation of an individual stratum along a bedding plane, which, being unable to carry the loads imposed by the weight of the overburden and the horizontal compressive stress, shears or buckles in bending and falls into the goaf.

The collapse progresses upwards until a stronger and more homogeneous strata beam is reached with the capacity to bridge the void. Such strata beam could be a thicker homogeneous rock of a particular type, such as a massive sandstone or conglomerate layer, or could be a combination of rock strata, which, acting together as a laminated beam, have sufficient strength to span the void. The height at which the progressive collapse of the strata towards the surface is arrested, i.e. the height of the fractured zone, is dictated by the width of the extracted void and the nature of the overburden strata.

The mechanism of collapse and the subsidence at the surface is further complicated by the cantilevering of the strata from the abutments on each side of the void and the elastic compression of the coal pillars and the strata above and below them.

After failure of the immediate roof, the lateral expansion of the strata at the abutments into the extracted void tends to form natural corbels, which support the strata above them and reduce the effective span. As the collapse progresses upwards the corbels extend further and further towards the centre of the goaf and form an irregular cantilever of strata at each abutment which transfer the weight of the overburden strata above the collapsed zone into the abutments. The angle, measured from the vertical, at which these corbels extend into the goaf area, is referred to as the angle of break.

The cantilevering strata and the overburden above the collapse zone span between the abutments and sag across the void and are partially supported by the collapsed rocks beneath them. At the same time, because the loads on the abutments are increased by the spanning strata, elastic compression occurs in the abutment coal pillars and in the strata above and below the pillars, causing settlement over the pillars. This settlement above the pillars is greatest where the depth of cover is high and the width to depth ratio of the extracted panel is relatively small. At higher width to depth ratios the settlement over the pillars reduces, because the strata collapses more freely into the goaf and less load is shed to the abutments. Additional settlement over the pillars occurs due to the lateral expansion of the strata at the abutments and the resultant vertical dilation caused by horizontal stress relief.

These separate mechanisms combine to cause subsidence at the surface, which extends over the extracted void and beyond the edges of the void to the limit of subsidence. Vertical subsidence at the surface is generally less than the thickness of the extracted coal seam, because the collapsed strata and the sagging strata above the collapsed zone contain a significant number of voids.

Rocks within the collapsed zone tend to fail by blocky delamination from the strata above them and collapse into the void in an irregular manner, which causes bulking of the collapsed strata to occur. Sometimes this can be sufficient to choke off the collapsed zone and prevent further progression of the collapsed zone towards the surface. In other cases it is possible that significant voids could be left at the top of the collapsed zone beneath a competent strata beam.

Above the collapsed zone is the fractured zone in which the strata are subject to significant vertical displacement and bending, which result in fracturing, joint opening, shearing on bedding planes and bed separation. The more competent rocks tend to span over the gaps beneath them, whilst weaker rocks tend to sag onto the stronger rocks beneath them. This results in vertical bed separation and void formation beneath the more competent strata with increased horizontal permeability. In this zone, it is possible that cracks could extend for the full depth of a stratum, thus increasing vertical permeability and connectivity between near surface aquifers and the mine workings.

Above the fractured zone is the constrained zone, in which the strata tend to sag and bend without failing and are laterally constrained by the horizontal in-situ stresses within the strata. In this zone, the bending of the strata results in the development of shear stresses at the interfaces between adjacent beds, causing horizontal displacements along the bedding planes and increased horizontal permeability. At low curvatures it is likely that some strata would crack on their convex surfaces, though the tension cracks would not penetrate the full depth of a stratum and hence would not provide hydraulic connectivity to the underlying strata. In the constrained zone, it is therefore possible that the horizontal permeability could increase due to subsidence, without an increase in vertical permeability.

Above the constrained zone is the surface zone, which comprises vertically unconfined strata and alluvial soils that essentially follow the bedrock movements downwards, but can still experience tensile cracking and surface buckling due to ground curvatures and strains.

1.8.2. Angle of break

The extent to which the corbels develop at the abutments and cantilever into the collapse zone is dependent upon the strength and thickness of the strata in the immediate roof and overburden, the locations of pre-existing joints and faults and the level of in-situ horizontal stress. The units that are thicker, stronger and more homogeneous will tend to cantilever further than those which are thinly bedded, weaker and more frequently jointed. The angle of break is therefore dependent upon local geology. It can also be affected by the choice of mining method and the speed of mining.

In a sequence of rocks comprising sandstones, conglomerates, shales, claystones and mudstones of moderate thickness it would appear, from the literature that has been reviewed, that the angle of break will be somewhere between 17^0 and 23^0. Based upon an angle of break of 17^0 the collapse zone would only extend through to the surface if the width to depth ratio was greater than 0.6 and if there was no significant stratum to span the void and arrest the upward development of the collapse zone at some horizon in the sequence. At an angle of break of 23^0, the width to depth ratio would have to exceed 0.84.

1.8.3. Variations in Terminology used to describe Strata Displacement Zones

A study of the various papers and texts that are listed in the references in Appendix B, reveals that the terminology used by different authors to describe the strata displacement zones above an extracted panel is inconsistent. Forster (1995) noted that most studies had recognised four separate zones, with some variations in the definitions of each zone. Peng and Chiang (1984) as illustrated in Fig 8.4.1 of the text book by Peng, which is reproduced in Fig. 1.32, below, had recognised only three zones, namely the caved zone, the fractured zone and the continuous deformation zone. McNally et al (1996) also recognised three zones, which they referred to as the caved zone, the fractured zone and the elastic zone.

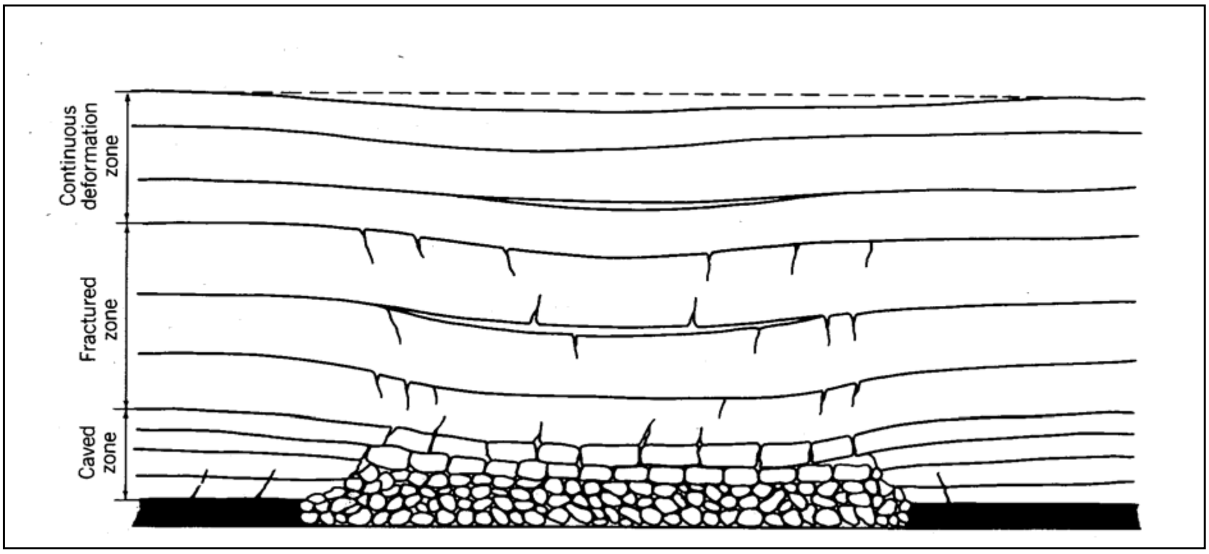


Fig. 1.32 Zones in the Overburden According to Peng and Chiang (1984)

Kratzsch (1983) identified four zones, namely the immediate roof, the main roof, the intermediate zone and the surface zone. For the purpose of this study, the following zones, as described by Singh and Kendorski (1981) and proposed by Forster (1995), have been adopted. These are further illustrated in Fig. 1.33.

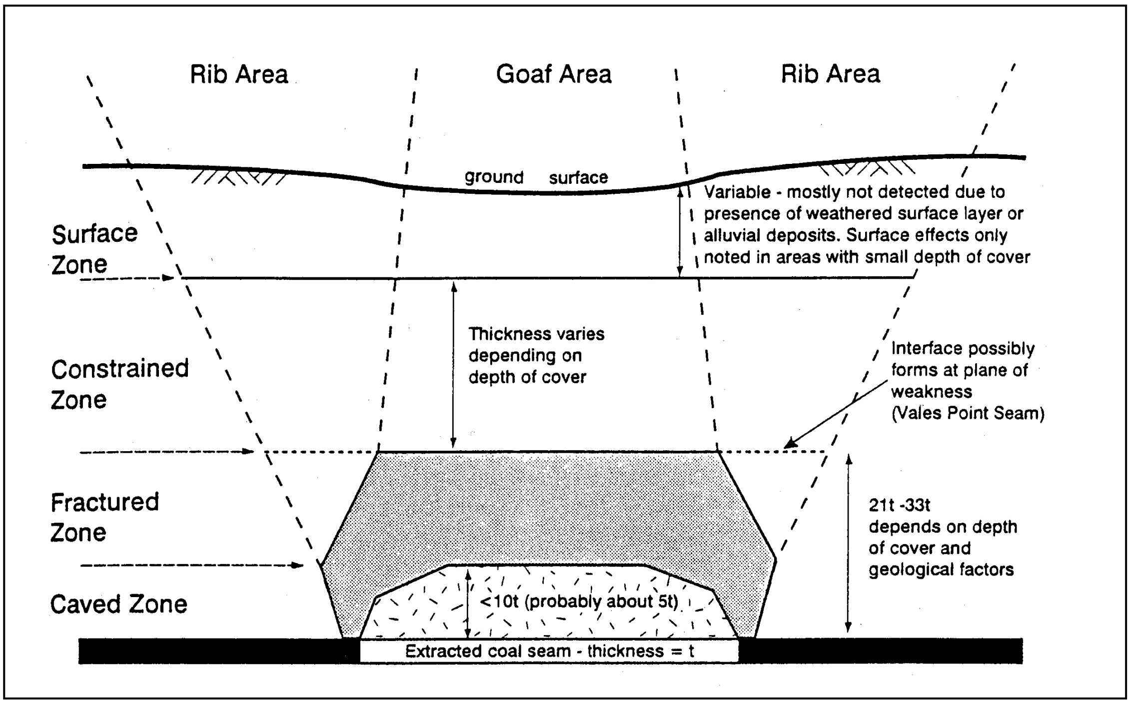


Fig. 1.33 Zones in the Overburden according to Forster (1995)

Caved or collapsed Zone. (Some authors note primary and secondary caving zones.) Comprises loose blocks of rock detached from the roof and occupying the cavity formed by mining. Can contain large voids

- *Disturbed or Fractured Zone.* (Some authors include the secondary caving zone.) Basically in-situ material lying immediately above the caved zone which has sagged downwards and consequently suffered significant bending, fracturing, joint opening and bed separation.
- *Constrained or Aquiclude Zone.* (Also called the Intermediate Zone.) Comprises confined rock strata above the disturbed zone which have sagged slightly but, because they are constrained, have absorbed most of the strain energy without suffering significant fracturing or alteration to the original physical properties. Some bed separation or slippage can be present as well as discontinuous vertical cracks (usually on the underside of thick strong beds). Weak or soft beds in this zone may suffer plastic deformation.
- *Surface Zone.* Unconfined strata at the ground surface in which mining induced tensile and compressive strains may result in the formation of surface cracking or ground heaving.

1.8.4. Permeability, Vertical Dilation and Collapse and Fracture Zones

The likely heights of the collapsed, fractured and constrained zones have been provided by various authors and these have been reviewed during the course of preparing this report. Generally, the height of the caved zone has been indicated to fall within the range 1.5 to 14 times the extraction height, with the majority of cases in the range 5 to 10 times the extracted height. Forster concluded that the maximum height would be less than 10 times and probably around 5 times the extraction height.

The height of the fractured zone has been indicated to lie within the range 10 to 105 times the extracted height, though Holla and Buizen (1991) indicated that the height of the fractured zone over Longwall 3 at Tahmoor Colliery extended to a height of 143 times the extracted seam thickness, based upon extensometer readings. Forster (1995) concluded that the height of the fractured zone should be taken as 21 to 33 times the extracted height of the seam.

An alternative method of measuring the heights of the collapsed and fractured zones is to express the height as a function of the extracted width. This method appears to be favoured by some authors, though definitive relationships have yet to be determined. The height of the disturbed zone, being the overall height of the collapsed and fractured zones, has generally been found to vary from 0.16 to 1.4 times the extracted width. A height of 1.73 times the extracted width was indicated by Holla and Buizen (1991) over Longwall 3 at Tahmoor Colliery, based upon extensometer readings.

Some of the difficulties in establishing the heights of the various zones of disturbance above an extracted panel stem from the imprecise definitions of the fracture and constrained zones and the interpretation of extensometer readings. The definition of constrained zone is based upon the assumption that bed separation in this zone will increase horizontal permeability without increasing vertical permeability. It is possible for considerable dilation to occur as differential bending of the strata layers occurs, but this is not considered to be the same kind or extent of fracturing that is to be found in the fractured zone, where vertical permeability is likely to be affected by bending or shear induced vertical fractures.

Where vertical dilation is measured by extensometer readings, it is possible that bed separation in the constrained zone could be misinterpreted as fracturing in the fractured zone. The measurement of vertical tensile strain is of some assistance in identifying the extent of the strata disturbance at different horizons, but where bed separation occurs in the constrained zone a large vertical strain at that point can be confined by low vertical strains above and below the point.

The interpretation of extensometer readings has to be undertaken with care, particularly where the extensometers are limited in depth and do not penetrate the full depth of the overburden. The researchers at the University of New South Wales (1984) noted that since there had been no direct permeability measurements, it was difficult to establish a relationship between the vertical strain variation and the permeability of the strata.

Another issue with regard to extensometer readings that should be highlighted is that the extensometers were affected by horizontal shear and displacement, which resulted in total extension readings that were greater than the extracted thickness of coal. Quite clearly the extensions included horizontal movements between strata units at particular horizons and such movements would give a totally wrong impression of the vertical strains between anchors.

1.8.5. Relationship between Vertical Dilation Heights and Mining Geometry

The effect of mining geometry on the heights of the collapse and fractured zones is not well documented. Theory would suggest that the height of the collapse zone would be directly related to the width of the extraction, the height of extraction, the depth of cover and the nature of the rocks in the overburden. Where the panel width-to-depth ratio is high and the depth of cover is shallow, it is clear that the fractured zone can extend from seam to surface. This is clearly indicated in the extensometer readings from boreholes above shallow areas of extraction, where the vertical strains close to the surface are as high as they are close to seam level.

This was apparent in the results of the extensometer readings above Longwall 2 at Invincible Colliery, where the longwall width was 135 metres, the height of extraction was 2.7 metres and the depth of cover was 116 metres. The width-to-depth ratio of the panel was, therefore, 1.16. In this case, the collapsed zone extended to approximately 9 times the extracted seam thickness above the seam roof. Above the collapsed zone, the vertical strain was almost linear through to the surface at approximately 8 mm/m, indicating that the fractured zone extended to the full depth of the overburden.

It was also apparent in the movements of the strata above Longwall 11 at Angus Place Colliery. In that case, the longwall width was 211 metres, the height of extraction was 2.47 metres and the depth of cover was 263 metres. The width-to-depth ratio of the panel was, therefore, 0.8. Bhattacharyya and Zang (1993) estimated that the height of the collapsed zone was 25 metres, or 10 times the extracted seam height. Above the collapsed zone, the vertical strain was almost linear through to the surface at approximately 5.6 mm/m, indicating that the fractured zone extended to the full depth of the overburden.

The extent of the collapsed zone has generally been defined with reference to the extracted seam thickness and the height to which collapse occurs before the bulking of the collapsed rocks chokes off further vertical progression of the collapsed zone. The extent of the fractured zone above the collapsed zone would appear to be more dependent upon the width of the extraction and the angle of break. The vertical strain would appear to be dependent upon the extracted seam thickness, the amount of subsidence and the depth of cover.

It is reasonable to suppose that as the width to depth ratio reduces, the height of the fractured zone would also reduce. Conversely, the height of the fractured zone would be expected to increase as the width-to-depth ratio increased.

CHAPTER 2. REFERENCES