Recent Developments in the Incremental Profile Method of predicting Subsidence, Tilt and Strain over a series of Longwall Panels

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Abstract: Incremental subsidence profiles show the settlement resulting from the extraction of an individual panel and can be derived by subtracting the observed subsidence profile before mining from the observed subsidence profile after mining. Whilst the final subsidence profiles over a series of longwall panels are irregular, incremental subsidence profiles have been found to be consistent in shape throughout the Southern, Western and Newcastle Coalfields of NSW, Australia.

The magnitude and shape of each incremental profile are determined by each panel's width (Wpa), adjacent chain pillar width (Wpi), position within the series of panels, seam thickness, depth of cover (H) and a new factor called 'overlap proportion'. Overlap proportion is a factor used to measure the extent of strata cracking above incremental panels resulting from adjacent mining.

Final subsidence at any point on the surface is predicted by adding together the appropriate increments of subsidence from each longwall panel at that point. Tilt and curvature predictions are derived directly from the predicted subsidence profile shape and strain is derived from the predicted curvature profile. Predictions have been carried out using the Incremental Profile Method over a number of monitored panels and close correlations between observed and predicted profiles have been achieved.

Key Words: incremental, subsidence prediction, strata cracking, profile overlap, strain

Introduction

Coal is often extracted in a series of parallel longwall panels separated by a series of chain pillars. The panels are extracted one at a time leaving chain pillars between the extracted panels that are required to provide support to the access headings on each side of the coal face. Depending on their size, these pillars partially crush and distort as the coal is removed but they continue to provide support to the overlying strata.

As coal is extracted, the strata immediately above the seam falls into the mined void initiating bending, cracking, and settlement of the overlying strata and finally resulting in surface subsidence. The observed maximum subsidence over a series of panels is commonly half the maximum subsidence over a fully extracted area due to the support provided by chain pillars. The final subsidence trough is not flat but comprises a series of troughs and humps, which are not necessarily positioned above the centres of the panels or pillars. Particularly where panels have a low width to depth ratio (Wpa/H), subsidence profiles from each panel overlap and the observed surface subsidence is thus a complex combination of the influence of a number of panels and chain pillars.

Various subsidence prediction methods are available, such as the Empirical, Graphical, Influence Line, Profile Function, Physical Modelling, Mathematical Modelling and the Incremental Profile Method. The choice of method is dependent upon the purpose of the prediction, the required accuracy and the availability of data.
Background to Incremental Profile Method

The Incremental Profile Method was initially developed as part of a study in 1994 for BHP Collieries Division, Sydney Water and The Natural Gas Company to assess the impacts of subsidence at surface infrastructure over proposed longwall panels in the Southern Coalfield of NSW. Standard empirical prediction methods could not be used to predict subsidence parameters at these locations because cover depths, seam thicknesses, panel widths and pillar widths all varied considerably from panel to panel. The Method evolved following detailed analyses of subsidence monitoring data, which showed that whilst the final subsidence profiles over series of longwall panels were irregular, the observed incremental subsidence profiles were consistent in both magnitude and shape.

Incremental subsidence is derived by subtracting the subsidence observed at a point before the extraction of a longwall panel from the subsidence observed at that point after mining the panel. An incremental subsidence profile shows the change in subsidence caused by mining of a particular longwall panel at many pegs along a monitoring survey line.

Most of the subsidence monitoring data used in developing the Method was measured along survey lines located across a series of longwall panels. Some longwall panels were monitored by more than one cross line and a smaller proportion of panels was monitored along longitudinal survey lines located down the centre of the longwall panels. Where possible, further information was derived from published literature, however, authors rarely provide all the required raw data on panel geometry, cover depths, seam thicknesses and/or the timing of surveys. It would be ideal if monitoring surveys were undertaken to coincide with the completion of extraction of each panel and if detailed records were kept of actual panel dimensions, seam levels, strata geology and extracted seam thicknesses along monitoring lines.

Figs. 1 and 2 show typical examples of observed subsidence profiles and the derived ‘incremental’ subsidence profiles. The ‘incremental’ subsidence profiles over every survey line reviewed in the study were observed to be regular in form and the viability of incremental profiles as a basis of a predictive method was immediately apparent.

![Fig. 1](image1.png)  
![Fig. 2](image2.png)
Measured incremental subsidence profiles were plotted on top of each other, as shown in Fig. 2, and were found to vary in shape within a fairly narrow band. The shapes of the observed incremental subsidence profiles fell into three separate categories:

- Profiles for first panels in a series, which were symmetrical about the panel centre
- Profiles for second panels in a series, which were almost symmetrical but showed more subsidence over the mined first panel. The point of maximum subsidence had, in all cases, shifted towards the previous panel, and, in a few cases such as shown in Fig. 1, the point of maximum subsidence was located over the previous panel.
- Profiles for third and subsequent panels, which were also asymmetrical with the maximum subsidence point shifting towards and sometimes over the previous panel.

Further development of Incremental Profile Method

In 1996 Powercoal Pty Ltd asked if the Incremental Profile Method could be applied in the Cooranbong area of the Newcastle Coalfield of NSW. It was appreciated that the Method had been developed based on monitored subsidence data from the Southern Coalfield of NSW where cover depths and strata geology were relatively consistent. Hence a review was required to confirm that similar empirical patterns could be observed in incremental subsidence profiles from the Newcastle Coalfield.

The review included detailed analysis of subsidence monitoring surveys over previous workings at Cooranbong, Wyee, Teralba, West Wallsend and Newstan Collieries. It was anticipated that a wider range of incremental subsidence profiles would be observed reflecting the increased occurrence of multi-seam mining, the wider range of panel widths and depths of cover, and the greater changes in geological conditions. Fig. 3 shows an example of observed incremental and total subsidence profiles from the Cooranbong area with high Wps/H ratios and low cover depth.

The review concluded that incremental subsidence profiles were consistent in shape throughout the Southern, Western and Newcastle Coalfields of NSW, Australia. The consistency of all the normalised incremental subsidence profiles is shown in Fig. 4.
The review confirmed that the Incremental Profile Method provides a more accurate representation of the final subsided shape than can be obtained using other empirical methods. The increased quantity of monitoring data enabled a better understanding of subsidence mechanisms and it necessitated some improvements to the Method.

**Overlap Proportion**

A new factor, referred to as ‘overlap proportion’, is used to determine the magnitude and position of incremental profiles. This proportion reflects the degree of cracking in the strata overlying a panel caused by extraction of adjacent panels. It is calculated by determining the proportion of an area above a panel that is overlapped with adjacent panels, see Fig. 5, and hence it’s value is determined by panel and pillar widths and cover depth.

Where panels have high Wpa/H ratios and wide chain pillars, subsidence effects from the previous panel do not significantly overlap the area above the new panel. Hence with this geometry, the observed maximum incremental subsidence (Smax,inc) and incremental profile shapes are not significantly changed from those of a single or first panel, see Fig. 3. However, the subsidence effects from panels with low Wpa/H and narrow chain pillars significantly overlap each other, see Fig. 1, and hence the extent of cracking above the new panel increases and, as a result, the Smax,inc of the second and subsequent panels are significantly higher than the first panel.

Fig. 6 shows the relationship between overlap proportion and panel and pillar width to depth ratios. The same value of overlap proportion can be obtained for different panel and pillar width combinations. Overlap proportion also influences the position and shape of profiles. For example, the Smax,inc of the first panel in Fig. 1 is located generally over the panel centre, whilst the Smax,inc positions of the subsequent panels are positioned above the previously extracted panel. This observed profile shift with increasing overlap proportion is further detailed in Fig. 7. It is hypothesised that the strata, that was cracked by previous mining, can migrate towards the extracted void more readily than the uncracked strata over the solid edge of the new panel.
Many alternative indexes were examined to reflect the overlapping influence from adjacent mined panels, such as pillar width to depth ratio, pillar proportion, depth cracked proportions, and various alternative parameters based upon the proportion of cracked strata. However the defined overlap proportion was judged to best reflect the changes in Smax,inc, the position of Smax,inc relative to the advancing goaf edge and the shape of the incremental profiles for changing panel and pillar ratios.

**Application of Incremental Profile Method**

The application of the Incremental Profile Method requires the following basic steps:

i) Obtain each panel’s rib to rib width and pillar widths between the panels.

ii) Position an appropriate number of cross sections over the longwalls, (generally cross sections are positioned at major infrastructure or at, say, 200 m centres).

iii) Obtain the proposed thickness of the seam or seams to be mined and the overburden depths for each panel increment along each cross section.

iv) Calculate Smax,inc/seam for each panel increment, see Figs. 8 and 9.

v) Determine each panel’s solid edge and tail gate edge incremental profiles about each panel’s advancing goaf edge, for example see Figs. 10 and 11.

vi) Position each of the above profiles with respect to distances on cover from the initial goaf edge of the first panel in the series.

vii) Accumulate incremental values from each longwall panel at set points along each cross section to determine the total subsidence at these points.

viii) Determine the end profiles at both the maximum and minimum subsidence positions over the commencing and finishing longitudinal ends of each panel.

ix) Collate the eastings, northings and predicted subsidence values for points on all cross sections and end profiles and then prepare subsidence contours over the series of longwalls for each required mining phase.

The two principal prediction steps are the determination of the magnitude and shape of each increment’s profile. Both steps are dependent upon many site specific factors including the panel and pillar width to depth ratios, overlap proportions, lengths of longwall panels, distances from the cross section to commencing and finishing ends, seam thicknesses, seam levels and geology of the strata.

Fig. 8 shows a series of prediction curves for first panels, i.e. with zero overlap, which are applicable in the Cooranbong area. These curves relate to panel width and cover depth. The same curves are reproduced in Fig. 9, plotted against Wpa/H ratios. It can be noted from Figs. 8 and 9 that, where the cover depth is deeper than 300 m, Smax,inc can be predicted from Wpa/H curves alone. However where cover is less than 300 m, the available data indicates that subsidence reduces with lower depths of cover. This observation is presented in the NCB curves and was discussed by Prof. Salamon during lectures presented in 1989.

Fig. 9 shows another series of Smax,inc prediction curves, for second and subsequent incremental panels in the Southern Coalfield for a range of overlap proportions, where cover depth exceeds 300 m. It can be noted that overlap proportion significantly increases Smax,inc. Fig. 9 also includes, for comparison, prediction curves published by the NCB, Dr. W. Kapp for Newcastle Coalfield, the Department of Mineral Resources for the Southern, Western and Newcastle Coalfields, and the available monitored data from collieries in NSW. It can be noted that the geology of the overlying strata has a significant effect on Smax,inc. Where the overlying strata includes strong, uncracked strata, such as conglomerates or sandstones, Smax,inc can
**Fig. 8**

Prediction curves apply to first panels only for the typical sandstones & shales found in the Cooma region, with subsidence factor = 0.65 & no residual subsidence.

**Curve labels = Depths of cover (m)**

- Smax inc./seam vs Width of individual panels (m)

**Fig. 9**

- Smax inc./seam vs Panel width on depth ratio (Wpa/H)

- Curves for Cooma area, H (m)
- Curves for Southern C, Overlap
- Curves for Southern C with overlap
- NCB prediction curves, shales & mudstones
- DMR’s Southern curve, H < 400m
- DMR’s Western curve, H < 700m
- DMR’s Newcastle curve, H < 2200m
- Cape’s Newcastle curve, VT seam
- Monitored data with conglomerates & H = 92m
be dramatically reduced, particularly where Wpa/H is low. Conversely, where the overlying strata includes mostly weaker mudstones, then Smax,inc is increased as evidenced by the NCB predictive curves in Fig. 9. Smax,inc also increases where overlying strata is cracked by mining in adjacent panels, or in a higher seam (multi-seam mining), intrusions, faulting, or other natural jointing. The prediction curves shown in Figs. 8 and 9 have been tailored to suit the geology in the Cooranbong area and the Southern Coalfield and to provide conservative predictions of Smax,inc for those regions. Site specific Smax,inc prediction curves can be produced for other sites after considering the specific local geology and local survey data.

The shapes of incremental subsidence profiles varied predominantly with Wpa/H, the pillar width to depth ratio (Wpi/H) and the position of the panel within a series of panels. Fig. 10 shows, for third panels in a series, the location of various proportions of Smax,inc plotted about the advancing goaf edge (AGE) divided by Wpa. It can be noted that low Wpa/H profiles are much wider with respect to their panel width than high wide Wpa/H profiles. Fig. 11 shows the profile shapes and positions, divided by local cover, of 'third on' normalised incremental profiles plotted about the AGE.

The shapes of incremental profiles also vary with the Wpi/H and adjustments to the current, empirically derived, profiles should be made where the pillar widths for a proposed longwall layout are significantly different from the range of pillar sizes used to derive the model profiles.

Each profile is defined by two mathematical formulae, one for half of the profile commencing at the Smax,inc position and extending over solid coal and one for the tail gate side that extends over the previously mined goaf. First panels are defined by one formula mirrored about Smax,inc. Separate formulae are available for 2nd, 3rd, 4th and 5th on profiles and for each Wpa/H range of profiles modelled. All formulae are linear rational equations with up to 10 constants, fitted to the observed data.
Prediction of tilts, curvatures and strains, & influence of creeks & gorges

Once the final subsidence profile has been predicted, tilts and curvatures can be derived by calculating the first and second differences of subsidence between points on the profiles. These can be added to show the way in which tilts and curvatures develop panel by panel and to show the final cumulative tilts and curvatures.

Strains were generally more difficult to predict but a method was established for determining the systematic or underlying strains which gives reasonably good results when compared to the measured data. However due to the blocky nature of most surface areas, actual ground movement is concentrated at joints or planes of weakness and is more variable than the smooth curve predictions would suggest.

Furthermore the sequential extraction of longwall panels results in a cyclical application of tensile and compressive strains, the final surface profile and levels of strain are dependent upon the capacity of the cracks, when opened, to close as the strain is reversed. When compression occurs any resistance to closure of cracks and joints in the rock can result in local buckling or displacement which are reflected in the final profile and in the scatter found in the curvature and strain graphs. In these circumstances it is possible for survey measurements to indicate a tensile strain when in fact the ground is in compression.

Once the predictive method had been established it was used to predict the shape of the final profiles, tilts, curvatures and strains over a number of longwall panels. Good correlations were found between the predicted and measured values of subsidence and tilt for all cases compared, for example, see Figs. 12 and 13. An anomaly can be seen above Longwall 14 where local upsidence and high tilts were measured in a creek bed.

Reasonable correlations have generally been found between predicted and observed systematic ground curvature and strains. Many of the higher and non-systematic ground strains that have been observed have been associated with geological weaknesses and the alignments of creeks and gorges.
The non-systematic and scattered strains were analysed statistically in order to predict the magnitude of such strains and the likely frequency of their occurrence. Detailed study was made of the sudden fluctuations in the incremental subsidence profiles and the high concentration of compressive strains, which were observed at the base of most river gorges and crevices. Graphs were produced which now allow the prediction of the magnitude of upsidence, tilts and strains for different depths of surface scar, though the data does exhibit considerable variation.
Conclusions

The Incremental Profile Method combines aspects of the Empirical, Graphical, Influence Line, and Profile Function Methods in that;

- predictions are based entirely on empirical data,
- the influence from each longwall is calculated at each point, depending on the proximity and extent of neighbouring extractions,
- predictions can be made from appropriate empirical graphs, and
- functions have been derived to determine the shapes of incremental profiles.

As with other empirically derived relationships, the Incremental Profile Method can be used with confidence within the ranges of panel and pillar widths, depths of cover and seam thicknesses used to develop the method. If the method is to be used outside the ranges of panel and pillar widths, depths of cover and seam thicknesses that were used to develop the method, or in areas where the geology is different, then appropriate back analyses and model calibrations should be carried out and the model predictions should be cross checked against other predictive methods.

The benefits of the Incremental Profile Method are:

- Subsidence, tilt, curvature and strain predictions are provided at all positions across the series of panels.
- The method can be used even where seam thicknesses, pillar and panel widths, and the cover depths vary from panel to panel across a series of longwalls.
- The method can be used where panels are stopped short.
- Adjustments to predictions can be provided for geological anomalies, and sudden changes in surface topography, such as creeks or gorges.
- As the shape of final total subsidence profiles is predicted well, the method provides good predictions of the tilts, curvatures and systematic strains.
- The method also has the advantage that it can be used as a mine planning tool in order to consider the effects of alternative pillar and panel configurations.

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