Analysis of Mining Induced Strains

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Summary

Strain is an important parameter for assessing the potential impacts resulting from mine subsidence movements. However, strain resulting from mine subsidence is also one of the most difficult parameters to predict accurately. A number of methods can be used to predict strain, from simple empirical relationships, to more complex statistical approaches. This paper looks at some of these prediction methods and discusses the current research on improving the method of strain prediction.

1. Introduction

Ground strain comprises two components, being normal strain and shear strain, which can be interrelated using Mohr's Circle. The magnitudes of the normal strain and shear strain components are, therefore, dependant on the orientation in which they are measured. The maximum normal strains, referred to as the principal strains, are those in the direction where the corresponding shear strain is zero.

Normal strains along ground monitoring lines can be measured using 2D and 3D techniques, by taking the change in horizontal distance between two marks on the ground and dividing by the original horizontal distance between them. This provides the magnitude of normal strain along the orientation of the monitoring line and, therefore, this strain may not necessarily be the maximum (i.e. principal) normal strain. It should then be noted, that observed strains are dependent on the method of measurement, including the orientation of the monitoring lines, the spacing of the survey marks and survey tolerance.

Shear strains cannot be directly measured using traditional 2D or 3D ground monitoring lines. However, the shear deformations can be characterised from ground monitoring data using parameters including horizontal tilt, horizontal curvature, mid-ordinate deviation, angular distortion and shear index.

This paper discusses some of the methods used to predict normal strain (referred to just as *strain*), resulting from mine subsidence, and does not attempt to address the more complex interaction with shear strain.

The prediction of strain is more difficult than predicting subsidence, tilt, horizontal movement and curvature. The reason for this, is that strain results from a number of mechanisms, including the curvature due to sag subsidence, as well as the horizontal movements due to the redistribution of in-situ compressive stress and from downslope movement. The distribution of ground strain can also be affected by local variations in the near surface geology, the locations of pre-existing natural joints in the bedrock and the depth of bedrock. Survey tolerance can, in many cases, also represent a substantial portion of the measured strain.

For these reasons, the profiles of observed strain can be irregular even when the profiles of observed subsidence, tilt and curvature are relatively smooth.

2. Profiles of Observed Strain

It has been found from the extensive ground monitoring data that, whilst there can be extensive scatter in observed strain profiles, some locations above longwalls are more likely to experience tensile strains, whilst other areas are more likely to experience compressive strains.

Where there is a reasonable distribution of strain, comprising overall tensile zones and overall compressive zones, this is often referred to as conventional, normal, or systematic movements.

Localised and elevated strains can occur anywhere above extracted longwalls, which are often observed at collieries with very shallow depths of cover, multi-seam mining, steep or undulating terrain (i.e. valley related movements). These irregular strains are often referred to as non-conventional movements.

Irregular strains can also develop as a result of near surface geological features, including faults or dykes or other igneous intrusions, or abrupt changes in near surface geology. In some cases, the elevated strains cannot be explained, and these strains are often referred to as anomalous movements.

Examples of observed strain profiles along four typical monitoring lines from the Southern Coalfield are illustrated in Figure 1. The distances in this figure have been normalised, so that the locations of the measured strains are shown relative to the edges of the active longwall. These strain profiles have been taken from monitoring lines at several collieries, where the mining geometries (i.e. void widths, extraction heights and depths of cover) and the overburden geology are reasonably similar.

It can be seen from this figure, that the profiles of observed strain for these monitoring lines vary not only in shape, but in magnitude. Whilst there are differences, some similarities can be observed, with zones of tensile strain developing adjacent to the longwall maingates and zones of compressive strain developing towards the longwall centrelines.
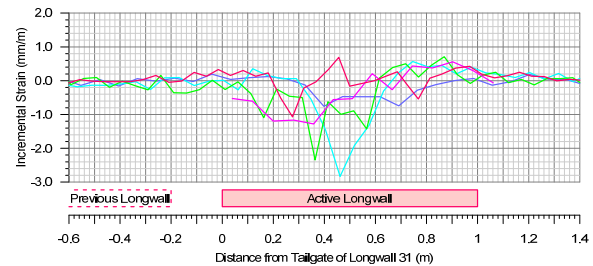

Figure 1 – Typical Profiles of Observed Incremental Strain from the Southern Coalfield

The following sections of this paper discuss some of the existing strain prediction methods and the ongoing research on the prediction of strain.

3. Distribution of Strain

A distribution of all raw observed strains above longwalls extracted in the Southern Coalfield, excluding valley closure strains, is illustrated in Figure 2. The distances have been normalised, so that the locations of the measured strains are shown relative to the longwall maingate and tailgate sides. Approximate confidence levels for tensile and compressive strain are also shown in this figure, to help illustrate the variation in the data.
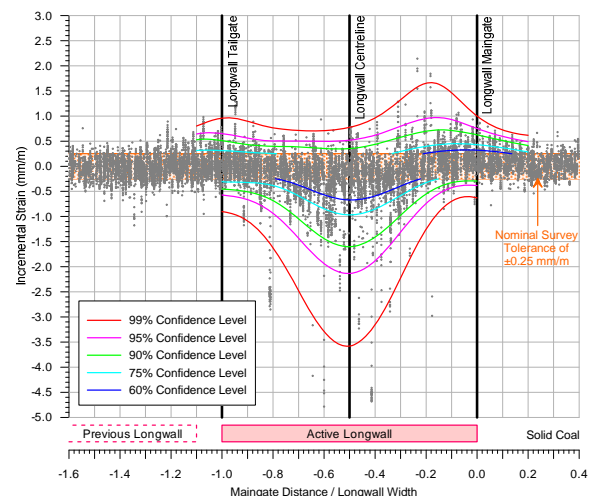

Figure 2 – Observed Incremental Strain versus Normalised Distance from the Longwall Maingate from the Southern Coalfield

It can be seen from this figure that, whilst there is a scatter in the raw observed strains, tensile strains are more likely to develop adjacent to the longwall maingate and that compressive strains are more likely to develop near the longwall centreline. That is, the tensile zone occurs in the location of hogging (convex) curvature and the compressive zone occurs in the location of sagging (concave) curvature.

This result helps to confirm that there is a relationship between curvature and strain. However, as there is significant scatter in the raw observed strains, it also indicates that there are also other factors which affect strain, such as horizontal movement, near surface geology, as well as the method of measurement (i.e. location and orientation of monitoring line, spacing of survey marks and survey tolerance).

Simple empirical relations have been used to predict the magnitudes of strains based on curvature alone. One such method adopts a linear relationship between curvature and strain. The maximum strain derived in the Handbooks for Predicting Subsidence in the Southern, Newcastle and Western Coalfields (Holla, 1985, 1987 and 1991) are based on this relationship.

Simple empirical relationships based on curvature alone can, in most cases, provide reasonable predictions for the maximum conventional strains, however, it is accepted that these predictions can be exceeded by non-conventional strains. Also, it is accepted that these strain predictions are less reliable, away from the locations of the maxima, due to the large scatter in raw observed strain.

Another disadvantage of empirical relationships, is that they provide a single predicted value for the maximum strain and, therefore, do not take into account the scatter observed in strain profiles. This scatter can be better addressed by looking at the statistic distributions of strain.

The distributions of raw observed strain in particular locations above extracted longwalls can be determined using the monitoring data from previously extracted longwalls. Survey lines are commonly measured a number of times during mining and individual survey bays can, in some cases, experience both tensile and compressive strains due to the travelling wave behind the longwall extraction face.

For this reason, the distributions for tensile strain and compressive strain should be treated independently and, hence, separate distributions established. Where survey bays are measured a number of times, during a longwall extraction, the maximum strain should be used in the analysis, i.e. a single tensile strain and single compressive strain measurement per survey bay per longwall.

A simple statistical distribution of strain can be determined using strains measured directly above extracted longwalls, regardless of their location to the longwall edges and regardless of the orientation of the monitoring line to the longwall. The histogram of the maximum observed tensile and compressive strains measured in survey bays above extracted longwalls, for monitoring lines from the Southern Coalfield, is provided in Figure 3.
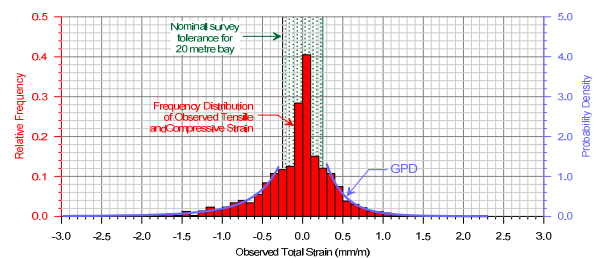
Figure 3 – Distribution of Observed Maximum Tensile and Compressive Strain in the Southern Coalfield for Survey Bays Located Above Goaf

The histogram illustrated in the above figure is based on around 20,000 individual measurements of survey bays located above active longwalls. The data does not include the strains resulting from valley closure.

The strain distributions were analysed with the assistance of the Centre of Excellence for Mathematics and Statistics of Complex Systems (MASCOS) at the University of New South Wales. A number of probability distribution functions were fitted to the empirical data. It was found that a Generalised Pareto Distribution (GPD) provided a reasonable fit to the raw strain data. The choice of GPD is also supported by theoretical arguments taken from the field of extreme value theory, as a credible distribution for the modelling of extreme levels of a process above some high threshold (e.g. Coles, 2001).

The GPD fits for high tensile and compressive strains above extracted longwalls in the Southern Coalfield are shown as the blue lines in Figure 3. The 95 % confidence levels for tensile and compressive strains, based on the fitted GPDs, are 0.8 mm/m and 1.5 mm/m, respectively.

As illustrated in Figure 2, the distribution of strain is not uniform above extracted longwalls. That is, tensile strains are more likely to be experienced adjacent to the longwall maingates and compressive strains are more likely to be experienced near the longwall centrelines. Hence, strain distributions can also be established for specific locations above extracted longwalls.

The distribution of strain (excluding valleys) observed adjacent to the longwall maingate, for monitoring lines from the Southern Coalfield, is illustrated in Figure 4.
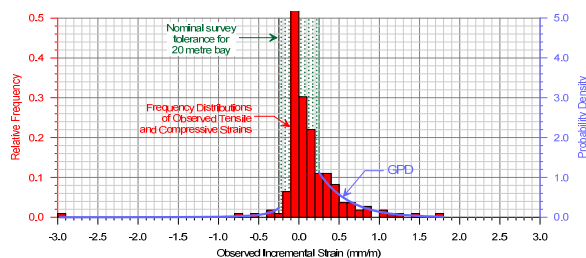
Figure 4 – Distribution of Observed Strain near Longwall Maingate from the Southern Coalfield

The 95 % confidence levels for tensile and compressive strains, based on the fitted GPD shown in Figure 4, are 1.0 mm/m and 0.5 mm/m, respectively.

The distribution of strain (excluding valleys) observed near the longwall centreline, for monitoring lines from the Southern Coalfield, is illustrated in Figure 5.
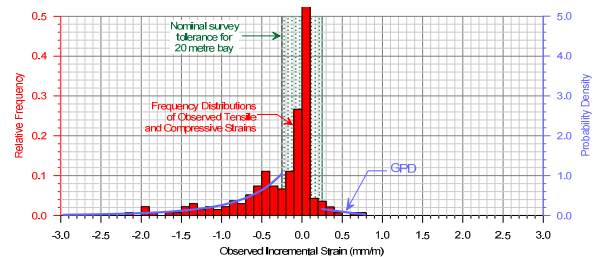
Figure 5 – Distribution of Observed Strain near Longwall Centreline from the Southern Coalfield

The 95 % confidence levels for tensile and compressive strains, based on the fitted GPD shown in Figure 5, are 0.5 mm/m and 2.0 mm/m, respectively.

These strain distributions provide good indications as to the range of strains which have been observed for specific locations relative to the longwall edges. It is noted, that survey tolerance was used as the thresholds for the GPD fits for consistency.

Strain distributions derived from raw observed data can be used to provide indications of the range of strains likely to develop from longwall mining. The disadvantage of this method, is that it is specific to longwall geometry (i.e. longwall void width, seam thickness and depth of cover) and only provides predictions for specific locations relative to the longwall edges. That is, these strain distributions are specific to the data that was used to fit them.

To resolve these limitations, the prediction of strain can be further refined using statistical methods to determine the relationships between strain and other mine subsidence parameters, rather than distance to the longwall edges.

4. Statistical Relationship between Curvature and Strain

As described previously, empirical relationships such as a linear relationship between curvature and strain, have been used to provide reasonable predictions of the maximum conventional strains. These predictions, however, can be exceeded by non-conventional strains, and are less reliable, away from the locations of the maxima, due to many factors as discussed previously.

These methods can be further refined using statistical methods to better define the relationship between curvature and strain. A number of issues arise in developing these relationships, which are described below.

One such issue, is that curvature is defined using three survey marks (i.e. differential movement of a mark, relative to the two adjacent marks, divided by the average of the bay lengths squared), whilst strain is defined using two marks (i.e. change in bay length). For the curvature defined at a survey mark, therefore, there are two corresponding strains in the adjacent survey bays.

Another issue is that scatter in observed curvature profiles can arise from, amongst other things, survey tolerance. Raw curvature profiles can be irregular, with the scatter representing a large proportion of the observed curvature.

Both of these issues can be overcome by adopting curvature derived from smoothed subsidence profiles. Several smoothing processes are available, which can be used to remove the small deviations in the subsidence profile and, hence, minimise the scatter in the derived curvature profiles, without reducing the overall maxima.

In this way, statistical relationships can be established based on the overall (i.e. macro) curvatures, rather than the localised (i.e. micro) curvatures. These macro curvatures are essentially those resulting from conventional movements and, therefore, are more readily predicable. From a statistical perspective, the macro curvatures are more likely to represent the signal and the micro curvatures are more likely to represent the noise.

A number of smoothing algorithms have been tested.

One such method is *Savitzky-Golay* smoothing (Savitzky, et al, 1964), which uses weightings to perform a local polynomial regression. The advantage of this method is that it is very simple to apply and provides reasonable results. The main disadvantage of this method, is that it requires uniform spacing of points and, therefore, cannot be used where the survey bay lengths vary, or where marks have been removed (i.e. disturbed or destroyed).

Another method is *Loess* smoothing (Cleveland, 1979), which uses local regression to fit low order polynomials to subsets of the data. The advantage of this method, is that is does not require uniform spacing of points and, therefore, can be adopted for monitoring data with disturbed or destroyed marks. One disadvantage of this method, it that it is computationally intensive, however, the fitting methods can be readily implemented using computer algorithms. For this reason, Loess smoothing has been adopted in the current research on strain.

The use of Loess smoothing is illustrated in Figure 6, which shows the raw observed subsidence and curvature profiles overlaid with the smoothed subsidence and curvature profiles for a monitoring line from the Southern Coalfield.
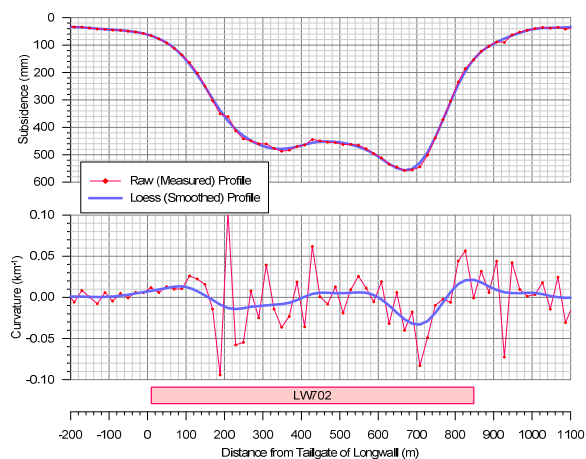
Figure 6 – Example of Raw and Smoothed Subsidence and Curvature Profiles

It can be seen from this figure, that the smoothed subsidence profile reasonably matches the raw subsidence profile, but the small deviations have been removed. It can also be seen, that the raw observed curvatures are very irregular, due to the small deviations in the raw observed subsidence profile. The curvature derived from the smoothed subsidence profile, however, more clearly shows the locations of overall hogging (i.e. convex) curvature and overall sagging (i.e. concave) curvature, rather than the localised deviations in curvatures at each survey mark.

The development of a statistical relationship between curvature and strain is currently a part of ongoing research. Early work is providing indications that a relationship, similar to that illustrated in Figure 7, could be developed as part of this research.

Such a statistical approach would allow the establishment of strain distributions, similar to those developed in Section 3, for any location above extracted longwalls. These distributions would be applicable for any mining geometry having predicted conventional curvatures within the range of the raw data used to develop the statistical relationships. These strain distributions would include those occurring from both conventional and non-conventional movements.
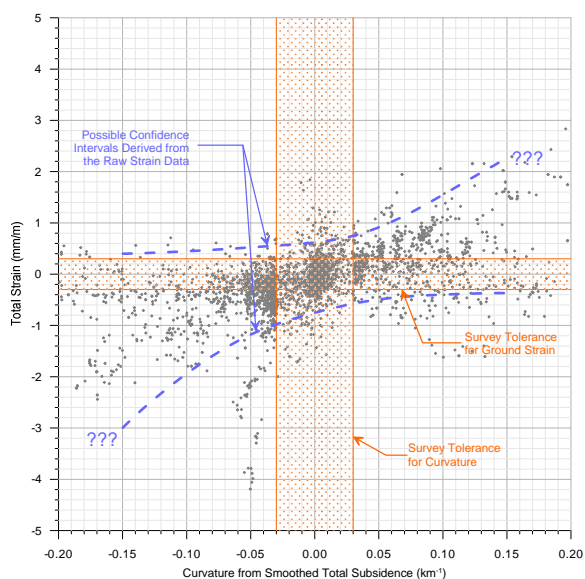

Figure 7 – Possible Relationship between Curvature and Strain (Ongoing Research)

5. Strains Measured over Long Bay Lengths

Strains are generally measured over bay lengths equal to the depth of cover divided by 20, so that strains can be more readily compared between different collieries and coalfields. In the Newcastle and Hunter Coalfields, the survey bay lengths are typically 10 metres or 15 metres and, in the Southern Coalfield, the bay lengths are typically 20 metres.

Strains can also be calculated over longer bay lengths using the changes in horizontal distance between non-adjacent marks along 3D monitoring lines. Long strains can also be calculated from 2D monitoring lines, by accumulating the changes in survey bay lengths, however, it should be noted that this also results in an accumulation of the measurement error from each survey bay.

For example, the observed changes in total length (i.e. strain) over bay lengths of 100 metres, for monitoring lines above longwalls extracted in the Southern Coalfield, is illustrated in Figure 8.
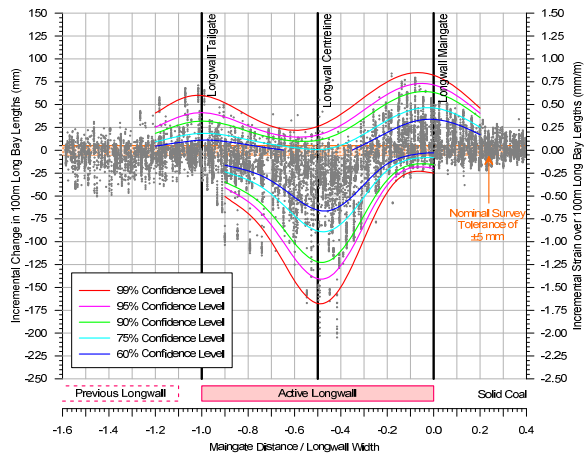
Figure 8 – Observed Incremental Opening and Closing Movements Over 100 metre Bays versus Normalised Distance from the Longwall Maingate from the Southern Coalfield

The distances shown in the above figure have been normalised, so that the locations of the measured changes in bay lengths are shown relative to the longwall maingate and tailgate sides. Approximate confidence levels for opening and closing movements are also shown in this figure, to help illustrate the variation in the data.

It can be seen from Figure 8, that the distribution of tensile and compressive strains above extracted longwalls, based on 100 metre long bays, are similar to those for strains measured over 20 metre bays, which were illustrated in Figure 2.

It has been found, by measuring strains over longer bay lengths, that the observed profiles of strain become more regular (i.e. smoother) and, hence, become more predictable.

This is also illustrated in Figure 9, which shows the profiles of observed strain along three adjacent monitoring lines from the Southern Coalfield, based on 20 metre, 60 metre and 100 metre bay lengths.
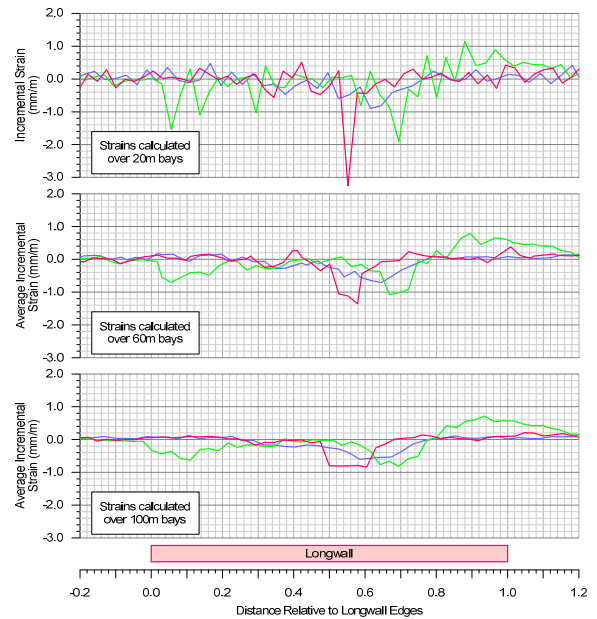

Figure 9 – Observed Strains Measured Over 20, 60 and 100 metre Bays for Three Adjacent Monitoring Lines from the Southern Coalfield

The shapes and the magnitudes of the strains profiles, based on 20 metre bays, are very different for the three monitoring lines, which was the result of localised and elevated non-conventional compressive strains. The shapes and magnitudes of the strains are more comparable, however, when the strains are measured over longer baylengths, such as 100 metres. There are still some differences in the locations of the maxima, which is the result of the non-conventional movements intersecting the monitoring lines in different locations.

This indicates that, whilst localised compressive strains occurred in different locations above the extracted longwall, the overall horizontal movements (i.e. closure) were similar for these three monitoring lines.

Curvatures over longer bay lengths can also be calculated from monitoring lines with traditional spacing of survey marks using the movements measured at non-adjacent marks, as illustrated in Figure 10.
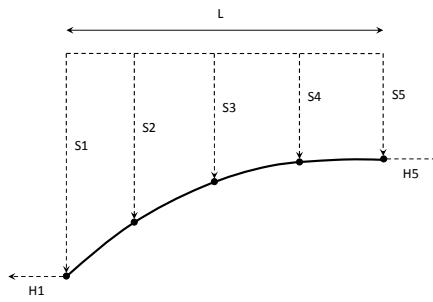
Figure 10 – Long Curvature and Strain

In the above example, curvature and strain can be calculated over a long bay length of "L" as follows:-

Long curvature:
$$K_L = \frac{4*(S1 - 2*S3 + S5)}{L^2}$$

Long strain:
$$\varepsilon_L = \frac{(H5 - H1)}{L}$$

The development of relationships between long curvature and long strain is currently part of ongoing research.

The simplest method adopts a linear relationship between long curvature and long strain, similar to that discussed in Section 3 for traditional survey bay lengths. In this way, predicted strains over long bays can be calculated by applying a constant factor to the predicted curvatures based on long bays.

This is illustrated in Figure 11, which shows the observed and predicted strains along a monitoring line from the Southern Coalfield, based on 20 metre, 60 metre and 100 metre bay lengths. The predicted strains were determined by applying a constant factor to the predicted curvatures calculated over the long bay lengths.

It can be seen from this example, that the predicted profile more closely matches the observed profile using the longer bay lengths.

This is important, as strains over long bay lengths are more relevant whenever assessing the potential for impacts on large infrastructure, including bridges, buried pipelines, railways and road pavements.
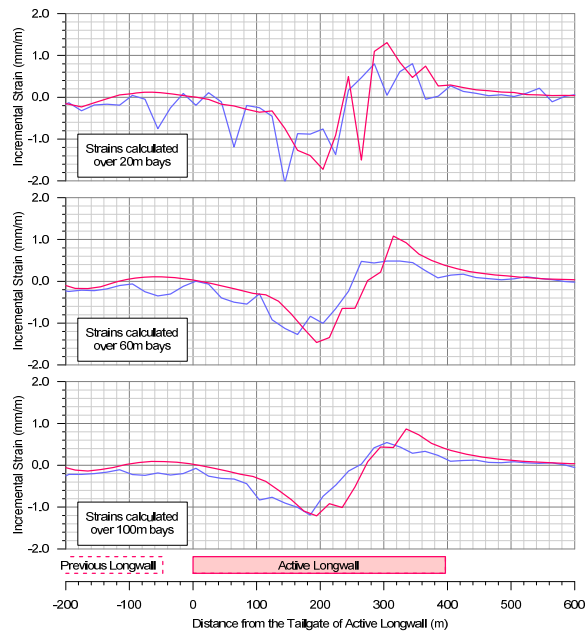
Figure 11 – Observed and Predicted Strain Based 20 metre, 60 metre and 100 metre Bay Lengths for a Monitoring Line from the Southern Coalfield

The development of statistical methods for strains over long bay lengths is part of ongoing research.

6. Summary

Mining induced strain is one of the most difficult parameters to predict, as it is affected by a number of mechanisms. Observed strain profiles can be very irregular, even though the observed subsidence, tilt and curvature profiles are reasonably regular.

The distribution of strain above extracted longwalls indicates that, whilst there is a scatter, the tensile strains are more likely to develop in the location of hogging (convex) curvature and the compressive strains are more likely to develop in the location of sagging (concave) curvature.

Empirical methods can be used to provide reasonable predictions of the maximum conventional strains, however, they generally do not take into account localised and elevated strains resulting from non-conventional movements, or the scatter in observed strain data.

Statistical methods can be used to better establish the relationships between strain and other mine subsidence parameters, including curvature and horizontal movement, as well relationships with position relative to extracted longwalls. The development of some of these statistical methods is part of ongoing research.

Strains can also be calculated over longer bay lengths using the changes in horizontal distance between non-adjacent marks. In doing this, the strains become more regular (i.e. smooth) and, hence, more readily predictable. Strains over long bay lengths are important for assessing the potential for impacts on large infrastructure. The development of statistical methods for strains over long bay lengths is also part of ongoing research.

7. References

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