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# Prediction of horizontal movement and strain at the surface due to longwall coal mining

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ABSTRACT

Strain is an important parameter for assessing the potential for impacts on surface features due to mine subsidence. However, this parameter is also one of the most difficult to predict. Research is being undertaken with the objective to improve the currently available predictive methods for horizontal movement and strain at the surface. The methodology predominantly follows an empirical approach, using a large database of ground monitoring data, which was supplemented using numerical modelling. Predictive equations have been developed for the relative horizontal movements across various zones above longwalls based on the vertical subsidence and the influence of topographical features. These relative horizontal movements are then used as the basis to predict the distributions of strain within each of these zones. This paper provides an overview of the methodology and the current findings from this research project.



## 1. Introduction

There are several well-established empirical and mechanistic methods used to predict mine subsidence due to longwall mining. These methods can provide reliable predictions of vertical subsidence, tilt and curvature when properly calibrated to local conditions. The prediction of horizontal movement and strain are much more difficult, as they are sensitive to variations in the surface topography and the presence of near surface geological features. Strain is also one of the most important subsidence parameters for assessing the potential for impacts on natural and built surface features.

Early methods for the prediction of horizontal movement and strain were generally based on simple empirical relationships with mining geometry or other predicted subsidence parameters. These empirical methods generally provide reasonable predictions of the regular ground movements, when the surface and overburden are relatively flat and uniform and when there are no significant near surface geological features. However, predictions of horizontal movement and strain obtained using these methods are often exceeded at discrete locations due to irregular movements. These irregularities develop due to the presence of incised terrain or variations in the near surface geology.

More recently, statistical methods have been used to predict the distribution of strain based on both the regular and irregular movements. These methods provide the likelihoods of exceeding strain thresholds based on previously measured ground monitoring data. However, the application of these statistical methods is often limited to locations where the mining geometry and overburden lithology are similar to the mining areas from which the monitoring data were collected.

The objectives of this current research are to develop improved methods for the prediction of absolute and relative horizontal movement, normal strain and shear deformation at the surface. The predictive methods have been developed predominately using an empirical approach supplemented with numerical modelling.

A large database of ground monitoring data from the Australian coalfields was available for this research project. The predictive methods have therefore been derived based predominantly on Australian conditions. These methods can be applied to coalfields elsewhere by calibrating them for the local conditions using the available ground monitoring data.

## 2. Historic and current methods of prediction

Predictive methods for longwall mine subsidence broadly fit into two categories. *Empirical methods* are developed based on the relationships that are observed between the ground movements and the mining geometry. These methods include graphical, profile function and influence function methods. *Mechanistic methods*

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are developed based on modelling the underlying mine subsidence mechanisms. These methods include simple analytical models through to more complex numerical models, which require detailed knowledge of the mechanical properties of the overburden strata.

Historically, subsidence prediction methodologies have been predominantly based on simple empirical relationships. Many of these methods have evolved from those initially developed by the National Coal Board (NCB) of the United Kingdom (UK). The Subsidence Engineers Handbook (SEH) was originally published by the NCB in 1965 and was updated in 1996 and 1975.[1] The maximum predicted strains are obtained using the SEH by applying *multipliers* to the ratio of maximum vertical subsidence to the depth of cover. The multipliers are presented graphically in the handbook versus the width-to-depth ratio. The SEH also provides a relationship between strain, the differential slope and bay length for the UK Coalfields. The curves suggest a relationship between strain and the square root of curvature.

The SEH has been used internationally in locations including Europe, Australia, India, China, Canada and the United States of America. The methods have been found to over-predict subsidence in some coalfields such as those in Australia,[2,3] the United States[4,5] and India.[6,7] The lower levels of observed subsidence was identified to be predominately due to the stronger or more competent overburden strata when compared with the strata in the UK. In addition the predictive curves used to develop the SEH were based predominantly on multi-seam mining conditions.

The empirical methods presented in the SEH have been modified or calibrated to suit coalfields located outside the UK. The predictive equations typically have similar forms as those presented in the SEH, where strain is determined by applying multipliers to the ratio of maximum vertical subsidence to depth of cover. The multipliers for each coalfield have been derived from the locally available ground monitoring data.

It is often observed that the shapes of the horizontal movement profiles are similar to the shapes of the tilt profiles. This similarity occurs when the surface, overburden strata and seam are relatively flat and uniform and when the ground subsides regularly. These conditions are often referred to as the *conventional model*. On this basis, linear relationships between tilt and horizontal movement have been suggested by various authors including Salamon,[8] Tandanand and Powell[9] and Hornby et al.[10]

The horizontal movement and tilt profiles can differ considerably when mining beneath undulating or incised terrain.[11,12,13] Increased horizontal movements develop in the downslope direction when mining occurs beneath slopes, scarps, hills and valleys.

Curvature can be approximated by the first derivative of tilt and normal strain is the first derivative of horizontal movement. On this basis, a number of empirical relationships have been developed between curvature and strain. These relationships have been discussed by numerous authors.[14–20] Predictive methods for strain have been proposed based on curvature, the square root of curvature, or curvature raised to a fixed power.

These empirical relationships are often exceeded by localised and elevated strains. These *irregular* strains develop from a number of mechanisms including variations in the surface topography or near surface geology.

Irregular strains can develop when longwalls are extracted beneath steeply sloping or incised terrain. Localised and elevated compressive strains generally develop in the bases of valleys or steep slopes. Elevated tensile strains can also develop at the tops of scarps and hills. Irregular strains also develop due to the presence of near surface geological features. These features include local variations in the surface lithology or jointing, or the presence of a soft inclusion within a more competent rock mass. The locations and properties of these small scale features are generally unknown.

Strain therefore includes an irregular component that cannot be directly predicted. The term *anomaly* has been used to describe this random component. These irregular horizontal movements and strains are more noticeable at higher depths of cover, as their magnitudes can be many times greater than those which develop from the regular movements. Irregular ground movements can also dominate at much shallower depths of cover due to blocky movement of the near surface strata, where the highly fractured zone extends from the seam up to the surface.

Profile function and influence function methods predict horizontal movement and strain based on relationships with tilt and curvature. Linear relationships are often adopted. These methods therefore have the same limitations as empirical methods.

Numerical methods adopt constituent models that provide approximate equations for the relationships between stress and strain and between strain and displacement. Continuum methods comprise elements with shared nodes and the displacements are derived directly from the calculated strains. Discontinuum methods comprise discrete elements that interact via compliant contacts. The displacements of the elements are determined at small time increments allowing contact, separation and slip to occur.

Numerical methods allow for more complex relationships between strain and deformation based on the modelled properties of the rockmass and joints. These methods can also incorporate the influence of varying surface topography, lithology and large-scale structure.

However, it is not possible to model all the small-scale variability in the near surface lithology or the small-scale structure, as the locations, distributions and properties are generally not known. Numerical methods therefore cannot accurately predict the irregular movements that often dominate the strain profiles.

Statistical methods can provide confidence intervals for strain based on both the regular and irregular ground movements. These methods are developed by analysing the distribution of strain from large sets of ground monitoring data. However, the application of these statistical methods is often limited to locations where the mining geometry and overburden lithology are similar to the mining areas from which the monitoring data were collected.

All predictive methods are developed, reviewed and calibrated using ground monitoring data. This data comprises strains that are measured along the alignments of the monitoring lines and at specific epochs. Strain is a tensor that comprises three components, two orthogonal normal strains and one shear strain. The measured strains therefore do not always reflect the maximum or principal strains. Also, the magnitude, sign (i.e. tensile and compressive) and orientation of strain vary during active subsidence and in many cases the surveys may not measure the peak values. The reliability of the predictive methods is therefore limited by the quality and the quantity of the available monitoring data.

## 3. Review of existing predictive methods

The existing predictive methods for strain have been reviewed as part of the current research project. Extensive ground monitoring data was available from the Australian coalfields. For this reason, the reviews were based on the predictive methods that have been historically used in Australia.

The Department of Mineral Resources (DMR) Handbook method for the Southern Coalfield[21] was reviewed using the latest available ground monitoring data. This data was obtained from 84 monitoring lines above 231 longwalls in 18 separate mining areas from the Southern Coalfield. The predicted strains are determined from the handbook using the tensile strain factor ($K_1$),