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REVIEW OF HORIZONTAL SURFACE MOVEMENTS DUE TO LONGWALL COAL MINING USING NUMERICAL MODELLING

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Strain is an important parameter for assessing the potential for impacts on surface features due to longwall mine subsidence, but it is also one of the most difficult parameters to predict. Whilst profiles of strain can be highly variable and irregular, zones of net compression and net tension generally develop above longwalls. By considering the relative horizontal surface movements over longer bay lengths, they become more regular and, hence, more predictable. Numerical modelling has been undertaken using universal distinct element code (udec) to assist with the development of predictive methods for the relative horizontal movements over the various zones above an active longwall. The numerical modelling was used to assess the effects of varying surface topography on the horizontal movements, including slopes, scarps, hills and small valleys. Predictive equations have been developed for the net compression within the sagging curvature zone and the net openings within the hogging curvature zones. These equations are consistent with the findings from reviews of ground monitoring data in nsw coalfields.

BACKGROUND

The prediction of horizontal movement and strain due to longwall mine subsidence have historically been based on simple empirical relationships with mining geometry or other subsidence parameters. Whilst these empirical methods generally provide reasonable predictions of the regular (i.e. conventional) ground movements, they are often exceeded in discrete locations due to irregular or anomalous movements.

More recently, statistical methods have been used to predict the distribution of strain based on measured ground monitoring data. These methods provide the predicted probabilities of exceedance (i.e. confidence intervals) for strain based on both the regular and irregular movements. However, these statistical methods are often limited in use to locations where the mining geometry and overburden lithology are similar to the mining areas from which the monitoring data were collected.

Research is currently being undertaken to improve the predictive methods for horizontal movement and strain at the surface due to longwall coal mining. It has been found that by considering the relative horizontal movements over longer bay lengths, they are more regular and, hence, become more predictable when compared with those measured across the standard survey bay lengths.

It has also been identified by various authors that areas of sagging curvature tend to be net compressive zones and areas of hogging curvature tend to be net tensile zones above the active longwall. For this reason, the predictive methods for strain have been developed based on a two-step process. The relative horizontal movements are predicted across each of the zones above the active longwall and then the distributions of strain within each of these zones are predicted based on the net or overall movements.

The zones above a subcritical longwall and the idealised profiles of incremental vertical subsidence (S) and incremental horizontal movement (u) are illustrated in Figure 1. The incremental parameters are the additional ground movements due to the extraction of the active longwall within the series.

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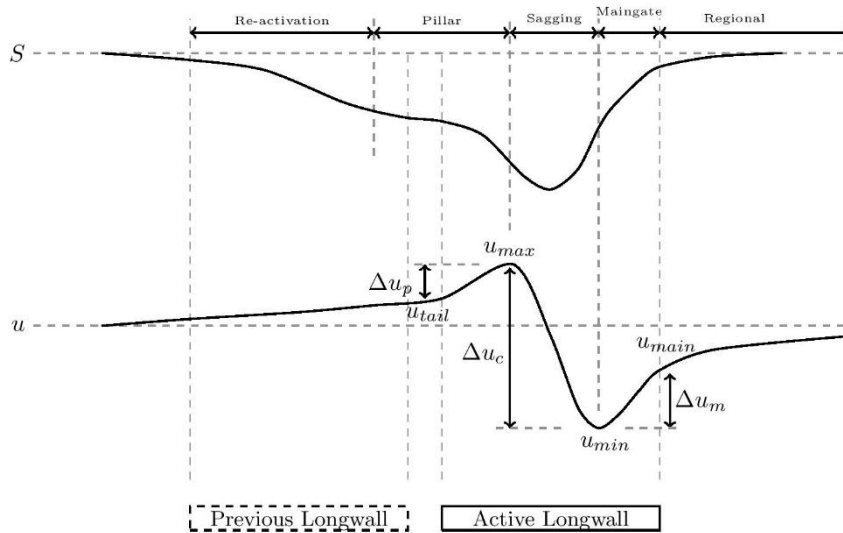
Figure 1: Zones above a subcritical longwall and the idealised profiles of the incremental vertical and incremental horizontal components of mine subsidence

The initial research has focused on the net compression across the sagging zone above the active longwall, referred to as '*panel closure*' (Δu_c). This parameter is the difference between the maximum (i.e. most positive, u_{max}) and the minimum (i.e. most negative, u_{min}) horizontal movements transverse to the longwall, i.e. at right angles to the centreline of the active longwall. The research has also investigated the net tensions across the maingate and pillar zones, referred to as '*maingate opening*' (Δu_m) and '*pillar opening*' (Δu_p).

The relationships between panel closure and the mining geometry and other subsidence parameters were reviewed using the available ground monitoring data from the Southern Coalfield. It was identified that there is a strong relationship between the measured panel closure and the maximum incremental vertical subsidence, as illustrated in

Figure 2, based on the available 3D monitoring lines from the Southern Coalfield.
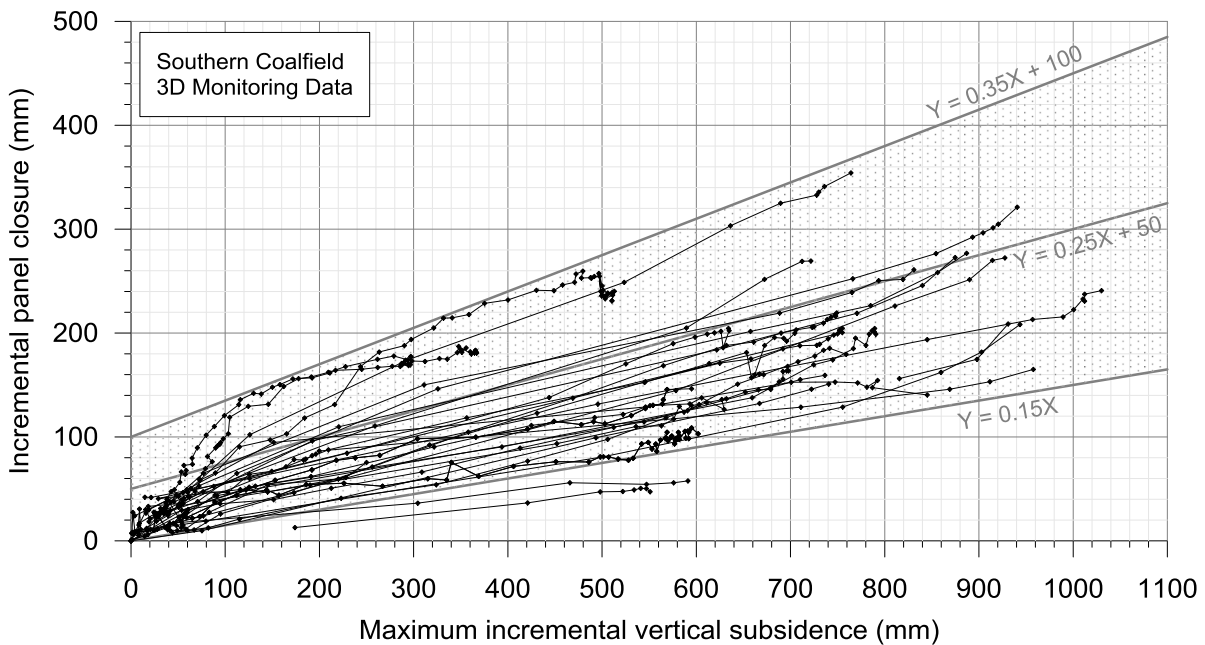

Figure 2: Measured incremental panel closure versus maximum incremental vertical subsidence for 3D monitoring lines from the Southern Coalfield

It was found that, after an initial development of vertical subsidence up to around 100 mm, there are reasonably linear relationships between panel closure and vertical subsidence for each of the monitoring lines. Similar relationships were also found based on monitoring data from the Newcastle, Hunter and Gunnedah Coalfields, comprising a wide range of mining geometries (i.e. longwall widths, depths of cover and extraction heights) and overburden lithology. The relationships appear to be non-linear during the initial development of subsidence (i.e. less than around 100 mm) at which time the extraction face is either approaching or partially beneath the monitoring lines.

The gradients of the linear segments typically vary between 0.15 and 0.25, but are up to 0.35 for some cases. A review of the empirical data found that the gradients were generally towards the lower end of the range for the cases where the surface topography and seam were relatively flat and the ground subsided regularly with no localised or elevated irregular/anomalous strains. Conversely, the gradients were generally towards the upper end of the range for cases with incised topography, including steep slopes and small valleys, and for cases with irregular ground movements comprising localised and elevated strains.

The empirical data suggests that a simple predictive equation can be developed for panel closure based on a linear relationship with maximum incremental vertical subsidence, when the magnitude of subsidence is greater than about around 100 mm. The generalised equation for panel closure is:

$$\Delta u_c = \alpha + (\beta + \delta).S_{max.inc}$$ (1)

The first coefficient alpha (α) represents the component of movement due to horizontal compression of the overburden strata, which is largely due to the redistribution of horizontal *in situ* stress. The second coefficient beta (β) represents the component of horizontal movement that is directly related to the vertical component, when the surface, overburden and seam are relatively uniform and flat and when the ground subsides regularly. The third coefficient delta (δ) represents the component of horizontal movement due to topographical features (such as sloping terrain, scarps, hills and small valleys), sloping overburden strata, sloping seam and irregular ground movements.

NUMERICAL MODELLING

Numerical modelling was carried out to further investigate the relative horizontal movements across each of the zones above an active longwall and their relationships with maximum vertical subsidence and varying surface topography. The numerical modelling was undertaken using *Universal Distinct Element Code* (Itasca Consulting Group, Inc.). UDEC is a two-dimensional distinct element method that models the rock mass as an assembly of discrete elements that interact via compliant contacts or interfaces.

Development of the generic numerical model

A generic two-dimensional numerical model was initially developed for the Southern Coalfield based predominantly on the conditions around Appin and West Cliff Collieries. The initial model assumed a flat surface, seam and overburden strata. The discontinuities were modelled as a series of parallel horizontal and vertical joints.

The properties of the overburden were predominately based on the testing results from three boreholes at Appin and West Cliff Collieries (MacGregor and Conquest 2005), but also considered information available in literature and from previous UDEC numerical studies including CSIRO Petroleum (2002), Keilich (2009) and Zhang (2014).

The thickness of the strata layers adopted in the model are included in Table 1. These thickness values were based on the three boreholes, but were adjusted so that the total depth of cover above the Bulli

Seam was 500 metres. The generic model allows the longwall widths to be varied between 150 and 600 metres and, therefore, considers width-to-depth ratios ranging between 0.3 and 1.2.

There is a wide range of material and joint properties documented in literature. It was considered that no single value could be representative for each of these properties due to variations in the testing results, scaling effects, variations over depth and in plan and effects of inclusions and discontinuities. There is inherent uncertainly in these properties *in situ*, let alone when the strata are subjected to mine subsidence.

The generic numerical model was reviewed, therefore, based on a range of material and joint properties and then calibrated using ground monitoring data. The main variables considered in the initial calibration were the block size (i.e. discontinuity spacing), horizontal *in situ* stress, rock mass properties and discontinuity properties.

The calibration process considered three block sizes, referred to as Types B1, B2 and B3 (from smallest to largest). The spacing of the horizontal discontinuities varied between 9 to 15 metres for the sandstone formations and between 3 to 5 metres for the claystone formations. The ratio of the horizontal to vertical block dimensions was taken to be 1.5. The vertical discontinuities were staggered so that the blocks formed a 'brick' type pattern. The horizontal *in situ* stress was modelled as equal to the vertical stress (Type S1) and two times the vertical stress (Type S3).

Three groups of rock mass properties were considered in the initial calibration, referred to as Types M1, M2 and M3 (from weakest and most flexible through to strongest and stiffest). The rock mass properties at the upper end of the range (i.e. Type M3) were based on the mean of the test results of the 48 core samples taken from the three boreholes at Appin and West Cliff Collieries (MacGregor and Conquest 2005), i.e. no reduction for scale. The properties at the lower end of the range (i.e. Type M1) were based on the reduction for scale proposed by McNally (1996) and represented values around one-standard deviation below the mean of the test results.

There is a wide range of discontinuity properties documented in literature and adopted in the previous UDEC modelling studies. The available information in literature is predominantly for intact rock and there is little guidance on the appropriate properties when the joints are subjected to mine subsidence movements. The models considered a range of joint properties, based on reviews of the available information, and are referred to as Types J1, J2 and J3 (from weakest and most flexible through to strongest and stiffest).

The joint normal stiffness (jkn) for Sydney sandstone and shale provided by Bertuzzi and Pells (2002) range between 10 GPa/m (5 to 10 mm thickness) and 4000 GPa/m (tight) for major erosional bedding planes, and between 500 GPa/m (3 mm thickness) and 4000 GPa/m (tight) for joints. The joint normal stiffness adopted in the previous UDEC modelling studies in the Southern Coalfield were 3000 GPa/m (CSIRO Petroleum 2002), between 21 and 204 GPa/m (Keilich, 2009) and 26 GPa/m (Zhang 2014).

An initial review of the numerical models found that joint normal stiffness towards the lower end of the range of those documented in literature provide results that more closely match the available ground monitoring data. The lower stiffness is likely to reflect the large scale post peak deformation (i.e. horizontal shear and vertical dilation) that develop as a result of mine subsidence. The range of the joint normal stiffness adopted in the generic numerical models was between 10 GPa/m (Type J1) and 50 GPa/m (Type J3). The joint shear stiffness (jks) was taken to be one-tenth of the normal stiffness, as adopted in the previous UDEC numerical modelling studies.

The peak cohesions (C) for the discontinuities considered in the initial models ranged between 1.5 MPa and 6.25 MPa for the sandstone units and between 1.0 MPa and 3.5 MPa for the claystone units. The joint cohesions represented values up to around one-quarter of the tested cohesions for the rock mass. The peak friction angles (ϕ) for the discontinuities ranged between 22 and 27° for the sandstone units

and between 20 and 26° for the claystone units. The residual cohesions (C_{res}) and residual friction angles (ϕ_{res}) were taken to be 60 % of their peak values.

The tensile strengths of the discontinuities (T) were taken to be zero. A dilation angle of 5° was adopted for all horizontal and vertical discontinuities. A *Coulomb slip with residual strength* model was adopted for the horizontal and vertical discontinuities.

Calibration of the generic numerical model

The numerical model was initially calibrated by comparing the modelled maximum vertical subsidence with those provided by empirical prediction curves. The calibration process considered 378 models based on combinations of the three block sizes (B1, B2 and B3), two levels of horizontal *in situ* stress (S1 and S3), three groups of material properties (M1, M2 and M3), three groups of joint properties (J1, J2 and J3) and seven longwall widths of 150, 225, 300, 375, 450, 525 and 600 metres.

A template text (*.txt) file was developed which could be 'called' into UDEC to generate the numerical models based on each of the block sizes, horizontal *in situ* stresses, material properties and joint properties.   The models could be batched allowing each of the 378 models to be run in succession.

The modelled maximum vertical subsidence divided by the seam thickness versus the longwall width-to-depth ratio are illustrated in Figure 3. The empirical prediction curves for a single isolated longwall based on the Incremental Profile Method (IPM) (Waddington and Kay 1995) and Holla and Barclay (2000) are also shown for comparison in both the graphs provided in this figure.
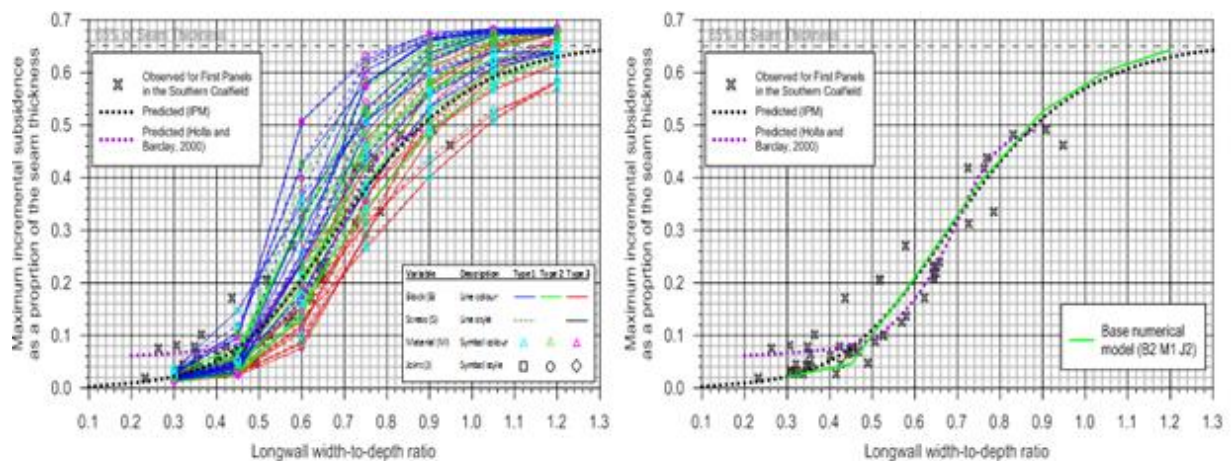

Figure 3: **Maximum predicted vertical subsidence divided by seam thickness versus width-to-depth ratio for a single isolated longwall**

The range of results obtained from the 378 numerical models are shown on the left side of Figure 3. The model that matched the empirical prediction curves the closest is shown as the green curve on the right side of this figure. This model was based on Block Type B2, Material Type M1 and Joint Type J2 and was adopted as the 'base case', i.e. the standard model with a flat surface and seam.

A summary of the adopted strata thickness and rock mass properties (i.e. Type M1) for the base case numerical model is provided in Table . These properties were based on MacGregor and Conquest (2005) and modified for scale based on McNally (1996). A summary of the joint properties adopted in the base case numerical model (i.e. Type J2) is provided in

Table 2. The joint normal stiffness (jkn) is 30 GPa/m and joint shear stiffness (jks) is 3 GPa/m in the base case numerical model.

Table 1: Strata thicknesses and rock mass properties adopted in the base case model

Unit	Thickness (m)	ρ (kg/m³)	K (GPa)	G (GPa)	C (MPa)	φ (deg)	T (MPa)
Hawkesbury Sandstone	150	2400	3.33	2.00	7.0	34	0.5
Newport Formation	20	2400	3.45	2.48	4.0	30	0.5
Bald Hill Claystone	30	2700	5.00	2.31	6.0	25	0.5
Bulgo Sandstone	200	2500	5.56	4.17	10.0	30	0.5
Stanwell Park Claystone	10	2700	6.17	4.07	9.0	30	0.5
Scarborough Sandstone	30	2500	7.47	5.37	7.0	38	0.5
Wombarra Claystone	30	2600	6.90	4.96	10.0	25	0.5
Coal Cliff Sandstone	30	2600	7.78	5.83	12.0	30	0.5
Bulli Coal	3	1500	1.54	0.97	2.0	25	0.5
Sub-Bulli Strata	-	2500	8.00	4.80	15.0	25	0.5

Table 2: Joint properties adopted in the base case model

Unit	C (MPa)	φ (deg)	C_{res} (MPa)	$φ_{res}$ (deg)
Hawkesbury Sandstone	2.50	24.8	1.50	14.9
Newport Formation	2.25	24.0	1.35	14.4
Bald Hill Claystone	2.75	21.2	1.65	12.7
Bulgo Sandstone	4.50	24.0	2.70	14.4
Stanwell Park Claystone	2.75	24.0	1.65	14.4
Scarborough Sandstone	3.25	26.0	1.95	15.6
Wombarra Claystone	3.00	22.0	1.80	13.2
Coal Cliff Sandstone	4.75	23.2	2.85	13.9
Sub-Bulli Strata	4.25	22.0	2.55	13.2

The base case numerical model was reviewed using ground monitoring data from the Southern Coalfield as described in the following section.

Review of the base case numerical model

The results obtained from the 'base case' numerical model were compared with the ground movements measured along a number of monitoring lines at Appin and West Cliff Collieries. Examples are provided in

Figure 4 for the M-Line in Area 3 at Appin Colliery, Figure 5 for the ARTC, HW2 East and HW2 West Lines in Area 7 at Appin Colliery, and Figure 6 for the B-Line in Area 5 at West Cliff Colliery.
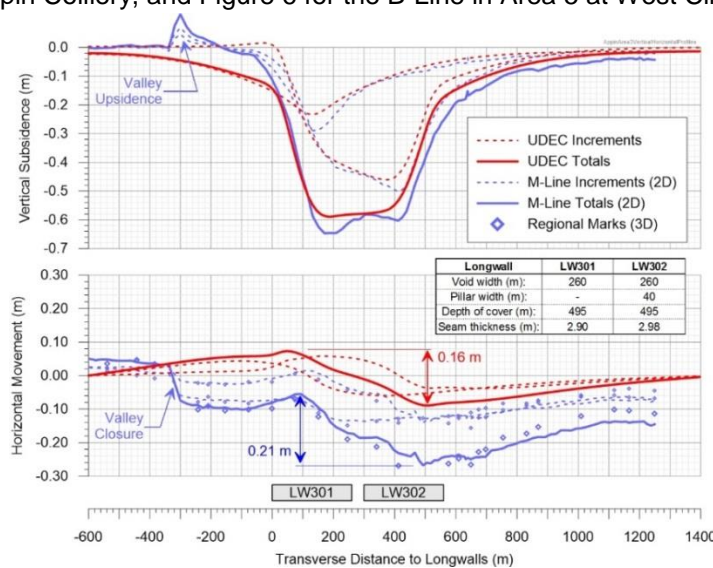

Figure 4:   Measured versus predicted vertical subsidence and horizontal movement along the M-Line in Area 3 at Appin Colliery
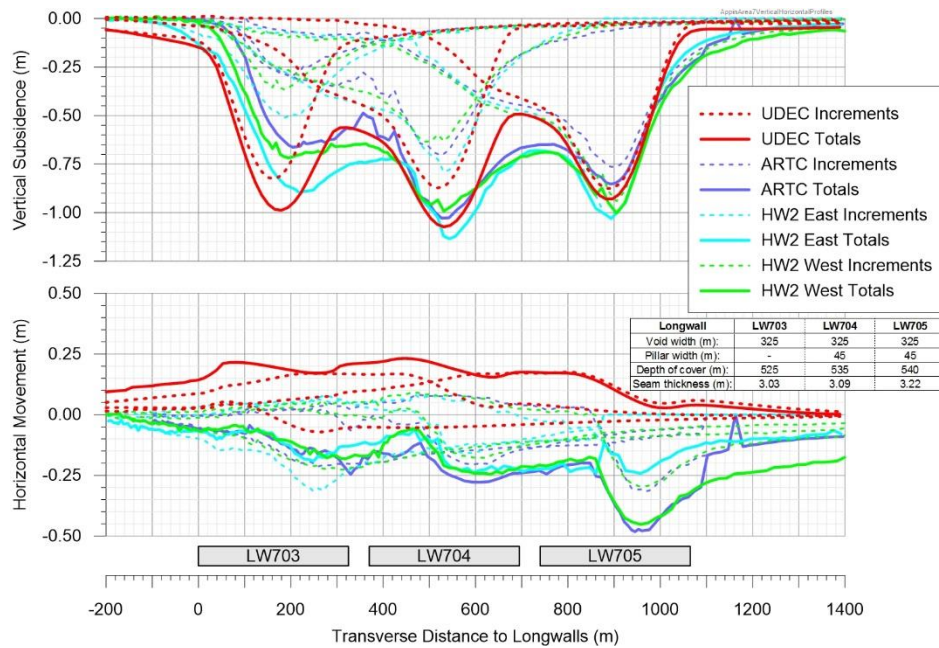
Figure 5: Measured versus predicted vertical subsidence and horizontal movement along the ARTC, HW2 East and HW2 West Lines in Area 7 at Appin Colliery
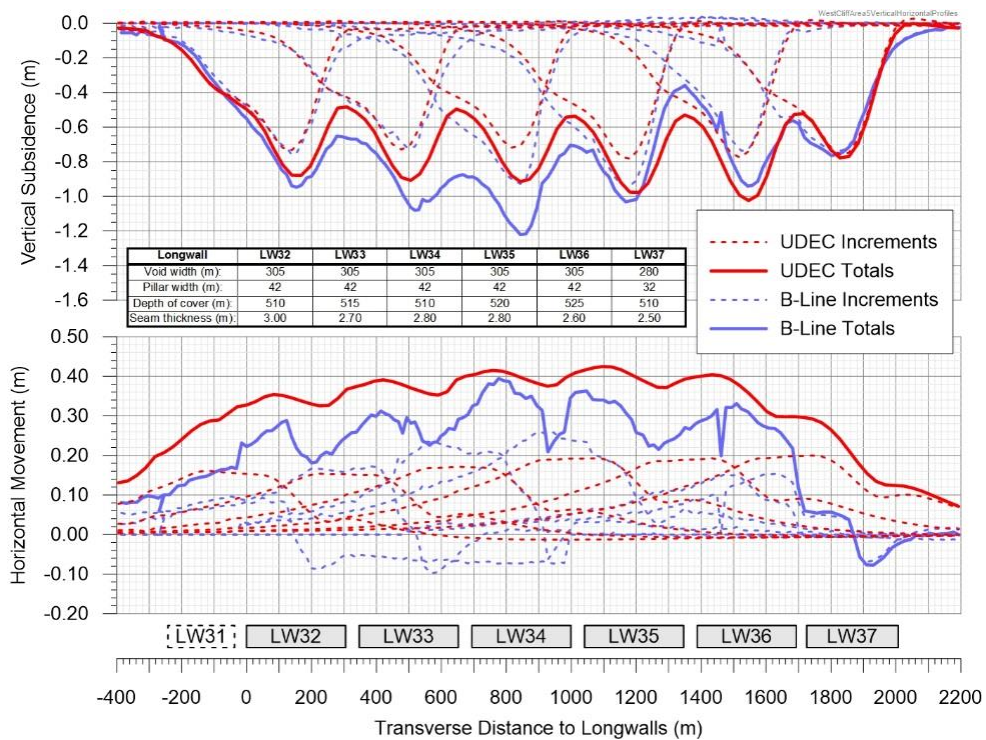

Figure 6: Measured versus predicted vertical subsidence and horizontal movement along the B-Line in Area 5 at West Cliff Colliery

The modelled vertical subsidence profiles in Appin Area 3 (refer Figure 4) reasonably match those measured along the M-Line. The observed subsidence adjacent to the tailgate of LW301 (i.e. left side of figure) was less than that obtained from the numerical model, however, this area was affected by a large valley closure movement across a nearby stream. There is a small lateral shift between the measured and predicted profiles above the maingate of LW302 (i.e. right side of longwall). This lateral shift could possibly be due to the influence of the sloping terrain or the proximity of the Nepean River valley.

The shapes of the modelled horizontal movement profiles in Appin Area 3 are reasonably similar to those observed above the longwalls. There is, however, a relatively uniform difference in magnitude (i.e. vertical shift) that appears to be largely due to the valley closure movement at the nearby stream. The modelled total panel closure above the longwalls of 0.16 metres is less than the measured total panel closure of 0.21 metres. The difference between observed and predicted panel closure could be partly the result of the influence of the sloping terrain or the proximity of the Nepean River valley.

The modelled vertical subsidence profiles in Appin Area 7 (refer Figure 5) reasonably match those measured along the ARTC, HW2 East and HW2 West Lines. The maximum predicted vertical subsidence movements above the longwalls are similar to the maxima observed. However, the minimum predicted vertical subsidence above the chain pillars are less than those observed.

The modelled horizontal movement profiles differ in shape and magnitude when compared with those measured in Appin Area 7. The observed horizontal movements in this area, however, were largely influenced by the sloping terrain, valley closure movements due to the creeks above the longwalls and the nearby Nepean River valley, and non-conventional ground movements due to near surface geological structures. This case study highlights the complexity of predicting horizontal movements where they are influenced by topographical and geological features. The surface slope, streams and near surface geological structures were not considered in the base case numerical model.

The modelled vertical subsidence profiles in West Cliff Area 5 (refer Figure 6) reasonably match those measured along the B-Line. The magnitudes of vertical subsidence obtained from the numerical model were less than the maxima measured. It is noted, however, that the vertical subsidence along the B-Line was greater than that measured along the J-Line, which was located above the opposite ends of these longwalls. This may indicate that increased vertical movements developed along the B-Line, possibly due to the influence of the nearby Georges River valley, or the non-conventional ground movements resulting from near surface geological structures.

The shape of the modelled total horizontal movement profile (i.e. solid red line) in West Cliff Area 5 is reasonably similar to that observed (i.e. solid blue line). The shapes and the magnitudes of the modelled incremental horizontal movement profiles (i.e. dashed red lines) differ from those observed (i.e. dashed blue lines). The main differences occur adjacent to the longwall maingates, where locally increased horizontal movements were observed. These differences could be partly the result of the non-conventional ground movements that developed along this monitoring line.

It has been considered that the base case numerical model provides reasonable predictions of vertical subsidence and horizontal movements based on the comparisons with the monitoring data. The three case studies using the monitoring data from Appin and West Cliff Collieries, however, highlight that the modelled horizontal movements obtained using the base case model (i.e. uniform surface, seam and overburden) can differ greatly from those observed. These differences were primarily due to the influence of the surface topography (i.e. sloping terrain and valleys) and non-conventional ground movements resulting from near surface geological structures.

The base case numerical model has been further refined to include varying surface topography in order to review its influence on the horizontal movements resulting from longwall mining.

Review of varying surface topography using the UDEC numerical model

Several numerical models have been developed to review the effects of sloping terrain, scarps, hills and small valleys. An example of the model with sloping terrain is illustrated on the left side of Figure 7. The profiles of vertical subsidence and horizontal movement obtained from the numerical model based on varying surface slopes are shown on the right side of this figure.
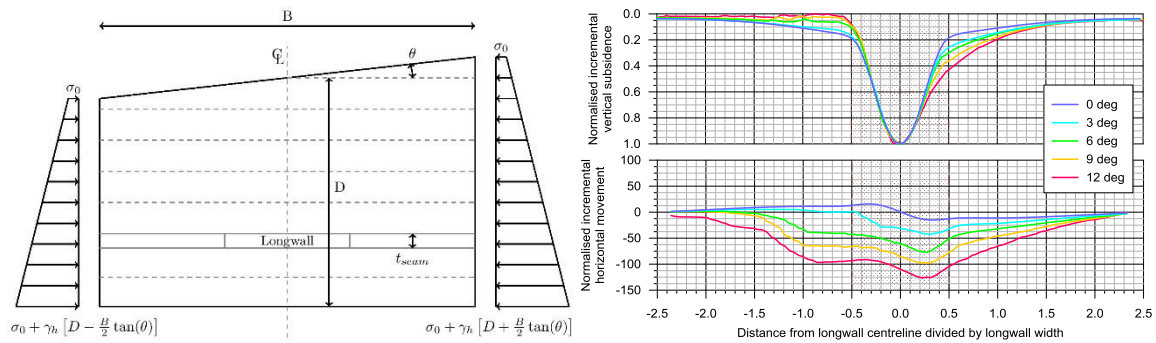
Figure 7: Numerical model with sloping terrain (left side) and the modelled profiles of vertical subsidence and horizontal movement (right side)

The numerical models indicate that an increasing surface slope results in greater vertical subsidence on the upslope side and lower vertical subsidence on the downslope side. The surface slopes also result in greater panel closure (i.e. differential horizontal movement above the longwall) and increased net horizontal movement in the downslope direction. These results are consistent with observations from the NSW Coalfields.

The ratios of the incremental panel closure to incremental vertical subsidence obtained from the numerical models are illustrated in Figure 8 for sloping terrain (left side) and scarps (right side). The different curves shown on the left and right sides of this figure are for longwall widths varying between 300 and 600 metres, i.e. width-to-depth ratios varying between 0.6 and 1.2, based on an average depth of cover of 500 metres.
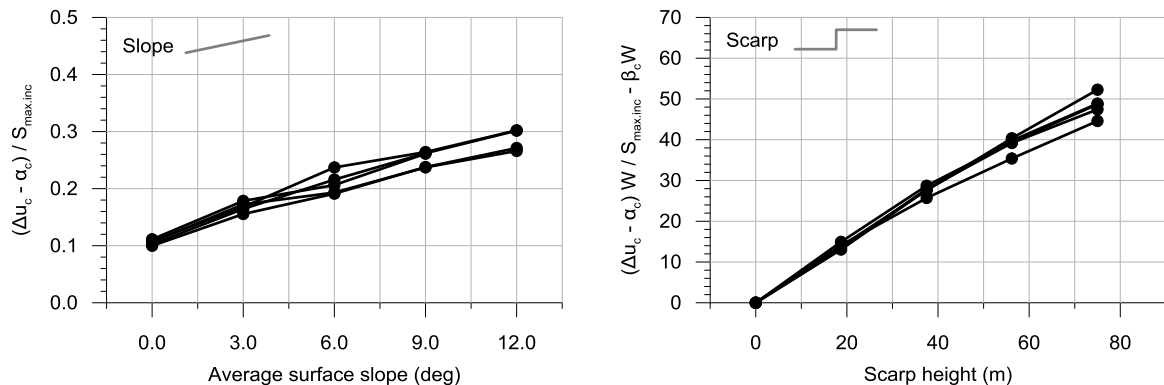

Figure 8: Components of predicted panel closure divided by maximum vertical subsidence versus average surface slope (left side) and scarp height (right side)

The ratios of panel closure to maximum vertical subsidence obtained from the numerical models vary between 0.10 and 0.30, i.e. the y-axis on the left side of the figure for slopes. This range is consistent with the monitoring data from the Southern Coalfield, as represented by the gradients of the lines illustrated in

Figure 2, which were generally measured between 0.15 and 0.35.

It can also be seen from Figure 8, that the ratio of panel closure to maximum vertical subsidence increases as the surface slope or the scarp height increases. The relationship between panel closure and maximum vertical subsidence is reasonably consistent over the range of longwall widths considered in the numerical analysis. The component of panel closure due to the presence of a slope or scarp can be represented by a term based on the change in elevation (Δz) across the width of the longwall, i.e. $\delta.(\Delta z)^\zeta$. The coefficient delta (ζ) has a value less than one, as the curves illustrated in Figure 8 have slight curvatures, with the gradients decreasing with increasing slope or scarp height.

The generalised predictive equation for panel closure is provided in Equation 2. This equation has been developed based on the review of the ground monitoring data and the numerical modelling.

$$\Delta u_c = \alpha_c W + \eta_c \left[\beta_c + \delta_c \left(\tfrac{\Delta z}{W} \right)^{\zeta_c} \right] S_{max.inc} \qquad (2)$$

The coefficient alpha (α_c) and the variable for the change in surface elevation (Δz) have been non-dimensionalised based on the longwall void width (W). The change in elevation across the width of the active longwall is illustrated in Figure 9 based on a slope (left side) and a scarp (right side).
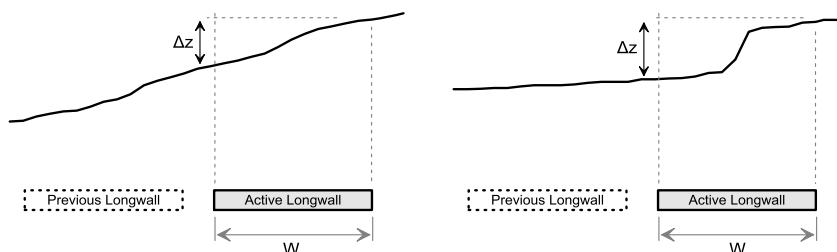

Figure 9:   **Change in elevation due to a slope (left side) and scarp (right side)**

The coefficient eta (η_c) is the localisation factor to account for the higher panel closures observed when irregular ground movements develop, due to the presence of small valleys or due to anomalies. The value varies between 1.0 when the ground subsides regularly and 1.6 when irregular compressive strains in the order of 5 and 6 mm/m develop.

The preliminary coefficients for the panel closure predictive equation for the Southern Coalfield, derived from the available monitoring data and the numerical models, are summarised in Table 3. The terms '*up slope*' and '*up step*' refer to the cases where the surface elevation above the maingate is greater than that above the tailgate and vice versa for '*down slope*' or '*down step*'.

Table 3: Preliminary coefficients for panel closure for the Southern Coalfield

α_c	β_c	Case	Type	δ_c	ζ_c
0.1 ~ 0.4 x10^{-3}	0.11	Slope	Up slope	0.60	0.8
			Down slope	0.20	0.8
		Scarp	Up step	1.50	0.8
			Down Step	1.20	0.8

The predictive equation for panel closure can be used in other mining areas outside the Southern Coalfield by modifying the coefficients to suit the local conditions. This can be achieved by reviewing the available ground monitoring data to establish the relationship between panel closure and vertical subsidence (α_c and β_c) and the effects of topography (δ_c and ζ_c) and irregular movements (η_c).

CONCLUSIONS

Predictive equations have been developed for the relative horizontal movements across various zones above an active longwall based on a review of ground monitoring data and numerical modelling using UDEC. The predictive equation for panel closure in Equation 2 represents the maximum or net compression above the active longwall.

The numerical modelling was used to extend the preliminary equation developed from the empirical review to include the influence of varying surface topography. Further numerical modelling will be undertaken to assess the influence of the near surface lithology and geological structure.
The predictive equations for panel closure, maingate opening and pillar opening are being used as the basis for the ongoing research into the development of the predictive equations for strain.

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