Some Time Dependent Aspects of Longwall Mining Subsidence

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Abstract: Dynamic ground movements associated with a moving longwall face were monitored in different mining and geological environments in four collieries in New South Wales. The face advance rate varied between 4.1 and 7.2 m/day and the mining depth between 116 and 424 m. The subsidence development curves differed quite significantly indicating the dependence of subsidence development rate on the rate of extraction. In order to validate the dependence, subsidence development was monitored over two longwall panels under similar mining depth and geological conditions in the Newcastle Coalfield of New South Wales. The rate of extraction appeared to influence subsidence development, a faster rate resulting in less severe ground movements. The dynamic movements were approximately 50%-100% of final movements over the edges of longwall panels and were large enough to cause surface damage. They occurred over an area where post-mining movements were considered insignificant. The magnitude of the residual subsidence varied from 30% of the total subsidence near the edges of extraction to less than 6% over most of the goaf.

Keywords: longwall mining, mine subsidence, dynamic profile, ground movement, rate of extraction

Introduction

A typical longitudinal subsidence profile over the moving end of a longwall panel is shown in Figure 1. The profile applies to an extracted panel which extends for a distance of at least the mining depth (H) to the right from the moving end. This minimum distance, usually referred to as the radius of mining influence (R), permits the development of full subsidence and the subsidence profile represents the active subsidence associated with a panel of critical length. The profile moves forward with the moving face until it reaches the end of the panel. When the face stops at the end of the panel, the subsidence profile above the edge of the panel will be the dynamic profile. The dynamic profile above the edge changes with time to the final subsidence profile when all the residual subsidence takes place. The difference between the final profile and the dynamic profile is the residual subsidence. In coal extraction by the longwall method, it may take 6 to 24 months for final subsidence to occur after the completion of mining. The dynamic subsidence profile is also accompanied by a dynamic strain profile as shown in Figure 1.

While dynamic deformation over the edges of an extraction panel may increase after the completion of mining to reach its final value, the deformation over a moving face is transient and may decrease to insignificant levels after the moving face passes. For example, in theory, the surface along the centre line of a critical extraction panel will only subside without experiencing significant deformations after the final state of
equilibrium, even though during mining it may experience large transient deformations. A structure located over the centre of the panel therefore may be unstressed after the completion of mining, though it may be stressed and damaged by transient movements during mining. Thus knowledge of transient deformations is essential in order to correctly assess the subsidence impact on undermined structures.

Most subsidence prediction methods, both empirical and numerical, attempt to predict final movements, but do not provide information on transient movements. This paper examines the nature of dynamic movements associated with a moving longwall face and compares them with the post-mining permanent movements. Residual movements that occur and remain after the completion of mining are also examined.

![Subsidence, slope and strain profiles accompanying a moving longwall face](image)

**Figure 1 - Subsidence, slope and strain profiles accompanying a moving longwall face**

**Theoretical Considerations of Dynamic Deformation**

The faster face advance is generally believed to cause a relatively flatter subsidence profile. The explanation for this behaviour is that the strata has less time to react to undermining when acting visco-elastically, resulting in more gentle bending of strata and less subsidence. Kratzsch (1983) explained the time dependence of deformation by a visco-elastic Kelvin body with a spring of stiffness $E$ and dashpot of viscosity $\eta$ in terms of equation (1). If a stress $\sigma$ is applied at time $t = 0$, then the time dependent deformation starts at $t = 0$ and tends asymptotically towards a final value given by equation (2). The time related deformation is given by equation (3). The constant $(E/\eta)$ is the reciprocal of the Kelvin relaxation time.

$$\sigma = E\varepsilon + \eta(d\varepsilon/dt) \tag{1}$$

$$\varepsilon = \sigma/E \tag{2}$$

$$\varepsilon(t) = \frac{\sigma}{E}(1-e^{-t(E/\eta)}) \tag{3}$$

Jarość et al (1990) reviewed the various simple visco-elastic models of subsidence development with a time coefficient of the following form.

Subsidence development rate = $c \left[ S(t) - S(t) \right]$ \tag{4} where

$S(t)$ = final subsidence
$S(t)$ = subsidence at time $t$
$S(t) - S(t)$ = subsidence potential at time $t$
c = time coefficient with units of reciprocal of time (reciprocal of relaxation time)
The solution to the equation (4) is of the following form

\[ S(t) = S^f(t) (1 - e^{-ct}) \]  

In a study involving subsidence development for three extraction rates in the Appalachian Coalfield in West Virginia, Jarosz et al (1990) concluded that for mining depths in the range of 90 to 245 m, extraction rates from 5 to 7 m/day and percentage of hard rock in overburden from 46 to 58%, the value of the time coefficient was constant at \( c = 0.075 \) day \(^{-1}\) or 27.4 year \(^{-1}\).

On the contrary, Wardell (1954) found that all eleven cases of subsidence development curves in the Yorkshire Coalfield were similar even though the rates of extraction varied from 0.38 to 1.18 m/day and the mining depth from 160 to 800 m. He therefore concluded that the subsidence development curve was independent of the rate of extraction. However, the average subsidence development curve for the slowest rate was still flatter than the final subsidence profile. The Subsidence Engineers’ Handbook reinforced Wardell’s view by giving a typical subsidence development curve, which was an average curve derived from a number of cases (National Coal Board, 1975).

Contrary to the observations of both Wardell (1954) and Kratzsch (1983), Pflaging (1985) noted that faster rates of extraction developed larger dynamic movements. With an extraction rate of 3 m/day, movements were negligible. However rates faster than 5 m/day resulted in large movements capable of causing surface damage.

Subsidence Development in Different Conditions

In order to understand the nature of subsidence development in New South Wales, subsidence data from four collieries was collected and analysed. The mining parameters for these four cases are listed in Table 1.

<table>
<thead>
<tr>
<th>Colliery-longwall</th>
<th>Longwall width (m)</th>
<th>Mining depth (H)</th>
<th>Rate of extraction (m/day)</th>
<th>Distance of inflection point / H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tahmoor - LW3</td>
<td>180</td>
<td>424</td>
<td>4.1</td>
<td>0.33</td>
</tr>
<tr>
<td>Wyee - LW1</td>
<td>216</td>
<td>206</td>
<td>4.4</td>
<td>0.33</td>
</tr>
<tr>
<td>Ellalong - LW2</td>
<td>150</td>
<td>368</td>
<td>7.0</td>
<td>0.44</td>
</tr>
<tr>
<td>Invincible - LW2</td>
<td>145</td>
<td>116</td>
<td>7.2</td>
<td>0.52</td>
</tr>
</tbody>
</table>

![Figure 2 - Subsidence development over different longwalls](image-url)

Table 1 Mining parameters
Figure 2 which shows the subsidence development curves for the four cases, indicates that unlike for the UK, the curves are not the same for New South Wales. The rate of extraction appears to influence subsidence development - the faster the rate the longer the subsidence profile and the further the point of inflection from the goaf edge. While for the Tahmoor profile with the slowest rate of extraction of 4.1 m/day, the inflection point was 0.33H from the goaf edge, for the Invincible profile with the fastest rate, the corresponding distance was 0.52H. However, the rate did not appear to have an obvious relationship with the subsidence development rate. Even though the rate was similar for the Invincible and Ellalong longwalls, subsidence development was significantly different. Obviously, there were other factors which affected the curves.

**Subsidence Development with Time**

The different subsidence development rates observed in Figure 2 were most likely due to the properties of the overburden strata and caving behaviour. The depth of mining may also have some influence through cover load pressure. In order to validate the dependence of subsidence development on the rate of extraction, it is necessary to compare the development rates for different rates of extraction in similar depths of covers and geological conditions.

The effect of the rate of extraction on the shape of the dynamic profile was examined by comparing the three dynamic profiles over two adjacent longwall panels at the Cooranbong Colliery in the Newcastle Coalfield of New South Wales. Longwall panels were 141 m wide, separated by one row of chain pillars 26.8 m wide. The immediate roof comprised up to 2 m of mudstone with the majority of the overlying strata being mudstones, sandstones and conglomerates (with 16% overall comprising conglomerate strata). The extraction height varied between 2.3 and 2.7 m and the mining depth between 115 and 122 m. The floor of the Great Northern Seam was the claystone of the Awaaba Tuff.

The extraction rate varied between 3.7 and 6.0 m per day. The panels were adjacent to each other and therefore the geological influence on subsidence development was considered the same. Since panels were under similar cover depths, observed differences in the dynamic profiles could be attributed to different extraction rates.

Figure 3 shows the layout of panels and the face positions over which subsidence was monitored along the two longitudinal survey lines. Monitoring was undertaken on eight occasions, three over the moving longwall face and five over the finishing ribs. The monitoring of levels of survey stations and distances between them was carried out during mining using conventional survey techniques. From the monitored levels and distances, mining induced ground slope and strains were calculated.

![Diagram](image.png)

**Figure 3 - Layout of longwall panels and face positions at survey dates**
Figures 4, 5 and 6 show the distribution of subsidence, slope and strains monitored at these locations. The maximum characteristics are listed in Table 2. The subsidence characteristics relating to the dynamic profiles with the slowest rate of extraction were more severe than those for the other two profiles with faster rates. However, the two profiles for Longwall 2 with different rates of extraction suggested a conflicting trend. This could be due to different caving behaviours at the two face positions.

Table 2
Maximum dynamic characteristics

<table>
<thead>
<tr>
<th>Face position (Fig 3)</th>
<th>Extraction rate (m/day)</th>
<th>E/mining depth (H) (m)</th>
<th>E/H*365 (year⁻¹)</th>
<th>slope (mm/m)</th>
<th>Strain (mm/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LW 1</td>
<td>3.7</td>
<td>115</td>
<td>11.7</td>
<td>19.7</td>
<td>3.5</td>
</tr>
<tr>
<td>LW 2</td>
<td>5.6</td>
<td>118</td>
<td>17.3</td>
<td>12.2</td>
<td>1.3</td>
</tr>
<tr>
<td>LW 2</td>
<td>6.0</td>
<td>122</td>
<td>18.0</td>
<td>13.2</td>
<td>3.9</td>
</tr>
</tbody>
</table>
Figure 7 shows the distance of the inflection point, maximum slope and strain for the three dynamic profiles plotted against the rate of extraction per year expressed in terms of mining depth. The faster extraction rate in Longwall 2 resulted in smaller slopes and strains than the slower rate in Longwall 1. The faster rate in Longwall 2 also caused the migration of the inflection point away from the goaf edge.

Magnitude of Dynamic Movements

Dynamic strains and slopes were large and caused extensive cracking of the surface. Strain profiles were quite erratic due to surface cracking. Figures 4, 5 and 6 compare the dynamic movements with the movements over the finishing rib after the completion of mining. The following observations were made:

- The dynamic movements were generally less than the post-mining movements. The maximum dynamic slopes were 50% to 70% of the post-mining slopes.
- The inflection point migrated as the goaf compaction continued. Its distance from the goaf edge decreased from 0.6 H for dynamic profiles to 0.5 H for the final profile.
- Dynamic compressive strains were larger than post-mining compressive strains. Dynamic tensile strains were smaller than the corresponding post-mining strains over Longwall 1. Because of disturbance to pegs in the maximum tensile zone, post-mining strains could not be monitored over Longwall 2.

In the Silesian Coalfield of Poland the maximum dynamic values ($K_{dyn}$) were expressed in terms of the maximum final values ($K_{max}$) by (Peng 1992):

$$K_{dyn} = K_{max}(1 - e^{-(r/V_p)})$$  

(6)

where ‘c’ is the time coefficient with the units year$^{-1}$, ‘r’ is the radius of major influence, ‘Vp’ is the face advancing rate per year. The value of ‘c’ is dependent upon the rock property and method of goaf treatment. When the overburden rock is hard, ‘c’ is small. In the Silesian Coalfield, $c=4-7$ year$^{-1}$ when longwall caving was employed and $c=1.6-2.4$ year$^{-1}$ when longwall backfilling was used.

In West Virginia, the maximum slope, strains and curvature were found to decrease with an increase in the rate of extraction (Peng 1992). When the rate increased from 3 to 12 m/day, the values of maximum dynamic slope, strain and curvature decreased by approximately 50%.
The ‘c’ value was calculated using equation (6) for the three maximum dynamic slopes in Figure 3. A value of approximately 0.045 days$^{-1}$ or 16 year$^{-1}$ appeared to satisfy all three maximum dynamic slopes. This value compares with the 0.075 day$^{-1}$ observed by Jarosz (1990) in the Appalachian Coalfield in West Virginia and 0.011 to 0.019 days$^{-1}$ observed in the Silesian Coalfield. No such ‘c’ value could be established for maximum dynamic strains.

Residual Movements

Even though the magnitude of residual movements is generally small, engineers dealing with subidence repairs would like to know how long such movements would continue after the completion of mining. Figure 8 shows the variation of residual subsidence at various distances from the finishing edge into the goaf of Longwall 1. The variation over time at various locations from the edge is shown in Figure 9. Figure 10 shows the variation along the centreline of the panel not affected by the deformation over the commencing and finishing edges of the panel. The following observations were made.

- The magnitude of residual subsidence at any point depends upon its location. While the residual subsidence was less than 70 mm at any point not affected by the deformation over the edges (Figure 10), it was more than 350 mm at a point 0.6H from the finishing rib (Figure 8). These two values of residual subsidence corresponded to 6% and 30% respectively of the final subsidence monitored 15 months after the completion of mining. The latter was the point where the movement within the goaf was intense at the time the longwall finished.

- Most of the residual subsidence occurred within 8 months after the longwall finished. Within the next 7 months, there was a residual subsidence of less than 25 mm. The nature of curves in Figure 10 indicates that almost all subsidence occurred 15 months after the longwall finished.

- The residual subsidence outside the goaf was less than 25 mm.

![Figure 8 - Residual subsidence over finishing rib - Longwall 1](image)

![Figure 9 - Variation of residual subsidence with time over finishing rib - Longwall 1](image)
In theory, the residual slopes and strains that exist along the centreline of a critical or super-critical extraction panel after the completion of mining are expected to be insignificant. On this basis the surface impact of mining over the central area goaf of a critical or supercritical extraction panel is considered minimal. Figure 11 shows the slope profile along the centreline 15 months after the completion of mining in Longwall 1. The profile excludes that part of the centreline affected by the deformation over the commencing and finishing edges of the panel. Post-mining residual slopes were as large as 4-6 mm/m in an area where theory suggests no significant deformation. The residual slopes were due to caving of shallow overburden, which was unlikely to be elastic. Post-mining ground movements in shallow mining conditions are therefore too large to be overlooked.

Discussion and Practical Implications

The available research suggests that the dependence of subsidence development on the rate of extraction is not conclusive. Reappraising the time dependence of subsidence development, Goulty and Al-Rawahy (1996) suggested that the subsidence development curve could be independent of the rate of extraction to a good approximation for low rates as observed by Wardell (1954), but the curve could behave in accordance with a simple visco-elastic model at greater rates of extraction as observed by Jarosz 1990). Pflang's (1985) observation however did not suggest a visco-elastic behaviour of subsidence development.
In a study by Holla (1991), subsidence development was compared in two adjacent longwall panels in the Western Coalfield of New South Wales. The extraction rates in the two panels averaged over the panel length were 4 m/day and 5.7 m/day. The distribution of subsidence over the two longwall panels appeared similar. In fact the slower rate appeared to give a flatter subsidence profile, but definitive conclusions were not made given the scatter of the results. It was also observed that the dynamic profile for a relatively slow moving face at an average rate of 1.4 m/day was almost identical with the final profile over the finishing rib (Holla, 1991).

The decrease in dynamic movements with an increase in the rate of extraction observed in this study is consistent with the observations by Jarosz (1990), Peng (1992) and Kratzsch (1983) but differed from the observations of Pfalzinger (1985) and Wardell (1954). The observed decrease is however not conclusive given the small sample size. It appears that the nature of the rate of extraction dependence of subsidence development depends upon many factors including overburden properties, caving behaviour and magnitude of the rate of extraction itself. Simple visco-elastic models may not adequately describe subsidence development and more research is required in this area.

There is a tendency to overlook dynamic movements while assessing the surface impact of a proposed mining activity on the basis that they are transient and in any case they are much smaller than the final movements. The basis may not always be valid for two reasons. Firstly, dynamic movements may be as large as final movements or at least as large as to cause surface damage. Secondly they may occur in an area away from where maximum final movements occur, usually over the edges of extraction panels. In both cases the impact assessment could become inadequate. Dynamic movements would therefore require more attention, especially in shallow mining conditions. For the same reasons, post-mining residual slopes and strains should not be overlooked in any impact assessment.

Summary Remarks

The ground deformation associated with a moving longwall face was found to be quite severe in the shallow mining cases. The deformation was observed even in areas where the post-mining permanent deformation was considered to be insignificant. The deformation was large enough to cause surface damage. Dynamic deformation was less severe than the post-mining permanent deformation over longwall edges. In the cases investigated, dynamic values were 50% to 100% of final values over the edges. The magnitude of dynamic movements depended upon the rate of extraction. Faster rates appeared to result in less severe dynamic movements than slower rates. While the trend is consistent with that observed in the USA, it is different from that observed in the UK, Germany and in some cases in the Western Coalfield of New South Wales. More research involving a larger sample size is needed to confirm the trend.

Large post-mining slopes remained in areas where in theory post-mining deformation was considered to be insignificant. These movements again were large enough to cause surface damage. The assessment of the surface impact needs care in light of large dynamic movements and post-mining residual movements.
Acknowledgments

This paper is published with the permission of the Director General, Department of Mineral Resources, New South Wales, Australia. The views expressed are those of the author and not necessarily of the Department. The Cooranbong Colliery as a condition of approval collected the field data. The other field data from the Tahmoor, Invincible, Wyee and Ellalong collieries were collected by the Department’s survey team as part of a research project financed by the Department of Primary Industry and Energy, Canberra.

References


