

Regional Horizontal Movements Associated with Longwall Mining

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SUMMARY

Tower Colliery is a longwall mine operated by BHP Coal – Illawarra Collieries, southwest of Sydney, Australia. It mines the Bulli Seam at a depth of approximately 450m. The surface topography overlying the mine consists of several steep-sided river gorges, up to 68m in depth, which run at oblique angles across a sloping terrain. Apart from some light rural development, the surface land is essentially natural bushland, but is traversed by a major freeway. This crosses one of the gorges on twin, six-span, box-girder bridges, with bridge piers up to 55m in height. Consequently, a major surface subsidence monitoring program has been in place for several years now, including intensive conventional, GPS and EDM surveying, plus real-time monitoring of critical components of the bridge structure.

Although the bridge and freeway are outside the conventional ‘angle of draw’ subsidence influence criteria, and have seen only negligible vertical deformation as a result of mining, there has been widespread evidence of regional horizontal deformation of the land surface, large distances away from the mining area. The effect at the bridge has been well within acceptable tolerances, primarily because of the regional nature of the movements, with very little differential movement observed at the bridge piers. Gorge closure and evidence of large headlands of land moving ‘en masse’ have been observed. Horizontal movements of hundreds of millimetres have been recorded in some locations where gorge closure has been monitored.

Possible explanations of these movements include one or a combination of mechanisms such as pre-mining stress relaxation, valley notch effects, valley bulging, regional joint patterns, movement toward active goaf areas, vertical gorge ‘shearing’ and shear failure of horizontal bedding planes below the surface. This paper presents a case study of the regional horizontal “subsidence displacements” measured during mining, and a discussion of the possible explanations for these phenomena.

This paper is an update of the paper presented to the 19th International Ground Control in Mining Conference in Morgantown, USA, August, 2000. The original paper was titled “Regional horizontal surface displacements due to mining beneath severe surface topography”, by B Hebblewhite, A Waddington and J Wood.

1. INTRODUCTION

Tower Colliery is one of a number of underground coal mines to the south and south-west of Sydney, operated by BHP Co. Ltd, which mines the Bulli Seam at a depth of approximately 450m using the retreat longwall method. Mining height is typically about 2.4m. Longwall panels have a face length of approximately 180m, with panel lengths variable, depending on both geological and subsidence constraints.

1.1 Geotechnical Environment

The overlying strata consist of a series of sandstones, shales, claystones and mudstones. Some of these strata are quite massive and thickly bedded, but with dominant vertical jointing persisting through most horizons.

There are a number of major and minor geological structures running through the area, typically normal faults, or fault regions, which generally have a northwesterly strike. This direction also coincides with the dominant joint direction in the near-surface Hawkesbury Sandstone, in the Tower Colliery region. A secondary, northeast trending joint set creates a blocky nature to the surface sandstone.

The geological features of the Tower Colliery lease area, with particular reference to subsidence considerations, have been described by Holt (1).

A feature of the geotechnical environment in the Sydney Basin, and the region around Tower Colliery in particular, is the high ratio of horizontal to vertical pre-mining stress. A stress ratio in excess of 3:1 has been measured in a number of locations at Tower Colliery, with a predominant northeast orientation for the major principal stress direction. This results in pre-mining horizontal stress levels of in excess of 33 MPa in some parts of the mine. This dominant horizontal stress direction has resulted in some directional mining considerations in the mine, particularly in relation to gateroad direction. However, local stress magnitude changes, and directional rotations, together

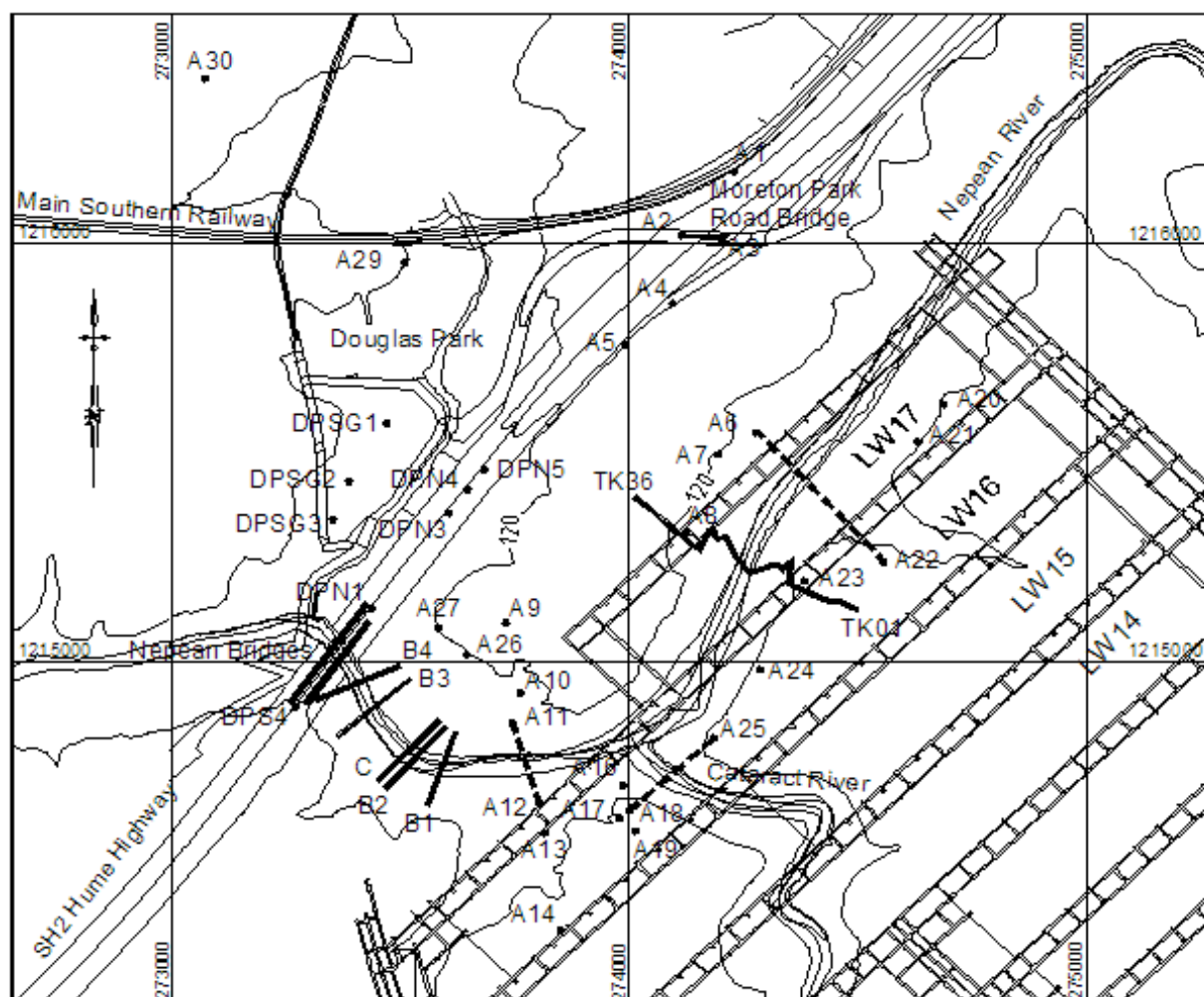


Figure 1. Plan of Tower Colliery, surface topography and features.

with other constraints, have resulted in several different mining directions being adopted, to date.

1.2 Surface Features

Figure 1 is a plan showing the location of the current Tower Colliery workings (and in particular, Longwalls 16 and 17), together with the surface topography and civil infrastructure on the surface. This diagram indicates that the closest distance between the Nepean Bridges and the goaf edge of both LW16 and LW17 was in excess of 600m. (Note: 1,000m grid lines on plans.)

The surface land above Tower Colliery, and in the neighbouring environs, consists of an overall tableland of gently sloping, but relatively uniform terrain, intersected by some severe topographic changes caused by deep, steep-sided erosional river gorges. These can be up to 70m in depth and 60m to 100m in width, in places. The gorges of both the Nepean and Cataract Rivers can be seen in Figure 1 overlying LWs 16 and 17, with a gorge intersection directly above these panels. There are several smaller gorges which cross the terrain, including the Harris Creek gorge, which runs from the Nepean River, immediately to the west of the Nepean (or Douglas Park) Bridges, in a northeasterly direction towards the Douglas Park township. This Harris Creek gorge is sub-parallel to the section of Nepean Gorge overlying LW 17, forming a large, block landmass, bounded by these two gorges on either side, and to the south.

The other surface infrastructure shown on Figure 1 includes the Hume Highway - the major, six-lane highway connecting Sydney and Melbourne, and the Main Southern Railway, in the north west corner of the plan. The Highway crosses the Nepean Gorge on twin, six span box-girder bridges, with up to 55m high piers at the base of the gorge. The Moreton Park bridge is a smaller, dual span, secondary road bridge, which crosses the Highway at an oblique angle.

The nature of the surface land coverage and land use consists of wooded areas, cleared in places for light industrial/agricultural and residential use. Within the gorge regions, the surface is extremely rugged and difficult to access, heavily timbered, including vertical sandstone cliff lines and steep slopes to the rivers at the gorge bases.

Mining in this vicinity is therefore strictly controlled and very carefully monitored in relation to surface subsidence and environmental impact, especially in and around the gorges.

1.3 Mining Constraints

A particular concern for the extraction of Longwalls 16 and 17 was the potential subsidence impact on the twin Douglas Park Bridges over the Nepean River. Mining approval by the NSW Department of Mineral Resources was granted, subject to the ongoing assessment and advice from a Management Committee which comprised representatives from BHP, Mineral Resources, Road and Traffic Authority (the bridge owners) plus several independent experts, including representatives from the University of New South Wales (UNSW). The main criterion for ongoing mining approval was that bridge serviceability would not be lost at any time.

Previous experience had indicated that severe surface topographic changes in other areas of this lease, and elsewhere, could result in significant 'anomalous' subsidence behaviour. This included significant horizontal gorge closure, gorge base uplift and large-scale, regional, mining-induced horizontal displacement. Gorge closure was a particular concern at the bridge location, since the bridges, whilst designed to accommodate a certain amount of vertical subsidence, were not designed with any significant tolerance to differential horizontal movement, or excessive closure.

This paper discusses the results of the monitoring program which was implemented across the surface region above and adjacent to Longwalls 16 and 17 as part of the overall bridge management program. The paper is particularly focused on the regional behaviour of the surface, including the gorges, and the development of possible geomechanical explanations for such behaviour.

2. PREVIOUS EXPERIENCE

There does not appear to be a large body of local evidence or understanding of large-scale horizontal movements as a result of mine subsidence, especially under the type of severe surface topographic conditions encountered at Tower Colliery. However, there have been several instances documented in recent years in the Sydney Basin, of significant horizontal deformations and anomalous effects.

In 1998, Reid (2) reported several instances of large horizontal displacements being measured in the terrain surrounding the Cataract Dam over preceding years. This is an area of quite severe topography, southwest of Sydney, where mining has been taking place at depths of 400m to 500m. Reid states *“The results show horizontal movements of up to 25mm occur even when underground coal mining is about 1.5 km from the survey monuments.”* He further states *“The results also show that horizontal movements are typically at least as great as the vertical component, that the maximum horizontal movement occurs soon after undermining, and that the movements are generally directed towards the goaf.”*

A significant event relating to infrastructure damage, which has been subsequently investigated by Salamon and Hocking (3), concerned severe damage to an old, curved railway viaduct, of masonry construction, across a deep valley. The actual report is a confidential document, however, it has been publicly claimed that the damage can most likely be attributed to the activation of a geological fault line which ran through the valley, beneath the viaduct. It is claimed that the activation of the fault was brought about by pillar extraction in a bord and pillar mine, also on the fault line, but some hundreds of metres distant from the viaduct, and well outside conventional ‘angle of draw’ subsidence influence.

In 1997, Holla (4) reported a number of different behaviours associated with subsidence in severe terrain conditions. He stated *“In high relief areas, e.g. creeks and gullies, the observed pattern of movement was asymmetrical about the centre of the extraction panel. The lateral movement of both sides of the valley caused large compressive strains and a hump at the creek bed. A major geological fault caused both sides of the valley to move laterally away from the fault plane. ... the horizontal movements outside the goaf appeared to be rigid body type movements ...”*.

A recent paper by Milner and Seedsman (5), refers to the same geographic region around the Cataract area. They claim that if elastic techniques are used to evaluate horizontal deformations, rather than the empirically-derived prediction methods based primarily on vertical subsidence, then the observed horizontal movements, at angles of draw in excess of 45° , will exceed the vertical movements. However, even such high horizontal movements are predictable using elastic theory.

There have been further undocumented claims that horizontal deformation and gorge closure measurements can be attributed to stress relaxation due to mining, with horizontal deformation in the direction of the major principal stress.

3. MONITORING PROGRAM

The monitoring program instituted by the Bridge Management Committee consisted of the following :

- GPS monitoring of targets across the terrain for horizontal movement.
- Conventional precise levelling and theodolite surveys on selected, accessible traverse lines across the overall terrain, gorges and adjacent to, and on the bridge, pier and foundation structures.
- EDM surveys of gorge closure at nominated cross-gorge locations.
- Remote electronic monitoring of critical locations on the bridge decks, expansion gaps, bearings and other key structural locations.

This paper is focused on the landmass movements, rather than the detail of the structure response at the bridge.

The data presented here consists primarily of the GPS data (which had an accuracy of ± 15 mm), plus some specific gorge horizontal and vertical monitoring data.

Figure 1 shows the location of the GPS monitoring data points, indicated as "A" stations, plus some additional points, such as the stations adjacent to the bridge abutments, DPN1 and DPS4 (also surveyed by GPS). Figure 1 also indicates the location of a gorge closure line, which included vertical subsidence monitoring (TK Line), and several other cross-gorge closure lines.

4. MONITORING RESULTS

4.1 GPS Stations

Figures 2, 3 and 4 present a summary of the GPS monitoring data, in the form of vector plots for total horizontal movement. The vector displacements on these diagrams are displayed as directional arrowheads, with the arrow length proportional to the total horizontal displacement recorded. The arrows are located with their mid-length point positioned on the survey station. A 100mm scale vector is shown in the top left corner of each diagram. Figure 2 represents the results of horizontal movement recorded between the start of LW 16 and three months after LW 16 completion (most results took approximately three months before movement diminished to an insignificant level, after mining ceased). Figure 3 is the horizontal movement as a result of LW 17 extraction. Figure 4 is the sum of the horizontal movement due to both Longwalls 16 and 17. Furthermore, there would undoubtedly have been additional, movement of some of these stations due to mining of the previous longwall panels also, but this was not measured.

Some of the features of these GPS results are as follows:

- Maximum deformation of approximately 200mm from each panel extraction, for stations in the A20 to A24 location, directly above the two goaf areas.
- Several of the above locations recorded the maximum values for each panel, resulting in a cumulative +400mm horizontal displacement, directly above the goaf areas.
- Movement of these overlying stations was generally directly towards the adjacent Nepean Gorge.
- Movement of more remote stations, not above a goaf area was generally towards the active goaf, with progressive rotation as the faces retreated.
- Movement of stations A1 to A5 (close to the Highway at the Moreton Park Bridge location) was up to 65 mm, due to LW16, and a further 70mm due to LW17 (A4 is respectively 680m (56° angle of draw) and 450m (45°) away from the two panel goaf edges).
- There was only a small differential movement between the western edge of the Nepean Gorge and these A1 to A5 locations, suggesting minimal horizontal strain and a significant component of rigid block movement of this entire landmass.
- Station A30, 1.5 km distant from the edge of LW17 (73° angle of draw), recorded in excess of 60mm movement towards the goaf due to mining LW17.
- The station at the northern end of the Nepean Bridge abutments recorded a total of in excess of 40mm movement towards the goaf edge (roughly 50% from each panel extraction), although the ± 15 mm survey accuracy must be borne in mind with this and all GPS results.
- The station at the southern end of the bridge has not recorded any significant movement outside the above accuracy band of the survey data.
- The above abutment location movements were sub-parallel to the gorge direction, resulting in only very low levels of gorge closure at the bridges.
- The stations located on the southern side of the Cataract/Nepean Gorge intersection (A12 to A18) exhibited some anomalous rotation of movement direction during the extraction of the two panels. This is indicated by the resultant position of the movement in Figure 3 (after LW17) where these stations tended to move towards the previous goaf areas (LW14 – LW16) rather than the current

goaf area.

4.2 Gorge Closures

Figure 5 presents the results from a series of survey stations along various A peg lines which cross the gorges at various positions. The results are expressed as closure (between the extremities of the referenced lines, incorporating across the gorge) relative to proximity of the gorge/line intersection position to the current longwall faceline. A proximity of 0 distance represents the faceline being coincident (even if offset laterally) with the survey line across the gorge. Once again, data from LW16 is separate to that from LW17, and so the combined effect can be determined by adding the two appropriate datasets together, for a given A line.

Significant results can be summarised as follows:

- Closure is insignificant until within 300m to 400m ahead of the face position.
- Maximum rate of closure occurs within 200m of the face passing the gorge position.
- Closure appears to be effectively complete within approximately 500m of the face passing.
- Maximum closures due to LW16 mining were recorded on the A6 – A22 line across the Nepean Gorge (160mm) and A18 – A25 line across the Cataract Gorge (170mm).
- Maximum closure due to LW17 mining on the A6 – A22 line was in excess of 300mm.
- Total gorge closure (between stations A6 and A22) during extraction of both LW16 and LW17 was in excess of 460mm.

4.3 Differential Subsidence and Closure

Due to the nature of the gorge topography, access to the gorge edges and within the gorges for survey purposes was extremely

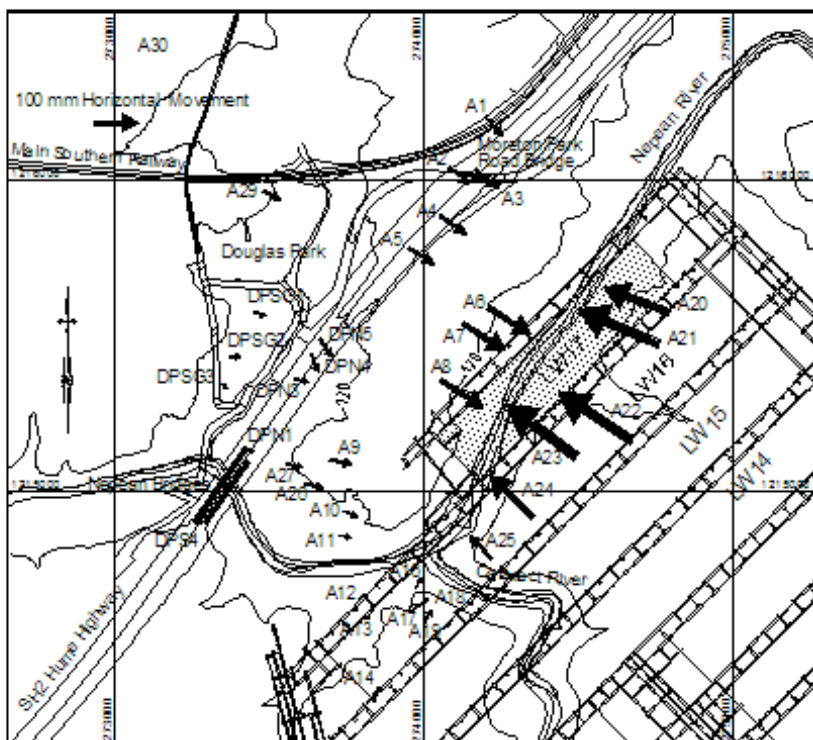
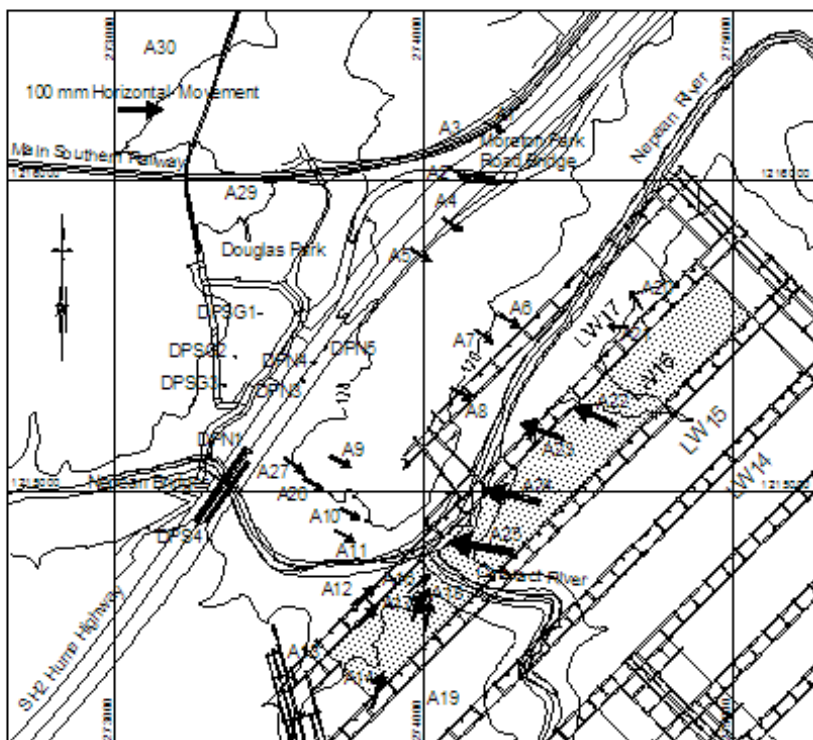


Figure 2. Horizontal Movements due to Longwall 16.

Figure 3. Horizontal Movements due to Longwall 17.

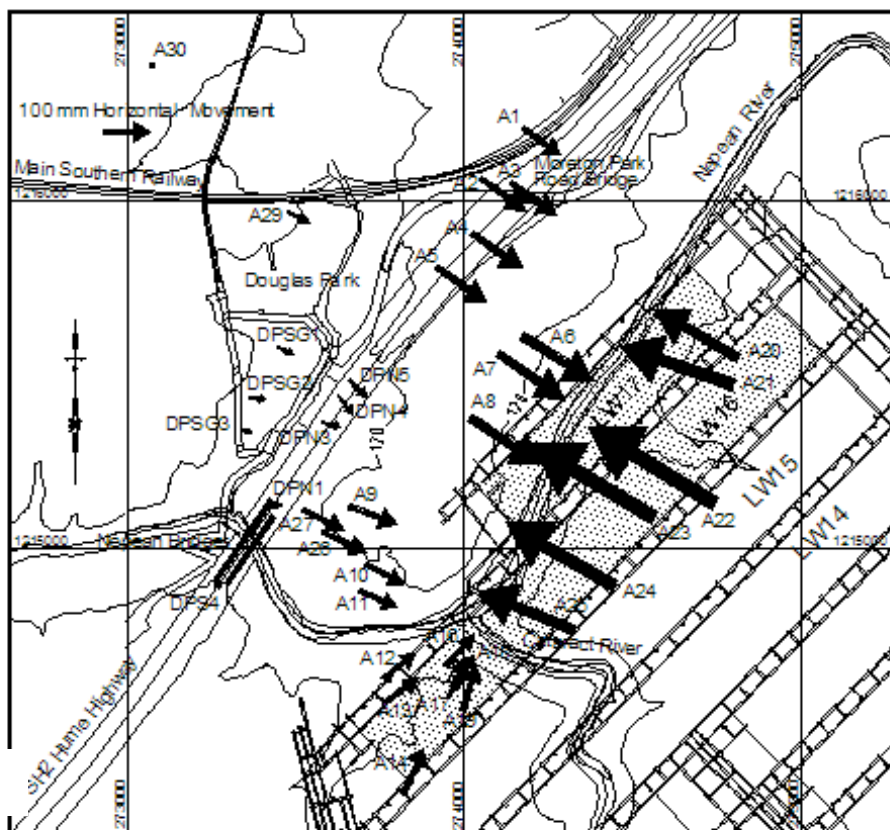


Figure 4. Total Horizontal Movements due to Longwalls 16 and 17

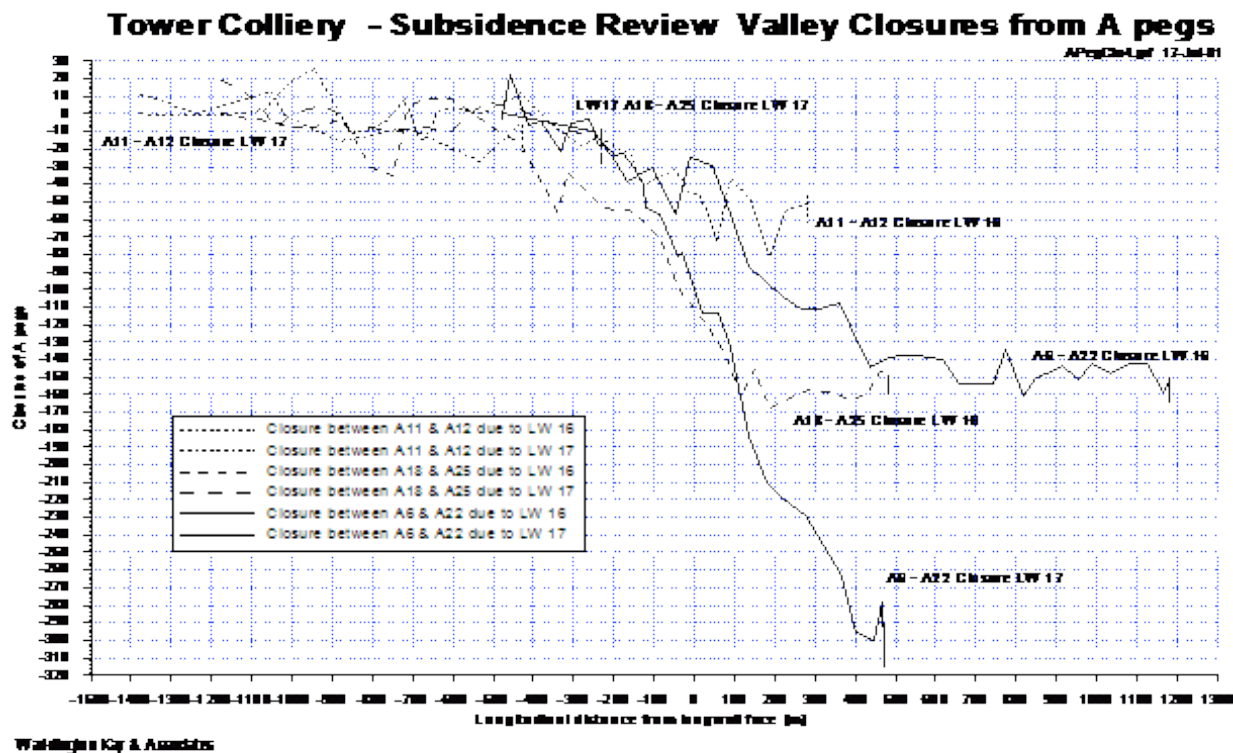
**Fig. 4**

Figure 5. A Line Closures across gorges.

restricted. However, at least one complete survey line was established across a gorge and the adjacent surface terrain. The TK line is marked on Figure 1 as a survey line which crosses the Nepean Gorge at a location approximately two thirds along the length of LW17, at a point where the gorge is running parallel with the panel orientation, over the centreline of the panel.

Figure 6 presents both the differential vertical subsidence along the TK line at 6 different time intervals during extraction of LW17, as well as differential horizontal gorge closure at a series of different gorge elevations from top to bottom of the gorge. (This data is presented, looking southwest, i.e. towards the Nepean Bridges.) The vertical subsidence is plotted relative to the distance from the gorge centreline, which can also be interpreted as approximately equivalent to the distance from the longwall panel centreline, so that 90m represents the approximate goaf edge on each side of the panel.

The top plot in Figure 6 also includes a superimposed plot of the cross-sectional gorge profile (referenced to the right hand axis of the plot). The LW17 faceline passed beneath the TK line during February, 2000.

Significant results from this data are as follows:

- Maximum subsidence of approximately 300mm was recorded on the top, eastern edge of the gorge, over the goaf edge (towards LW16), coinciding with the completion date for LW17.
- Maximum subsidence on the opposite side was also on the top edge of the gorge, just beyond the goaf edge, but only 180mm.
- In the centre of the base of the gorge, above the centre of the longwall panel, uplift, or 'upsidence' was recorded. Maximum uplift was 140mm in February, at about the same time that the TK line was undermined. This dropped back to approximately 20mm in May, 2000. (Note that these values are absolute vertical displacement. Relative to the conventional downward subsidence expectations above a longwall panel, the relative uplift would be far greater. It would be at least plus a further 300mm, as recorded at the gorge edge.)
- A maximum of 295mm horizontal gorge closure was recorded in May, 2000 as a result of LW17 extraction only. This was recorded at the cliff top (110m RL).

- Closure at the base of the gorge reached 255mm (86% of cliff top closure).

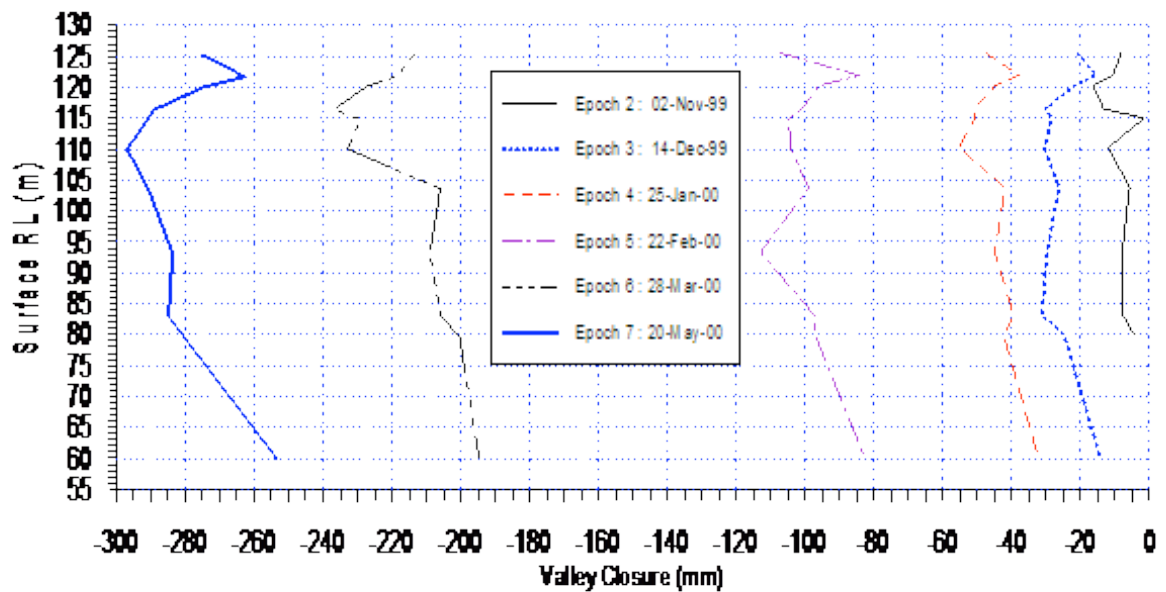
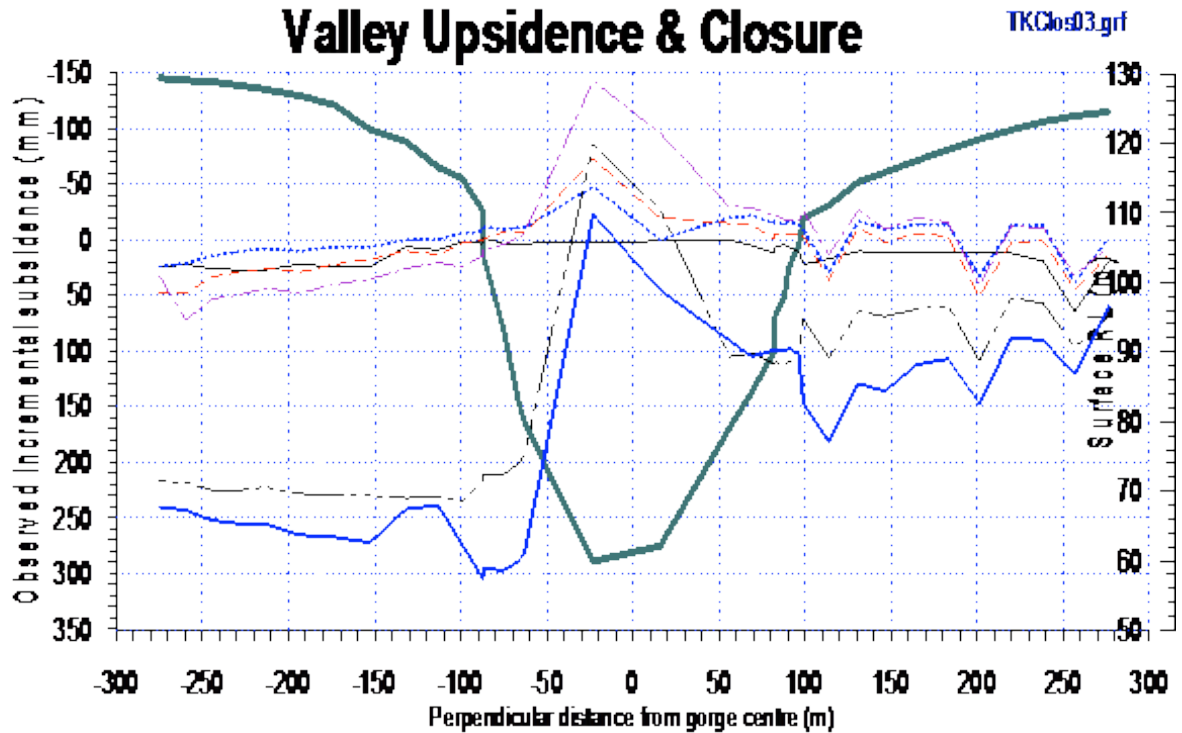
4.4 Summary of Results

The main features of these results can be summarised as follows:

- There is evidence of large scale, regional horizontal displacement of ground, at great distances away from the active mining location.
- Most of the horizontal movement takes place towards both the gorge and the active goaf area, although some movement has been observed towards old goaf areas.
- In the vicinity of the Nepean Bridges, the majority of movement has been of a regional, 'rigid-body' nature, with no effect on the bridge, which has simply moved 'en masse', with the ground. The small amounts of differential movement at the bridge location have been observed between the north and south sides of the gorge, in a shearing type motion along

Figure 6. TK Line – Differential subsidence and closure.

Tower Colliery TK Line Valley Upsidence & Closure



Waddington Kay & Associates

the gorge axis. Gorge closure at the bridge location has been minimal. Some minor differential movement has also been observed between the top of the gorge and lower down the gorge sides. The magnitude and nature of all of the differential movement at the bridge location has been within the design tolerances of the bridge, and has had no impact on bridge serviceability.

- Gorge closures of up to 460mm have been recorded, with maximum closure occurring within 500m of the longwall face passing beneath.
- Differential closure has been observed on the TK line due to LW17 mining, with up to 86% of the closure recorded at the cliff top also being evident at the base of the gorge.
- Significant gorge uplift has been recorded directly above an extraction panel, with the effect of offsetting the anticipated downward subsidence, and generating an absolute uplift reading at the time the face passed beneath the survey line.

5. POSSIBLE MECHANISMS

It is too early to draw any definitive conclusions about the mechanism(s) involved in the observed surface behaviour. However, there are a number of postulated mechanisms which should be considered. These are briefly outlined below.

5.1 Horizontal Stress Effects

In the prevailing high horizontal stress field, it has been suggested that caving above the longwall panel extraction would result in significant directional, horizontal closure toward the sides of the caved void. This would result in more widespread subsidence (including horizontal deformation) on the surface, in the direction of the principal horizontal stress field.

5.2 Valley Notch Effect

The presence of the gorges in the surface topography may result in horizontal stress concentrations around the base of the gorges. When mining occurs below or adjacent to these locations, there is possibly further mining-induced stress changes, and ground movement which 'unlocks' the strata and results in gorge closure and valley bulging, or base uplift.

5.3 Activation of Near-Vertical Geological Structures

There may be many reasons why the interburden rock mass moves as a result of subsidence. If such movement activates geological structures such as faults or joint surfaces, then the discontinuity planes may become horizontal movement surfaces, again 'unlocked' as a result of ground movement. These may then influence both the direction and extent of horizontal movement. This type of behaviour could also account for relative shearing between opposite sides of a gorge, if there is a geological feature running along the centreline of the gorge.

5.4 Activation of Sub-Horizontal Geological Structures

Subsidence of underlying strata may be sufficient to unclamp and release the confining forces acting on horizontal features such as weak strata horizons and bedding planes. This may then allow 'rigid-body' displacement of the overlying strata, through shearing along the reduced friction bedding planes. This could occur close to the surface, where bedding planes are exposed in gorge sides, and the overlying rock mass can move, 'en masse' towards the gorge. It could also occur below gorges which have been undermined, resulting in both rigid-body, and buckling type deformation of the strata.

5.5 Massive Strata Cantilevering

Although this does not necessarily account for all the horizontal movements observed, this phenomenon is known to cause subsidence and uplift effects at great distances from a mining excavation.

6. CONCLUSIONS

All of the above mechanisms are plausible explanations for different components of the observed behaviour. It is quite feasible, and likely, that a number of these mechanisms are involved in the surface response in conditions of severe surface topography, such as those above Tower Colliery. It is also feasible that the behaviour is quite consistent with conventional elastic response to excavation – complicated only by the highly irregular surface geometry and geological features.

There is clear evidence of valley basal uplift occurring.

There is also strong evidence that the horizontal movements being observed are extensive over great distances from the mining location, with low levels of differential strain, away from the gorge and mining proximity. This suggests that a regional, possibly rigid-body type of movement is occurring. It is possible, on the basis of evidence from the TK Line data, and differential movements around several of the bridge pier foundations, that bedding plane shear is occurring within the sides of the gorges. This may have contributed to the entire landmass bounded by the Nepean and Harris Creek gorges moving as a block towards the mining extraction.

In general, the horizontal movement is towards the active goaf area, although this has not been a universal observation. There is some evidence of movement towards old goaf areas and also preferentially towards a gorge location, once mining beneath, or immediately adjacent to survey stations has occurred.

Further investigation, data analysis and various parametric modelling studies are currently in progress to develop a better understanding of each of the potential mechanisms and their correlation with the observed behaviour.

At the Nepean Bridge location, throughout the extraction of the two longwall panels, the bridges have remained fully serviceable without any threat to their structural integrity.

7. REFERENCES

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