

Mechanics of Horizontal Movements Associated with Coal Mine Subsidence in Sloping Terrain Deduced From Field Measurements

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ABSTRACT

The ground movements associated with underground coal mining and, in particular, longwall mining, are recognised to include horizontal subsidence movements, but the mechanics of the processes that cause these horizontal movements are not well understood. Over the last two decades, three-dimensional subsidence monitoring has become routine in Australia and has provided a wealth of measurements of horizontal movements caused by mining subsidence. These measurements and other sub-surface observations allow the processes that cause mining-induced horizontal movements to be inferred and, subsequently, verified. In this paper, the mechanics of the processes that cause horizontal movements, particularly those in sloping topography, are described and discussed on the basis of field observations.

There are several processes recognised to generate horizontal subsidence movements. In flat terrain, systematic horizontal movements cause the surface to move initially toward the newly created goaf and, subsequently, in the direction of mining. Tectonic energy stored as horizontal stress is released by mining, and, when the horizontal stresses are high, the magnitude of this horizontal stress relief movement is large enough to be perceptible for some kilometres from the panel. In sloping terrain, there is an additional component of horizontal movement that occurs in a downslope direction. This movement, sometimes referred to as valley closure movement, has a magnitude that is typically much greater than systematic or stress relief movements.

INTRODUCTION

Vertical subsidence movements above coal mining operations have been observed and quantified for almost two centuries (Whittaker and Reddish, 1989). This is primarily because vertical movements can be readily measured using levelling techniques that were well-developed throughout this period. The mechanics of the two main processes that cause vertical subsidence, sag subsidence over individual longwall panels and elastic strata compression subsidence above the chain pillars, have also been recognised for some time (Mills, 1998).

By comparison, the measurement of horizontal subsidence movements has been hampered by challenges associated with

measuring exact horizontal position in an environment where large tracts of ground are moving differentially with low magnitudes. Gaining more of an understanding of the mechanical processes that cause these horizontal movements has been delayed by the challenges of obtaining reliable three-dimensional subsidence data.

For most of the last century, measuring horizontal movements has been limited to peg-to-peg distance along subsidence lines and converting changes in this distance to strain (change in length over length) without any measurement in the direction perpendicular to the line or even recognition that horizontal movements were occurring in this direction. In New South Wales (NSW) Australia, the ready availability of three-dimensional, total station, surveying instruments and their adoption in routine subsidence monitoring, from the late 1980s through the 1990s, has allowed a significant improvement in measurement capability allowing subsidence movements to be measured in three dimensions.

Since about 2000, the availability and routine access to satellite global positioning systems with sufficient accuracy for subsidence monitoring ($\pm 20\text{mm}$) has meant that distance-independent, three-dimensional survey control is now possible with careful design of the survey network, such as Anderson, Patterson, and Nicholson (2007) and Mills, Morphew, and Crooks (2011) describe. The more accurate measurement of three-dimensional ground movements over large areas has allowed better understanding of the mechanical processes that cause these horizontal movements.

This paper describes the mechanics of horizontal movements inferred from subsidence monitoring and other measurements. The three main components of horizontal movement are described in general terms. The mechanics of the horizontal movements in sloping terrain are discussed in detail.

COMPONENTS OF HORIZONTAL MOVEMENT

Three main components of horizontal movement are readily identifiable from the results of three-dimensional subsidence monitoring above longwall panels in NSW:

- Systematic horizontal movements associated with sag subsidence above individual panels or trough subsidence above multiple panels, involving a change of direction soon

after the longwall face has passed and, typically, with a magnitude of less than about 200–300mm.

- Horizontal movements associated with release of horizontal tectonic stresses within the overburden strata, typically, with a magnitude of less than 200mm at the goaf edge but extending up to several kilometres from the active panel.

Horizontal movements that occur in a downslope direction in sloping terrain (also referred to as valley closure movements). These movements have a magnitude that ranges up to about the magnitude of vertical subsidence in steep terrain but is usually less than about 0.3–0.5 times the magnitude of vertical subsidence.

Systematic Horizontal Subsidence Movements

Systematic horizontal subsidence movements are most readily observed in flat terrain and low horizontal stress conditions when the other two processes that cause horizontal movements are not present.

Figure 1 illustrates the horizontal movements typically observed above a single retreating longwall panel in flat terrain. Initial movements are in a direction toward the active mining area from all sides. Typically, the magnitude of this initial movement is of the order of 10% of the eventual vertical subsidence, so 100–150mm of initial movement is typical for subsidence of 1–1.5m.

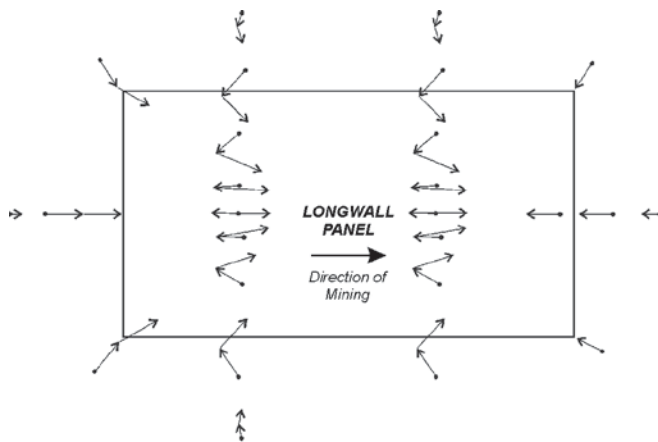


Figure 1. Sketch illustrating the direction of systematic horizontal movements observed in flat terrain.

When the vertical subsidence has reached about half of its maximum, typically, some 0.3 times the depth after the longwall face has passed, there is a change in direction so that subsequent horizontal movements occur in a direction toward the retreating longwall face.

Above the central part of the longwall panel, this change causes a complete reversal in direction. The magnitude of the subsequent movement is typically larger than the initial movement, so there is a permanent offset in the direction of mining. In other places around the panel, the change in direction is more subdued. At the start of the panel, both the initial movement and the subsequent movement are in the same direction, so the two are additive. Systematic horizontal movements are, therefore, typically greatest

at the start of the panel. At the finishing end of the panel, only the initial movement occurs. The subsequent movement does not occur because the longwall does not continue past the finishing line. As a result, systematic horizontal movements over the finishing rib of the panel tend to have lower magnitude than elsewhere around the panel edge.

Horizontal Stress Relief Movements

Horizontal tectonic stresses within the overburden strata store considerable energy as evidenced by the damage caused when these stresses are released suddenly during earthquake events. In coal mining areas, the release of energy occurs when the rock strata overlying the longwall panel fails in horizontal compression. This allows elastic stress relief to occur within the surrounding strata extending, when the circumstances are right, for several kilometres from the goaf edge of active mining.

Reid (1998, 2001) reports on first order surveys in the Southern Coalfield of NSW showing perceptible horizontal movements occur at distances of up to about 1.5km from active mining. The direction of movements observed is predominantly in a northeast, southwest orientation consistent with the regional horizontal stress direction.

Hebblewhite, Waddington, and Wood (2000) report on horizontal ground movements around the Cataract and Nepean Gorges at Tower Colliery. These movements are not aligned with the direction of the major horizontal stress but, instead, with the direction toward the free surface of the Nepean Gorge. The magnitude of horizontal closure across the gorge approached 300mm when the gorge was directly mined under.

Usually, stress relief horizontal movements occur incrementally with longwall retreat, but there is evidence from far-field monitoring observations at Ulan Coal Mine and elsewhere that initial movements could occur as several discrete events rather than incrementally (Mills, Morphew, and Crooks, 2011). The characteristics of the movements observed at Ulan are consistent with elastic stress relief of in situ horizontal stresses causing the ground to move laterally up to 200mm.

Pells (2011) presents the results of far-field horizontal subsidence monitoring from Appin West Colliery in NSW. A simple elastic model is shown to be capable of explaining the far-field movements. These movements have a magnitude at the goaf edge of about 200mm and are detectable using a well-controlled survey network for several kilometres outside the mining area.

The mechanics of the process of horizontal stress relief movements are consistent with the failure of rock strata directly above individual longwall panels. The interpretation of the sag subsidence above individual longwall panels combined with extensometer and other monitoring data indicate that a zone of rock failure extends upward to a height above the mining horizon equal to about 1.4–1.7 times the longwall panel width (Mills, 2012 and Mills and O’Grady, 1998). This failure process allows tectonic energy stored as horizontal stresses within the rock mass beyond the panel edges to be released and, thereby, allows the ground to move toward the failed rock strata above each longwall panel or in very steep topography toward the gorge.

Horizontal Movement in a Downslope Direction

The effects of topography are widely recognised to modify subsidence behaviour, although the mechanics of the processes have only become apparent relatively recently. Kapp (1973, 1980) reported high compressive strains at topographic low points in NSW consistent with valley closure. Holla and Barclay (2000) note similar experience in the USA as what is reported by Gentry and Abel (1978) and Ewy and Hood (1984). Holla and Barclay observe that, given the varying geological settings, the occurrence of large ground strains and reduced vertical subsidence in topographic low points appears to be due to forces generated by topography rather than being a unique characteristic of the geological setting.

Holla (1997) describes the results of horizontal movements in steep terrain in NSW based on levelling and peg-to-peg strain measurements. Holla recognised the effect of horizontal movements but, with only having strain measurements in one direction, found it difficult to interpret the mechanics involved.

Kay (1991) presents the results of a program of three-dimensional surveying at Baal Bone

Colliery that measured horizontal movements in steep terrain. These and other measurements conducted subsequently at the colliery (Mills, 2001) show that horizontal movements in steep terrain include a component of movement in addition to the systematic horizontal movements in a direction toward the valley (i.e., in a downslope direction).

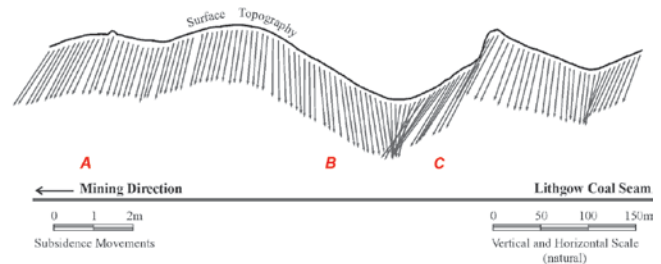
Seedsman and Watson (2001) illustrate this effect by removing systematic horizontal movements calculated for flat terrain from the measured subsidence vectors in an area where a topographic ridge had been mined under. The resulting vectors showed that the residual movement not associated with systematic subsidence occurred as movements in a downslope direction off both sides of the ridge in response to the surface topography.

Waddington and Kay (2004) present a handbook reviewing the experience of mining under cliffs and river channels. They recognise the effect of valley closure and present an empirical method for predicting an upper bound magnitude. This method remains the primary method for estimating valley closure in NSW.

Waddington and Kay also postulate on the mechanics of the processes that cause valley closure, but they focus on horizontal stress concentrations in the base of the valley as the primary cause of the phenomenon. While this mechanism could contribute to the observed valley closure in the Southern Coalfield (where the Waddington and Kay study is primarily focused), the phenomenon of horizontal movement in a downslope direction is also observed in areas where the in situ horizontal stresses have been measured, and the magnitude is small and insufficient to give rise to the magnitude of movements observed (Mills, 2001). The characteristics of a horizontal stress-driven mechanism for valley closure are also not consistent with the behaviour observed at multiple sites or with the low horizontal stresses measured in valley floors (ACARP, 2009).

Figure 2 shows the horizontal movements measured in section at natural scale and in plan above Longwall 7 at Baal Bone Colliery.

The subsidence line was surveyed in three dimensions before and after mining. The displacement vectors shown are exaggerated in magnitude but are drawn at natural scale so that both the vertical and horizontal components are at the same scale. The overburden depth ranges from 100m in the valley to 175m on the ridge tops. The longwall panels create a mined area that is 211m wide. The seam section mined is approximately 2.5m thick.



a) Vertical section showing longitudinal displacement vectors.



b) Plan showing longitudinal horizontal displacement vectors superimposed on topography.

Figure 2. Three dimensional subsidence movements observed above Longwall 7 at Baal Bone Colliery (after Mills 2001).

These measurements show that there is a general tendency for horizontal movement in the direction of mining, as in flat terrain. In addition to this general tendency is a downslope directional component that responds to surface topography. In the area where the direction of mining and the slope coincide (C), the horizontal movements occur directly downslope. In areas where there is a cross-slope (A), there is a component of horizontal movement in the direction of this cross-slope. In areas where the slope is opposite to the direction of mining (B), there is still downslope movement, but the absolute magnitude is lower because of the offsetting effects of the systematic movement in the opposite direction and other effects discussed in the next section.

MECHANICS OF HORIZONTAL SUBSIDENCE MOVEMENTS IN A DOWNSLOPE DIRECTION

Observations from multiple sites of horizontal subsidence movements at the surface and shear movements within the overburden strata are consistent with the following hypothesis as a potential explanation of the mechanics that cause downslope directional horizontal movements.

Longwall mining has the effect of removing the vertical stress supporting the overburden strata. The resulting downward movement releases potential energy that is available to do work. The downward movements associated with mining-induced

subsidence movements in a vertical direction cause the overburden rock strata to dilate or grow in volume as it fails and fractures are formed.

This process is recognised as a property of granular geomaterials, such as sand and rock, and is known in the soil and rock mechanics literature as dilatancy. The term dilatancy typically refers to the volume increase that is observed in the elastic range prior to rock failure, but dilatancy is used in this context to also include the volume increase associated with macro-scale rotations of adjacent blocks of rock strata and normal displacements on irregular fracture surfaces. Post failure dilation is also referred to as bulking in the context of caving and overburden fracturing but the term bulking does not adequately convey the lateral forces that are generated during displacement.

The effect of dilatancy is that the rock strata occupies more volume after it has failed and fractured than it does in its pre-failure state. Lateral horizontal movement associated with strata dilation is largely suppressed in flat terrain where systematic horizontal movements and horizontal stress relief movements tend to dominate. In effect, the horizontal dilation is largely constrained by the intact, undisturbed material on either side of the panel moving inward toward the extracted panel.

In sloping terrain, however, there is an imbalance in the constraint on the downslope side that is set up by the terrain. As the overburden strata subsides over the goaf below a hillside, the free surface of the valley cannot offer any resistance to the dilating strata within the slope. There is also no horizontal stress to oppose the tendency for dilation. The law of conservation of energy governs the direction of movement. Horizontal dilation occurs in all directions, but the path of least resistance is directly toward the valley in the direction of maximum gradient (i.e., in a downslope direction). As a result, horizontal movement occurs in this downslope direction.

As shown in Figure 2, the magnitude of horizontal movement in a downslope direction can be as high as 1.5m in steep terrain but is usually in the range 0.3–0.7m for more moderate terrain.

Dilatancy is recognised to be sensitive to confining pressure with greater dilatancy observed when the confinement is less. This phenomenon contributes to the different horizontal movement observed in Figure 2 on either side of the valley.

In the stretching phase of the systematic subsidence cycle that occurs ahead of and immediately behind the longwall face, confinement is reduced. Therefore, the potential for dilatancy is greater than during the compression phase of the systematic cycle that occurs subsequently over the subsiding panel. As mining approaches the valley from under the hill, the slope is being stretched at the same time as the hillside is subsiding and dilating laterally, so horizontal movements are large and, in the case shown in Figure 2, approach the magnitude of the vertical subsidence because of the steepness of the terrain.

As mining proceeds from the valley toward the hill, there is no dilatant lateral push to cause downslope movement until mining is well under the hill. By the time this push starts, the slope is in the compressive phase of the systematic subsidence cycle, and

dilatancy is suppressed by the increased confinement associated with this compression, so horizontal movements are decreased.

The result of these effects is much larger horizontal movements when mining from high ground toward a valley compared to mining from a valley toward high ground.

Basal Shear Horizon

Figure 3 shows how the propensity for horizontal movement in a downslope direction that can cause horizontal movements above the level of the valley floor is constrained below the valley floor by the presence of rock strata on the opposite side of the valley. The difference in horizontal movement above and below the valley floor needs to be accommodated within the rock strata. Visual observations, borehole observations, and inclinometer monitoring indicate that the difference in horizontal movements is accommodated as horizontal shearing along a bedding plane or similar horizon at the level of the valley floor or just above, but more typically, just below the valley floor, as illustrated in Figure 3.

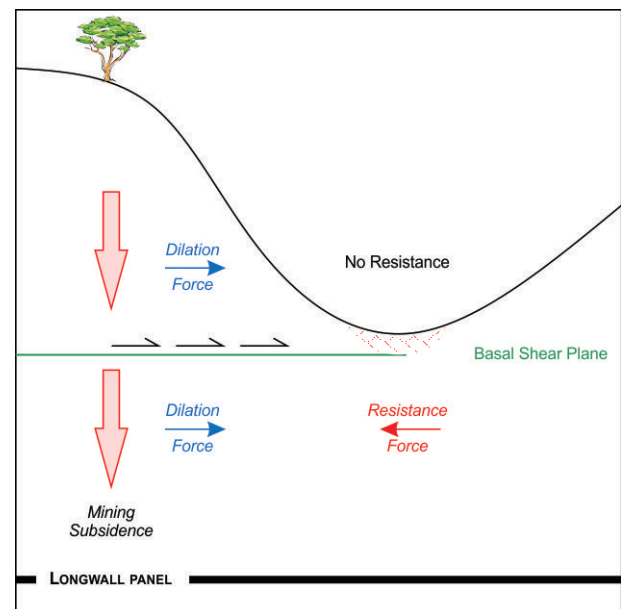


Figure 3. Sketch illustrating the mechanics of the process that causes horizontal movement in a downslope direction.

Although valley closure movements are common, it is less common to be able to directly observe the presence of shear horizons because they usually occur just below the floor of the valley where they cannot easily be seen. Lizard Creek Waterfall in the Southern Coalfield of NSW is located in an area adjacent to longwall mining. The waterfall spills from an incised valley half way up a vertical cliff into an amphitheatre of near vertical cliffs. The presence of the vertical cliffs provides a window into the sub-surface where a horizontal shear horizon can be observed directly. A mining-induced shear horizon is evident along the face of this cliff at the level of the base of the incised channel. Iron-stained water flows from this shear horizon, which is consistent with being freshly formed by mining, hydraulically conductive, and laterally extensive.

A borehole caliper logging program in approximately 100 shallow boreholes was conducted in the base of the Waratah Rivulet in the Southern Coalfield of NSW to characterise the nature of mining-induced fractures. These measurements are reported by Mills (2007) and in an Australian Coal Association Research Program report (ACARP, 2009). They indicate that a horizontal shear horizon located at approximately 4–6m below the surface of the river channel has accommodated valley closure of up to about 600mm. The shear horizon was observed in boreholes to extend at least 60m from the river channel as a fracture zone with elevated hydraulic conductivity. Surface subsidence monitoring indicated that the shear horizon most likely extended below the entire hillside to the centre of the ridge, but no confirmation of this inference was possible until recently.

Recent monitoring at Sandy Creek Waterfall (Walsh et al, 2014) provides definitive confirmation of the presence of horizontal shear horizons and mining-induced subsidence movement localised onto these planes. The bed of Sandy Creek drops about 30m in elevation at a waterfall. When horizontal closure movements were first detected on inclinometers distributed across the site up to 350m from the creek, they were localised onto two horizons that corresponded in elevation with approximately 6m below the base of Sandy Creek, upstream of the waterfall and about 10–15m below Sandy Creek downstream of the waterfall. The presence of large boulders in the bed of the creek downstream of the waterfall makes it difficult to determine the effective elevation of the creek bed, but it is likely that the deeper shear horizon also corresponded with an elevation at or just below the solid base of the creek downstream of the waterfall.

The effects of nearby longwall mining were closely monitored using a range of instruments, including several manual inclinometers and a shaped accelerometer array (SAA). First evidence of closure movements were observed across the array of inclinometers on two main shear horizons when the longwall panels approached the waterfall. The initial movements were of low magnitude and did not have potential to significantly affect the integrity of the waterfall rock structure. Mining continued for several hundred metres more before the movements were considered large enough to be a potential threat to the integrity of the waterfall, and the longwall was stopped (Walsh et al, 2014).

The SAA inclinometer recorded the inclination at 0.5m intervals over a 50m vertical section at 1 minute intervals allowing the nature of the initial shear movements to be determined. Figure 4 shows the initial movements that were observed and the changes that have been observed since. The initial step change occurred at 9:56pm on 16 November 2012. Movements since then have continued incrementally with additional longwall retreat, and then more gradually, once the longwall finished. Since the completion of mining, there have been several high-intensity rainfall events. These events have been accompanied by small step changes in shear, but the shear movements have gradually stabilised since adjacent mining finished.

At the Sandy Creek Waterfall site, the amount of available monitoring data was sufficient to allow an analysis of the body forces acting on a two-dimensional slice through the site, as shown in Figure 5. The horizontal stresses were measured at several locations, including high up on the slope and in the valley floor. Piezometers measured the groundwater level and a 4m rise in

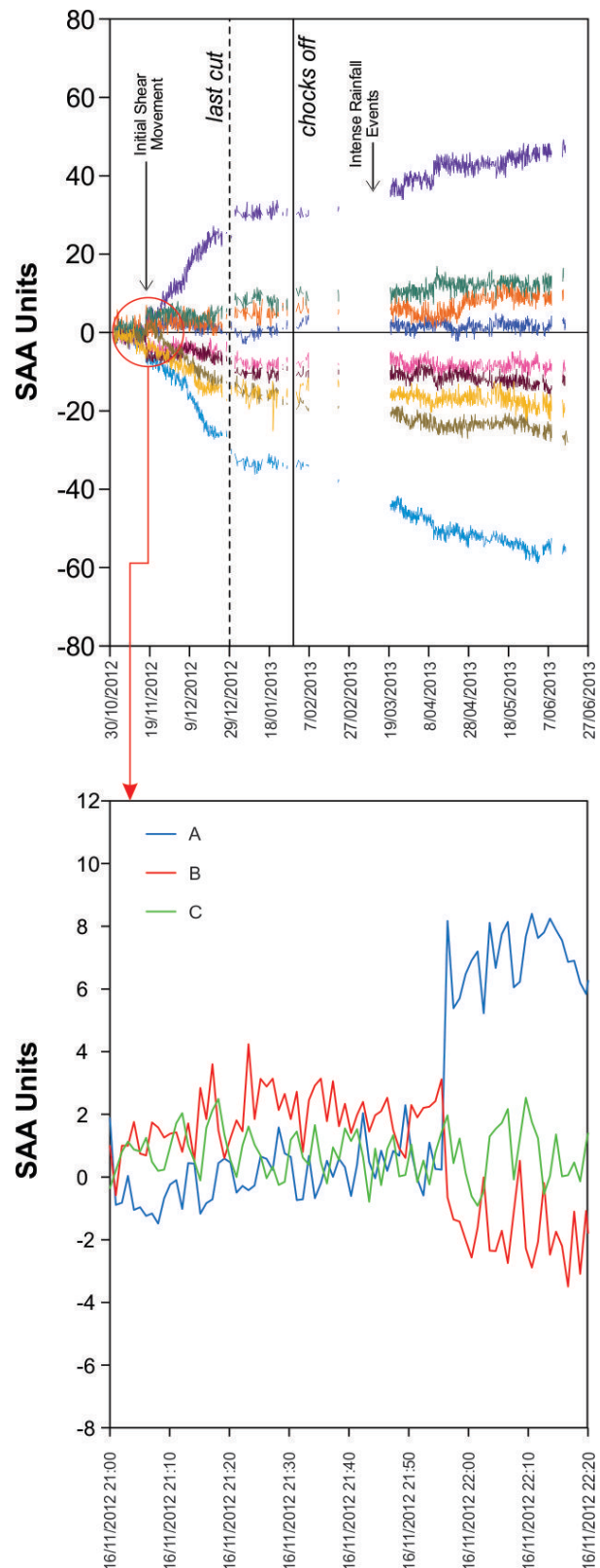


Figure 4. Results of shear monitoring observed on a Shaped Accelerometer Array (SAA) Inclinometer illustrating the deformation characteristics of the basal shear plane.

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water level due to two high-intensity rainfall events that occurred after mining was complete. These two events were sufficient to cause remobilisation of downslope movement and shear on the basal shear plane. By considering the balance of horizontal forces at limiting equilibrium in the two cases of no movement prior to the rainfall events and the movement following a 4m rise in pore pressure, the friction angle on the basal shear plane can be estimated with a high degree of confidence. This analysis indicates that the friction angle on the basal shear plane is in the range of 9° – 14° , depending on assumed pore pressure conditions within the rock mass. This friction analysis is consistent with the range that would be expected for bedding planes in Hawkesbury Sandstone based on laboratory shear tests.

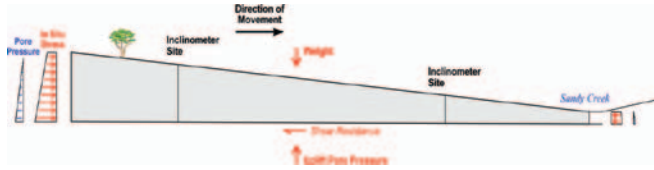


Figure 5. Free body diagram showing loads on the valley side above Sandy Creek sliding horizontally along basal shear plane.

The key observations of interest from the Sandy Creek Waterfall monitoring in terms of characterising the shear horizons are as follows:

- The nature of the shear movements observed is consistent with movement on near-horizontal shear surfaces at an elevation just below the base of the valley.
- A step in the elevation of the valley floor leads to the development of two shear horizons, each just below the floor of the valley.

The timing and magnitude of the shear movements are consistent with the valley closure movements observed.

- The movement observed is consistent with shear on a residual shear surface without the large energy release that would be associated with fracturing fresh rock.
- The remobilisation of shear movement following rainfall events and the gradual reduction in shear over time indicate that the shear surface is in a state of limiting equilibrium where even very small changes in horizontal load are capable of causing additional horizontal movement.
- The basal shear horizon extends outward from the valley as far as required to accommodate the horizontal movements observed on the surface.

Special Case: Horizontal Movements in Dipping Strata

A special case of dilatant strata behaviour and associated horizontal movement has been observed at a site where the strata dips at a rate faster than the surface topography.

Ashton Coal underground coal mine is located in the Hunter Valley of NSW. The longwall panels are located in strata that dips to the west more steeply than the surface topography. The horizontal movements observed directly above each longwall panel

consistently show movement of about 200–250mm in an upslope direction (SCT, 2009). This movement is atypical of subsidence movements at other sites but is consistent with dilation of the strata toward a free surface. Figure 6 illustrates the effect of rotating the strata so that the up-dip movement in dipping strata is essentially the same as the downslope movement in horizontally bedded strata. The observation of upslope movement suggests that the strata dilation process is capable of generating large forces within the overburden strata.

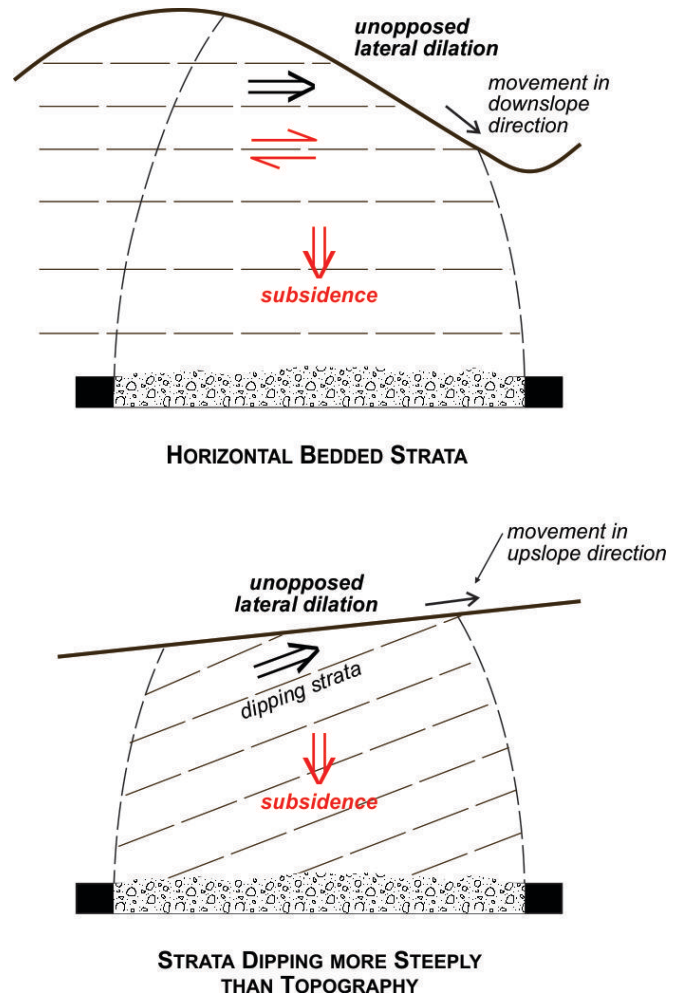


Figure 6. Illustration of the rock dilation processes inferred to be causing the horizontal movements in an up dip direction observed at Ashton Coal Mine.

CONCLUSIONS

An understanding of the mechanics of horizontal subsidence movements is developing as well-controlled, three-dimensional survey data becomes available from more and more sites.

Three separate components of horizontal movement are recognised:

1. Systematic horizontal movements with a magnitude of typically less than 200mm that occur in two stages toward the void created by mining—initially toward the approaching longwall face and, subsequently, in the direction of mining.

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2. Horizontal movements caused by stress relief with a magnitude of typically less than 200mm can occur up to several kilometres from mining in a direction toward the void created by mining but usually biased in the direction of maximum horizontal stress.
3. Horizontal movements in a downslope direction associated with topographic variation and dilation of subsiding strata below topographic high ground. The magnitude of this movement varies with the steepness of the topography but is usually much greater than other components and can reach the magnitude of vertical subsidence in steep terrain.

Observations and field measurements indicate that horizontal movements in a downslope direction occur along near-horizontal shear surfaces at an elevation just below the base of the valley. The basal shear horizon extends outward from the valley as far as required to accommodate the horizontal movements observed on the surface. The shear movement observed is consistent with shear on a residual shear surface without the large energy release that would be associated with fracturing fresh rock.

The remobilisation of shear movement following rainfall events and the gradual reduction in shear over time indicate that the shear surface is in a state of limiting equilibrium in its natural conditions where even very small changes in horizontal load are capable of causing additional horizontal movement.

In strata dipping relative to the surface topography, the same mechanism that causes horizontal movement in a downslope direction has been observed to cause horizontal movement in an up-dip direction. This observation suggests that the strata dilation process is capable of generating large forces within the overburden strata.

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