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EXPERIENCE OF MONITORING SHEAR MOVEMENTS IN THE OVERBURDEN STRATA AROUND LONGWALL PANELS

Luc Daigle[1] and Ken Mills

ABSTRACT: Surface subsidence monitoring shows horizontal movements occur around longwall panels for a considerable distance outside the footprint of a longwall panel; typically several hundred metres to several kilometres. Less is known about how these movements are distributed between the surface and the mining horizon. A range of systems have been developed to measure how horizontal movements are distributed within the overburden strata generally and sometimes around specific geological structures. This paper describes the experience of using a range of these systems at various sites and some of the insights that these measurements bring with particular focus on the use of deep inclinometers.

The capability to measure induced displacements has developed over time from surface observations to use of borehole systems such as multi-arm callipers, downhole camera imaging and specially installed inclinometers placed to depths up to 300 m. Some techniques such as open boreholes and the multi-arm, oriented calliper have mainly been used at shallow depths where breakout and squeezing ground do not compromise the measurements. Others such as the borehole camera provide context but are not so suitable for quantitative measurement. The inclinometer installed in a large diameter borehole backfilled with pea-gravel has been found to provide high resolution measurements up to a horizontal displacement on any one horizon of about 60-80 mm. Inclinometers have been used at multiple sites around Australia to measure shear displacements to depths of up to about 300m. Shaped array accelerometers are an alternative that provide temporal resolution of a few minutes and provide continuous monitoring over a limited interval but tend to be most useful for monitoring the onset of low magnitude shear displacements.

INTRODUCTION

Surface subsidence monitoring provided the first indications that horizontal movements occur around longwall panels in response to mining coal over considerable distances from active mining (Reid 1991). Mills (2014) characterises these horizontal movements as being caused by systematic ground movements in response to vertical subsidence, horizontal stress relief towards the disturbed ground above the extracted void and horizontal movements caused by the interaction between the dilation of subsiding strata and surface topography. Oblique movements that include vertical and horizontal components are also observed around longwall subsidence where geological features such as reactivated faults and joints are present. Other discordant features such as both sub-horizontal thick massive sedimentary channels filled with coarse sandstone or conglomerate and intrusive sills (Daigle 2007) form distinct boundaries which can focus shear displacement.

Underground surveying in development roadways adjacent to active longwall panels, micro-seismic monitoring and observations of changes in horizontal stress magnitude and orientation around active longwall panels also indicate that horizontal movements occur at seam level and within the overburden strata in response to mining. An understanding of the nature and distribution of these horizontal movements within the overburden strata is helpful for interpreting various phenomena associated with mining. But getting measurements of lateral movements within the overburden strata is something of a challenge.

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Observations and measurements from within boreholes located around longwall panels provide perhaps the best opportunity to quantitatively study lateral movements as they develop within the overburden strata. These lateral movements can occur as general body distortions within the rock mass or as shear displacements on discrete planes such as bedding plane horizons, mining induced fractures or pre-existing geological structures.

Mills *et al* (2015) identify that shear displacements on specific shear horizons and associated with general body block movement occur in the direction of the major horizontal stress (i.e. in response to stress relief) to distances of at least 400m ahead of mining. Furthermore specific shear horizons are able to be correlated between boreholes a kilometre apart indicating that lateral displacements due to stress relief occur throughout the overburden strata for considerable distances. Additional shear distortion is observed to occur within close proximity (30 m or so) of the mining void. These shear distortions are consistent with the shear distortions caused by vertical subsidence and the redistribution of overburden load around the goaf edge.

Boreholes located adjacent to extracted longwall panels provide opportunities to observe and measure lateral ground deformation as they develop. This paper describes the authors' experience of using a range of borehole methods to observe and quantify the nature of lateral movements.

DOWNHOLE SURVEYS IN SHALLOW HOLES

Large diameter open boreholes provide a simple method to observe large scale shear movements at shallow depth. This approach is particularly suited to sites where large deformations occur or are expected to occur near the surface. If shear displacements are so large that the hole shears off, a new hole can be drilled and deformations can continue to be monitored.

At one site where a low angle geological fault was expected to move and did move significantly as a result of mining subsidence, large diameter open holes (250 mm to 300 mm in diameter) proved very effective as a means to monitor the anticipated reverse fault movement. Shear displacements were observed on multiple horizontal bedding parallel shear surfaces. The offsets observed in the holes were regularly measured using a borehole camera and multi arm calliper. Figure 1 shows a photograph of a shear displacement observed at one horizon.

As shear movements occurred, the shear offsets were observed by the borehole camera on each of the several shear horizons using the construction shown in Figure 2. The direction of an offset was identified using a downhole compass. Multi-arm calliper surveys provided a secondary measurement of the magnitude of displacement. Figure 3 shows how the data was combined, compiled and reported with successive surveys showing the progressive change in deformation and magnitude of change on each individual shear horizon.

Once the hole was fully offset by the fault, the camera and calliper tool could no longer pass the shear horizon, a new hole was drilled so that monitoring could continue.

Figure 4 shows the deformations observed in the geological setting at the site. The observed ground deformations indicate displacement was distributed over several bedding parallel horizons as the reverse fault was reactivated by mining subsidence. These studies demonstrated how large diameter holes deform and were effective in surviving large shear deformations. Understanding this behaviour enabled greater confidence with use and interpretation of inclinometers installed in large diameter holes to investigate anticipated shear deformations

Figure 1: Shear offset imaged in large diameter borehole.

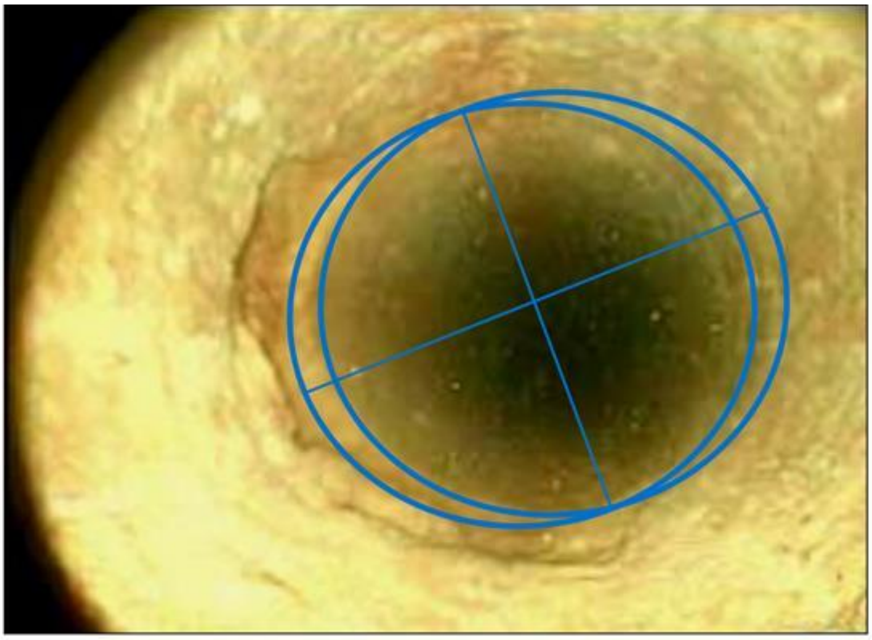

Figure 2: Graphic method utilised to determine the offset magnitude and direction relative to the borehole.

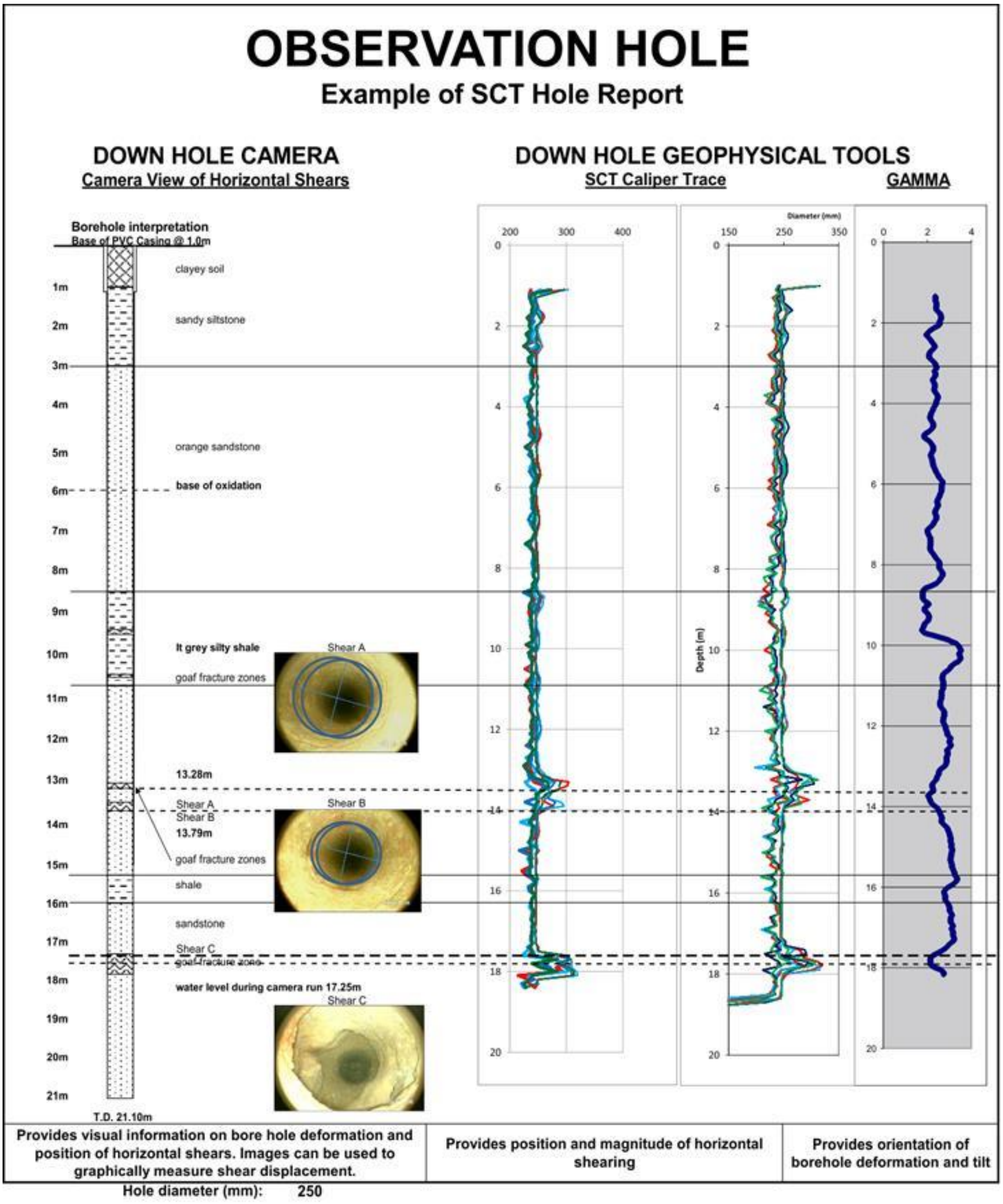

Figure 3: **Combined image survey data and multi-arm calliper surveys used to report the deformation of the observation borehole.**

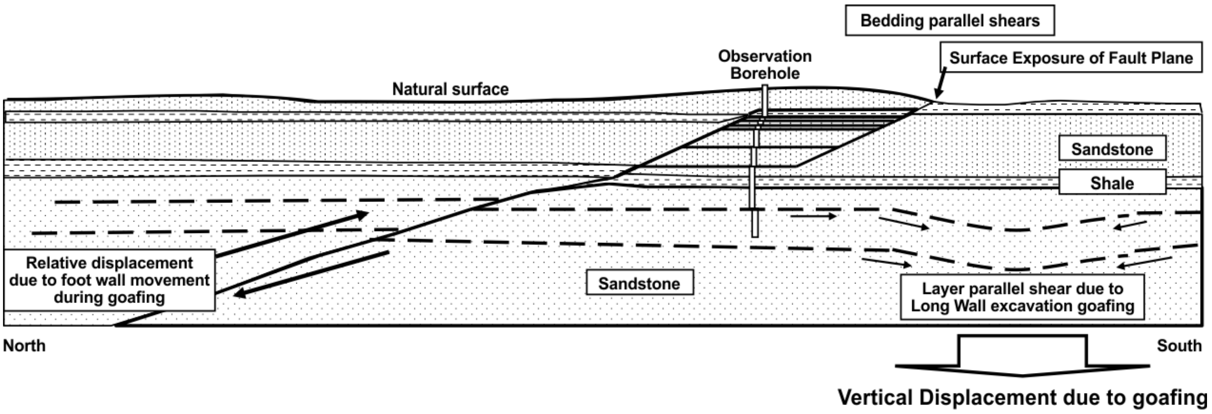

Figure 4: Shear displacement in observation boreholes.

INCLINOMETER MEASUREMENT SYSTEMS

Whilst the methods described above are suited to shallow open holes where large offsets are possible, an investigation method based on inclinometer monitoring is more suitable at greater depth where movements are smaller and may involve general body shear distortion that is not able to be observed using a borehole camera or calliper.

Inclinometer monitoring involves drilling a large diameter borehole in the area of interest through the full section where shear movements are expected to occur. The configuration is illustrated in Figure 5. A casing with two pairs of vertical grooves is installed in the borehole so an inclinometer probe can be lowered into the hole and withdrawn in steps of 0.5 m to get very accurate measurements of the incremental tilt in orthogonal directions. By repeating these surveys at regular intervals, incremental tilt is measured relative to the initial base survey and horizontal displacements can be integrated from these tilt measurements.

In some cases, the shear deformations become so large that the borehole shears sufficiently that the probe is no longer able to pass and further measurements are not possible. The survivability of the installation is dependent on the type of grout or backfilling used to hold the casing in place (Plinninger, Alber, Dullmann 2010). Vulnerability to shear displacements that preclude the probe passing is more common when shear occurs at specific shear horizons. Shear on specific horizons occurs more commonly within rock strata around coal mining activity whereas general body shear distortion occurs more commonly in soft soils and similar geotechnical applications.

Sensitivity of the inclinometer system to shear movement is improved if the annulus between the inclinometer casing and the borehole wall is backfilled with cement grout. However, this increased sensitivity comes at the cost of vulnerability to the holes being sheared off when shear displacements are concentrated at specific horizons. Grouting also requires control of the pressures differentials between inside and outside of the casing. Grouting of holes deeper than about 50 m typically requires staged grouting as the density differential between a cement grout outside the casing can become sufficient to collapse a water filled casing. However, stage grouting in deep holes can lead to sections of incomplete grouting where the inclinometer casing is not supported at all.

Backfilling with granular material has proved to be more effective method of backfilling in deep holes. Shear capacity of up to about 60mm of shear on a single shear plane are typically observed in a 200 mm diameter hole using this approach. The strategy is illustrated in Figure 6. Although there is some loss of sensitivity to first shear movements, this loss is more than compensated by increased shear capacity. A large diameter borehole (200-300 mm is common) is drilled and the annulus between the inclinometer casing and the borehole wall is backfilled with free-running pea gravel or similar material.

Use of adequately sized material allows the granular fill to sink effectively into position without bridging between the hole and inclinometer casing.

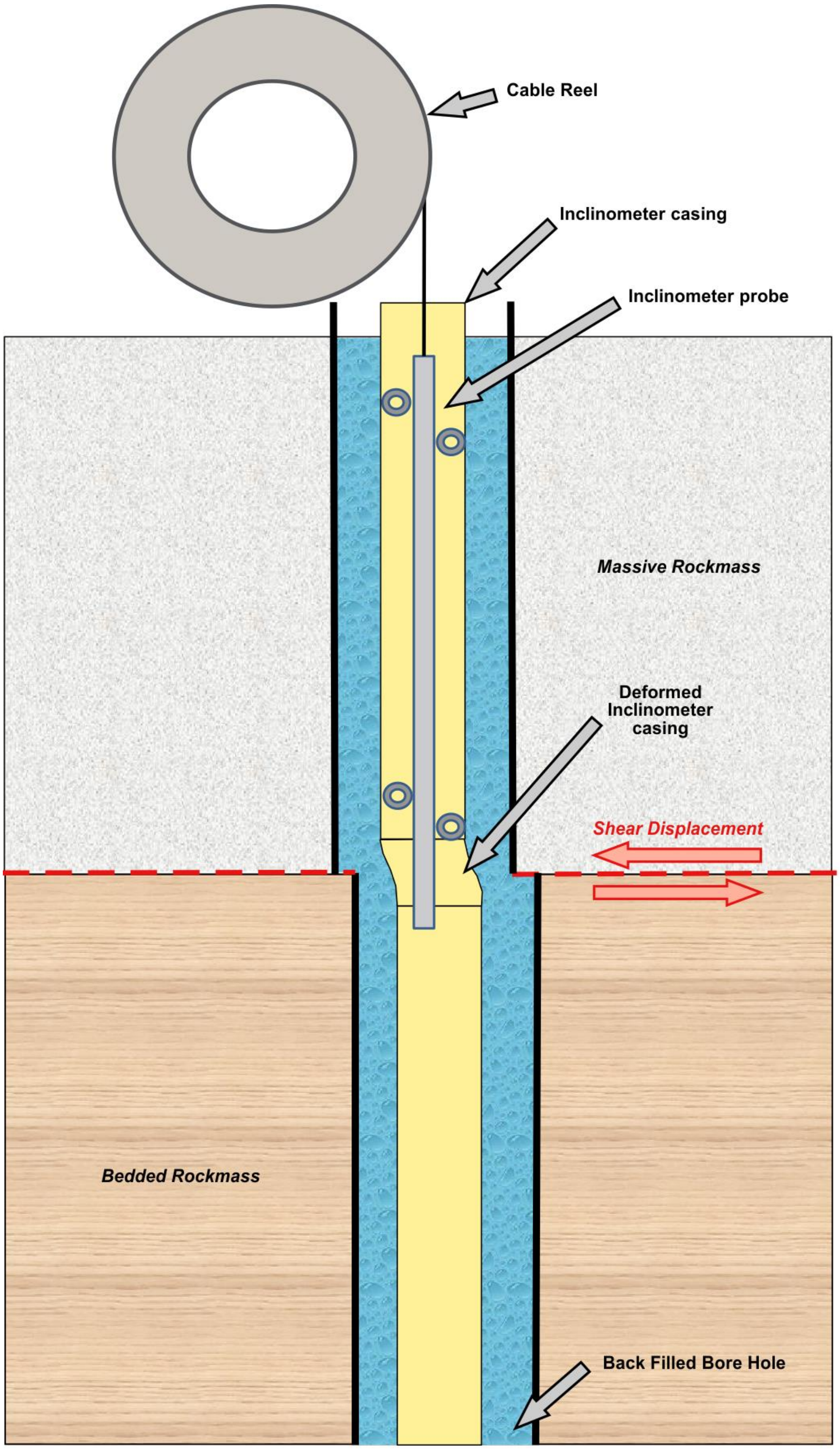

Figure 5: Schematic view of Inclinometer casing and Inclinometer probe.

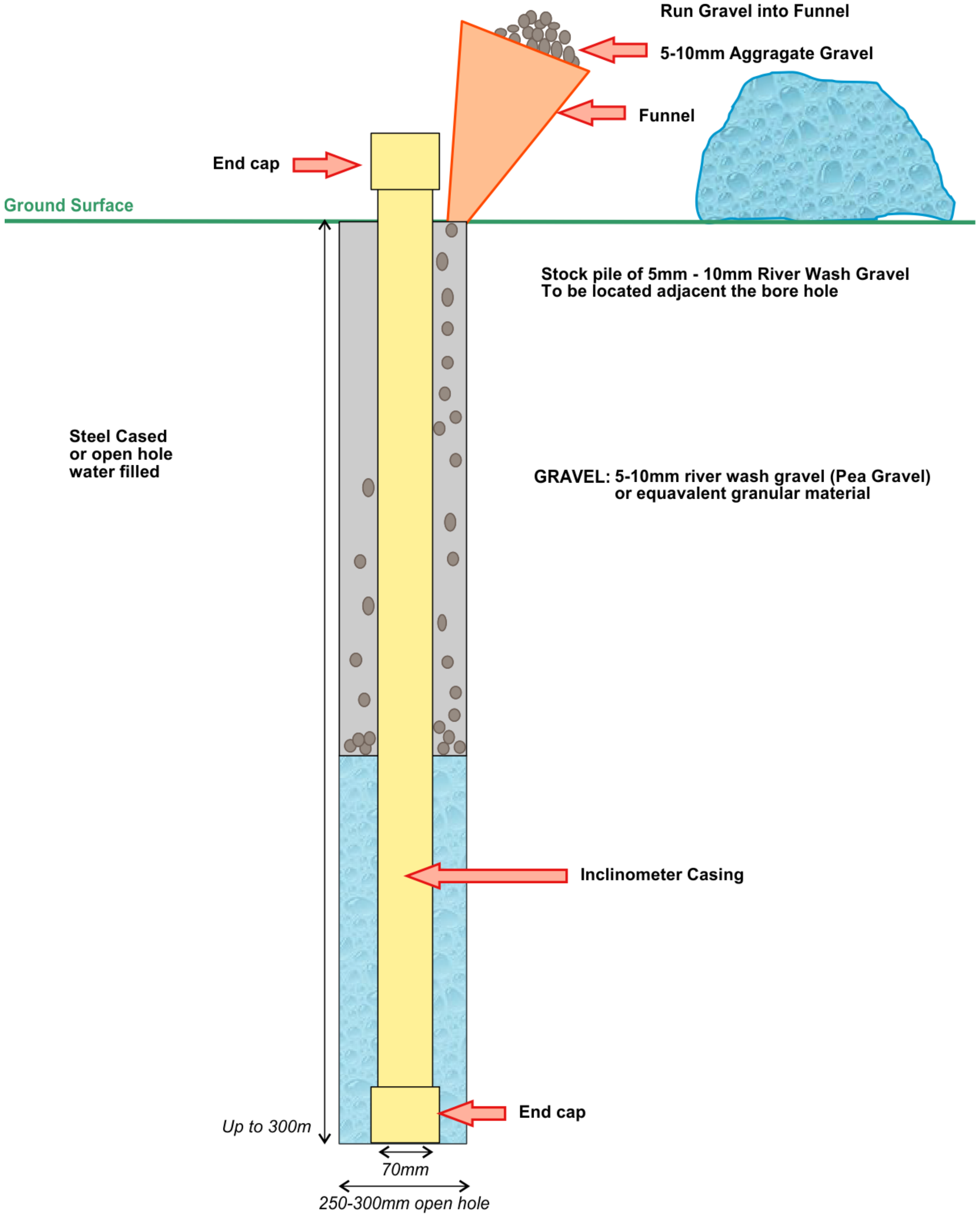

Figure 6: Schematic of typical inclinometer casing installation used by SCT.

Steel casing may be used to stabilise the large diameter borehole and prevent blockages associated with swelling clays or other types of borehole instability. The steel casing offers no resistance to ground movements but does help ensure that the backfill reaches the bottom of the hole and the inclinometer casing is thus fully supported.

The inclinometer probe measures the tilt on two orthogonal axes referred to as the A and B axes. The A axis is the primary axis of the instrument and readings on this axis are somewhat more accurate than readings on the B axis. The B axis measurement includes a component of tilt associated with the wheels wandering in the grooves in the casing. This effect can be eliminated by making a second survey at right angles to the first.

Small, permanent offsets in the instrument alignment can become significant when integrated over the length of a deep inclinometer hole. These offsets can be eliminated by taking two sets of readings on each axis with the instrument reversed during the second set and averaging the results.

A set of four readings on each survey provides a single high resolution measurement with equal accuracy in each direction.

Some inclinometer casings are subject to small amounts of twist in the grooves that accumulate in deep holes so that the A+ axis varies down the hole relative to its orientation at the surface. A one off survey with a spiral probe is used in deep holes to determine how the orientation of the casing grooves varies down the hole. Spiralling of up to 120° have been observed in deep holes, so having a measure of the casing spiral is important in the context of resolving the direction of shear movements.

With accurate baseline measurements typically repeated before the onset of any ground movements to confirm the repeatability of the measurements and a spiral measurement, it is possible to resolve from the inclinometer monitoring the direction and magnitude of shear movements. In the context of ground movements around longwall panels, the direction of movement is significant in determining the cause of these movements. Movements that occur well in advance of longwall mining in the direction of the major principal stress are typically the result of *in situ* stress relief. Movements that occur in a downslope direction near the surface are more likely the result of topographic effects.

One of the limitations of inclinometer monitoring is that the surveys are labour intensive and can only be conducted infrequently. Focussing only on the section of borehole where movements are expected to occur or are of interest can increase the frequency of surveys that are able to be made.

For close interval monitoring, another system involving the use of Shaped Accelerometer Arrays (SAA) provides a much higher density of information at intervals as low as a few minutes. The SAA remains in the hole for the duration of the monitoring. The instrument system is recoverable provided the shear movements are not so large as to shear the hole off. With the high initial cost of the instrument, the SAA has greatest application for monitoring a relatively short interval of a borehole (50-100 m) in circumstances where shear movements are expected to remain small. The SAA system is well suited to identification of shear horizon locations and the timing of initial movements on these shear horizons.

Walsh *et al* (2014) describe the use of an SAA inclinometer system to protect a sensitive sandstone waterfall features from subsidence impacts. This system also provided insights into the mechanics of the processes driving valley closure including those natural processes such as rainfall events and thermal variations (Mills 2014).

Horizontal shear displacements on specific horizon are commonly observed to occur at the following:

- Thin or low strength bedding planes that are continuous over large areas such as tuff bands, coaly horizons, and some clay bands
- The interface between lithological units with high strength or elastic modulus contrasts such as found at the boundaries of igneous sills, volcanic lava flows, massive sedimentary channels, dykes
- Pre-existing faults/joints forming defined blocks or wedges within the rock mass

These surfaces that are frequently the foci of induced slip, define a failure in the rock mass. The accumulation of stress/strain induced by the longwall excavation subsidence event refracts across the boundary until eventual failure. As ground movement due to the nearby mining activity occurs within the overburden strata, they become focussed at these horizons as shear displacements. These displacements may be progressive and gradual or rapid and sudden as mining progresses. Their characteristics provide insights into the nature of the shear surfaces and whether sudden rock failure is involved or the shear surface is at limiting equilibrium naturally and remobilised as a result of mining.

Survey frequency is dependent on the nature of the events being monitored. If the observation hole is established for a long term monitoring of infrastructure with only small movements anticipated, it may only require quarterly surveying to collect sufficient data to characterise the ground deformation. If more rapid and/or larger deformations are expected, frequent surveying may be required while the borehole remains open.

Plotting and interpretation of recorded data is achieved through use of propriety software supplied by the suppliers of various Inclinometer systems. The can also be processed reasonably easily in a spreadsheet to give greater flexibility.

Independent surveying of the position of the borehole collar is useful to confirm that any reference horizon assumed to remain stationary does indeed remain in the same position throughout the monitoring period. Knowing the borehole position and original orientation allows accurate determinations of the magnitude and orientation of ground movements. Relating the depth of ground movements to the stratigraphy provides useful insights into the key horizons that are mobilised by mining activity.

OBSERVATIONS FROM DEEP INCLINOMETER INSTALLATIONS

In this section, the results of inclinometer monitoring conducted at several sites are presented as an illustration of the effectiveness of inclinometer monitoring in determining horizontal movements around longwall panels.

Figure 7 shows an example from a site where stratigraphy is strongly influencing the deformation behaviour within the overburden strata. The horizon at an RL of 67m is clearly controlling lateral displacements as discrete shear while the 50m thick unit below this horizon is experiencing shear distortion en mass without the formation of discrete shear horizons.

The same inclinometer data can be viewed in a range of different plots to highlight active displacement horizons as well as the magnitude and directions of ground movements at different horizons within the overburden strata. A plot of mean deviation of both axes (Figure 8) again shows shears can be detected and the specific horizon attributed. Plots of vectors can be determined for specific horizons and subsequent surveys complied to reveal movement history at a specific surface (Figure 9).

At another locality, Figure 10, two nearby inclinometer holes E103A and NC533 and coincident stress monitoring holes were used to monitor subsidence over longwall two longwall panel. Figure 11 shows the vectors of horizontal movement observed shear movements on seven primary horizons within the overburden strata above a 15-20m thick conglomerate unit directly overlying the coal seam (Mills *et al* 2015). The vectors of horizontal movement closely align with horizontal stress changes measured at the same site and with the major *in situ* horizontal stress indicating that the movements are primarily associated with horizontal stress relief toward the approaching longwall goaf.

Initial shear movements were observed as soon as the longwall panel started at a distance of 425m ahead of the longwall face. This observation confirms that horizontal stress relief is able to mobilise the overburden strata over large distances

Two inclinometer monitoring holes located some 1,050 m apart at this site show a strong correlation between the elevations of activated shear horizons as indicated in Figure 12. This correlation suggests that the shear horizons may be continuous across large areas.

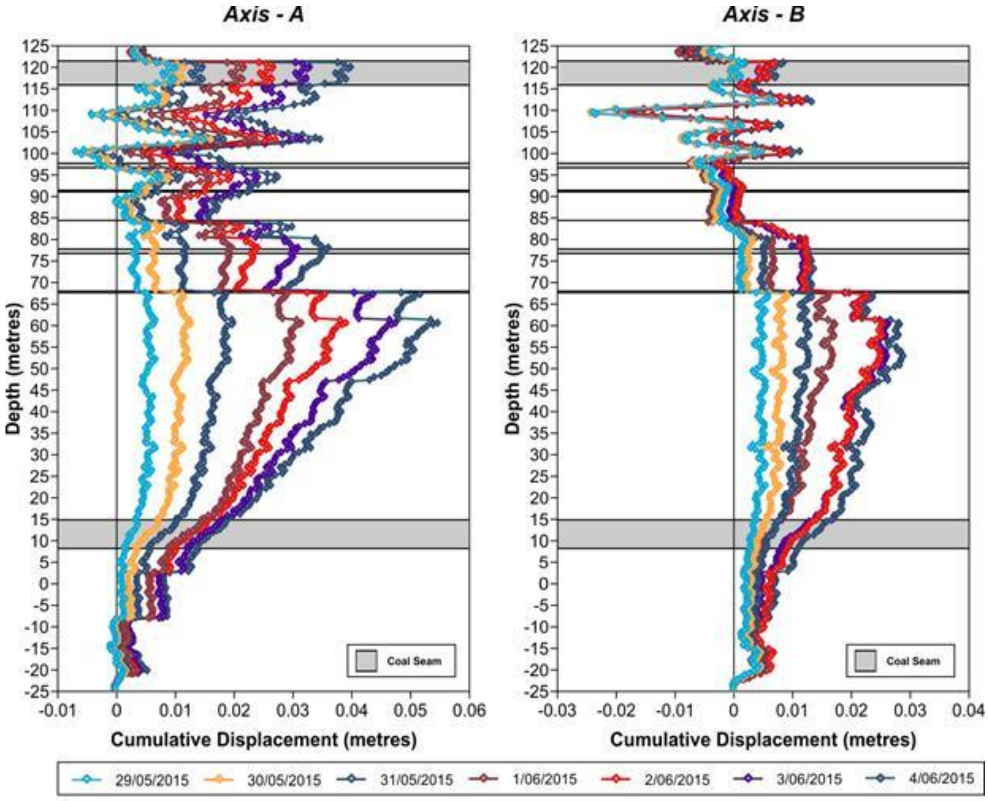

Figure 7: Example of Cumulative Displacement within a rock mass in stratified geology at an Australian coal mine shown relative to the inclinometer casings orientated A and B axis.

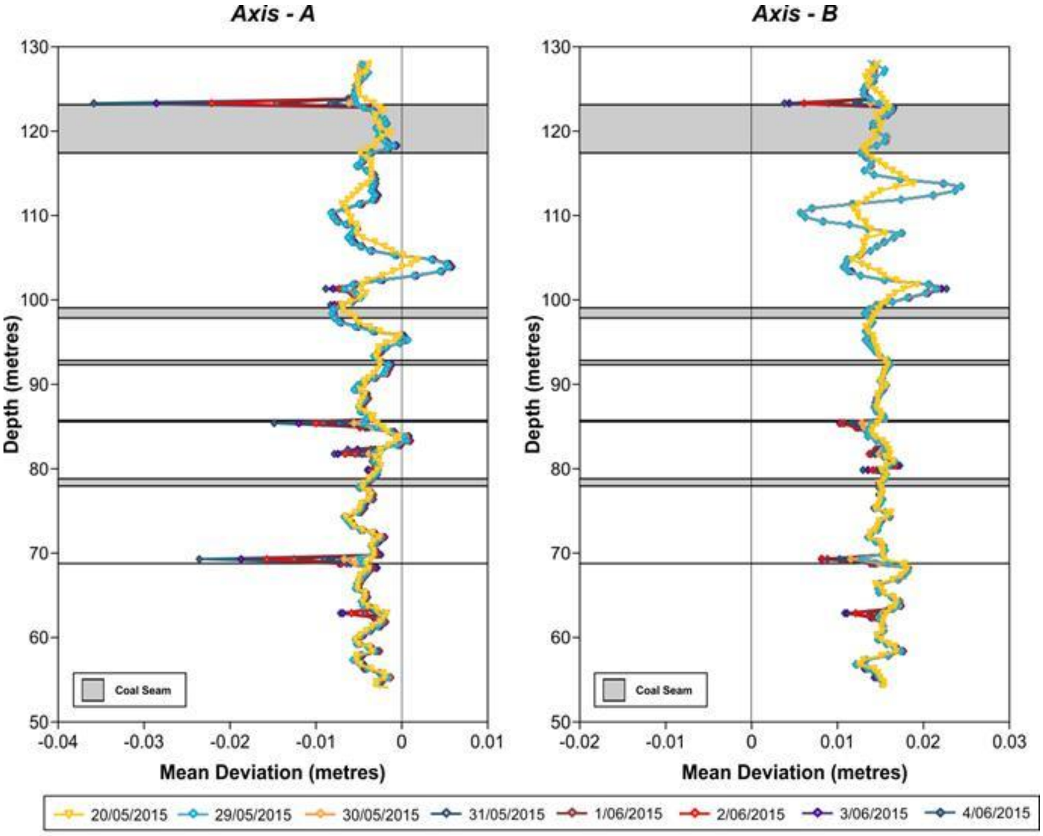

Figure 8: Mean deviation of displacement within a rock mass in stratified geology at an Australian coal mine shown relative to the inclinometer casings orientated A and B axis.

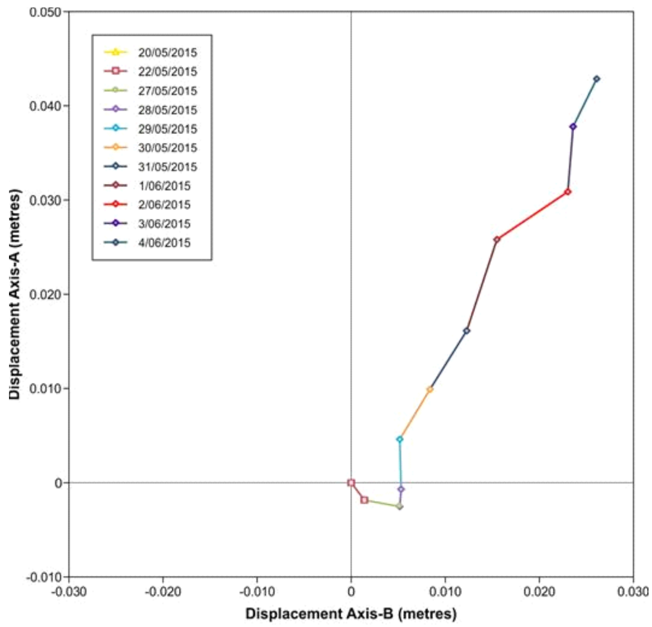

Figure 9: Vectore plot: 207.5 meters

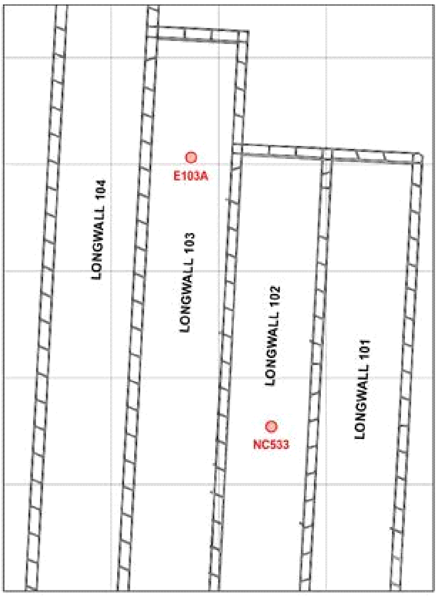

Figure 10: Example mine layout with inclinometer locations (after Mills *et al*. 2015)

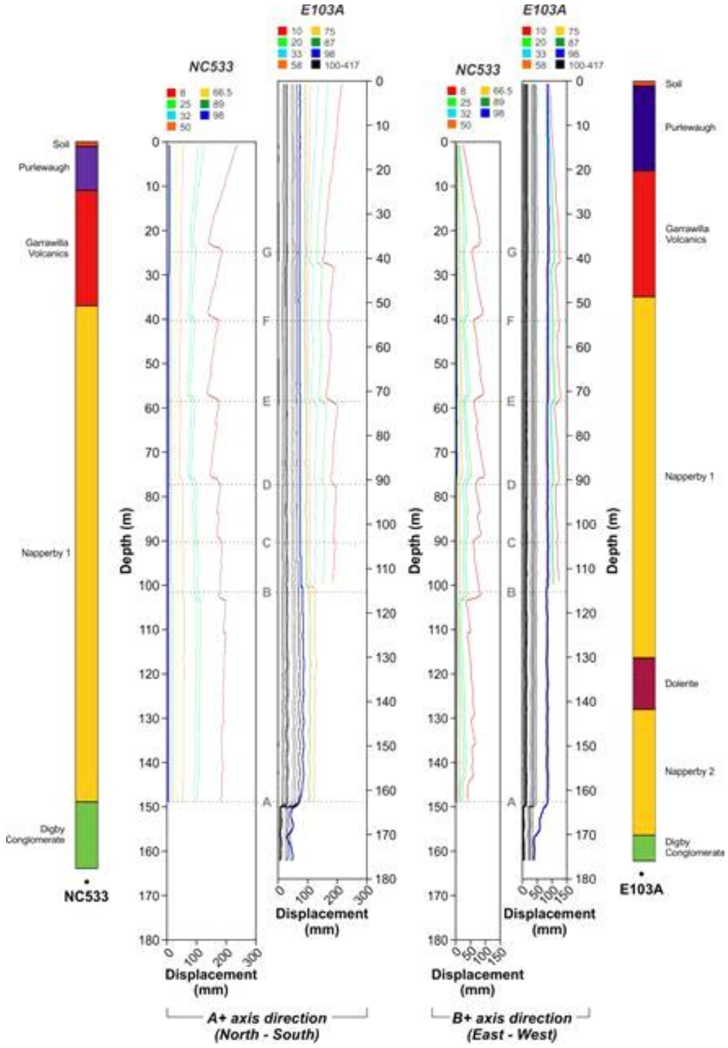

Figure 11: Inclinometer movements measured in the A+ (North - South) and B+ (Ease - West) axis directions (after Mills *et al*. 2015)

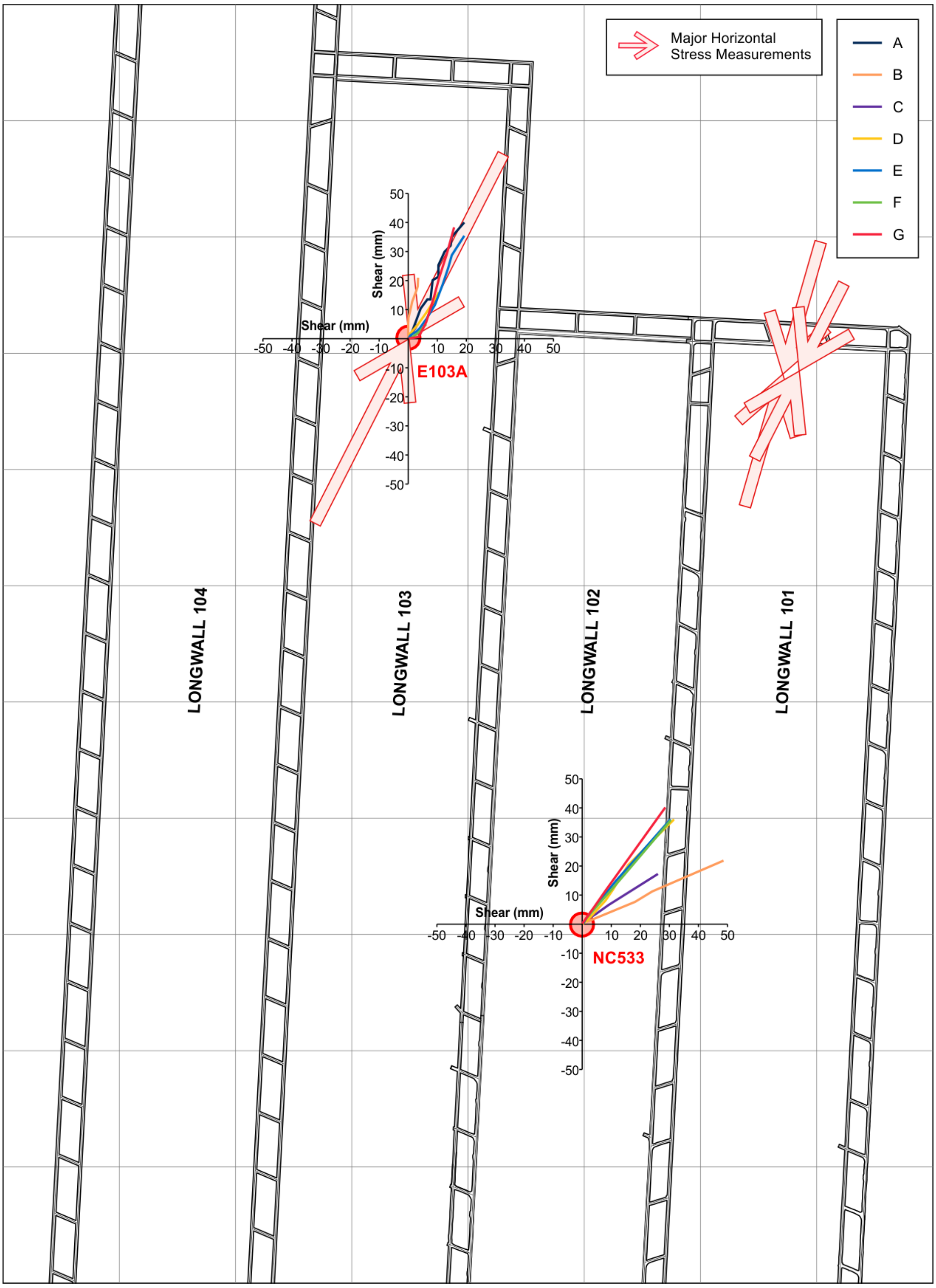

Figure 12: Orientation and magnitude of shear movement in relation to principal stress direction in actual measured locations (after Mills et al. 2015).

Figure 12 also indicates the onset of general body shear distortion when the longwall face is within about 30m of the inclinometer hole. This general body shear distortion has quite a different characteristic to the block movement on discrete shear planes observed at greater distances. General body shear distortion occurs within the rock mass itself and is associated with the shear in a vertical direction caused by the downward displacements of the overburden strata that occur immediately behind the longwall face. These shear distortions are much stronger than would be consistent with pure bending of individual stratigraphic units suggesting that interpreting displacements in an around the longwall face purely as a bending phenomenon may not correctly capture the key characteristics of ground behaviour in this area.

CONCLUSION

Measurements of horizontal and oblique displacements within the overburden strata can be made using a range of different systems depending on the particular circumstances. These circumstances include the magnitude of shear movements expected, the depth to the shear horizons of interest and the frequency and detail of the monitoring required.

Inclinometer casing installed in large diameter holes surrounded by granular material to accommodate shear displacements at discrete horizons are found to provide high confidence insights into ground behaviour about longwall panels to depths to 300 m plus.

Coincident use of stress cells and inclinometers provide further insights into the characteristics of ground movement. including have shown two distinct movement styles, firstly a horizontal stress relief horizontal shear, then a tilting and sagging as the excavation is close to undermining a position.

Inclinometer monitoring is providing significant insights into the mechanics of the processes that cause ground movements naturally and in response to longwall mining. Further studies are expected to expand this understanding.

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