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Experience of using the ANZI strain cell for stress change monitoring

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Abstract

This paper describes the ANZI (Australia New Zealand Inflatable) strain cell and some examples of its application for stress change monitoring. The instrument has been used over the past three decades to measure three-dimensional in situ stresses using the overcoring method of stress relief and monitor three-dimensional stress changes in a range of applications mainly associated with underground coal mining, but also with civil and metalliferous mining projects.

The ANZI strain cell has a pressuremeter design that allows 18 electrical resistance strain gauges at various orientations to be pressure bonded directly to the rock on a borehole wall. The instrument's soft polyurethane membrane and hollow pressuremeter design have characteristics that facilitate deployment, enhance data gathering, and simplify analysis. Further recent developments that improve deployment and monitoring have increased the capability of the instrument. Automatic, remote, and high speed monitoring at resolutions of just a few microstrain has significantly improved the capability to measure and thereby understand the nature of changes in the three-dimensional stress in rock strata around excavations in rock.

1 Introduction

The ANZI strain cell was primarily developed for three-dimensional in situ stress measurement but has also proved useful for three-dimensional stress change monitoring. This paper focuses on some of the applications where the instrument has been used for stress change monitoring. The in situ stress measurement capability is described in Mills (1997) and more recent developments are planned to be presented elsewhere.

The strengths of the ANZI strain cell for stress change monitoring include:

- Up to three instruments can be installed in the same hole at depths to several hundred metres from the surface or nearest underground opening.
- The instrument can be tested at any stage to confirm the integrity of each of the individual strain gauges.
- Analysis of the strain changes to determine stress changes is simplified because of the design of the instrument.

Three-dimensional stress changes are able to be determined from strain changes caused by mining, various construction activities, hydraulic fracturing, and step change events such as sudden shear movements or micro-seismic activity. Three examples of using the instrument to monitor stress changes are presented. These include stress changes induced by a large scale hydraulic fracture as the tip of the fracture passes, monitoring of subsidence effects above a longwall panel, and monitoring of a step change event that occurred within the overburden strata during adjacent coal mining while monitoring stress changes adjacent to a large sandstone cliff formation.

Available analysis techniques for converting measured strains to stresses are based on assumptions that the rock material is linear, elastic, isotropic and homogeneous. However, many rocks are not ideal materials. Rocks are commonly not isotropic, linear elastic, or homogeneous. Measurements of in situ rock behaviour made during measurements with the ANZI strain cell confirm that the material properties of many rocks are dependent on a range of external factors.

Recognising that the calculation of stress changes from measured strains is imperfect, the key to getting value from stress change monitoring is gaining a sense of the confidence that can be placed in each measurement as a coherent indication of the stress change at the point of the measurement. This process includes assessing how well the rock properties can be approximated as an ideal material. In the authors' experience, not all measurements aimed at measuring changes in stress are reliable, but having a basis to differentiate those that are from those that are not is invaluable for developing an overall understanding of the stress environment and rock behaviour within that environment. The ANZI strain cell is designed with focus on simplicity of operation, simplicity of geometry, and providing high levels of redundancy to give a sense of the confidence that can be placed in each individual point measurement.

2 Description of ANZI strain cell

The ANZI strain cell is a strain based instrument designed to allow 18 electrical resistance strain gauges with a variety of orientations to be pressure bonded directly to the rock on the wall of a borehole. The instrument's soft polyurethane membrane and hollow pressuremeter design have a number of characteristics that facilitate deployment, enhance data gathering, and simplify analysis.

Figure 1 shows a photograph of the 57 mm version of the instrument and an overcore of an instrument installed in coal.

2.1 Basic operation

The operation of the ANZI strain cell is similar to other strain gauged based instruments that can be used for stress change monitoring or in combination with the overcoring method of stress relief for in situ stress measurement. A significant difference is the ability to conduct an in situ pressure test at any time to confirm the material properties of the rock and the correct operation of the instrument.

Figure 1 Photograph of single ANZI strain cell and an overcore of the instrument installed in coal

The basic operation of the instrument for stress change monitoring involves the following steps:

1. An access hole is drilled to the location of the measurement that may be up to several hundred metres from the surface or an underground opening. A 60 mm (58-61) diameter pilot hole is then extended from the end of the access hole. In practice, it is common for the entire hole to be drilled using BQ coring equipment to give a 60 mm diameter hole.

2. Up to three ANZI strain cells, spaced at any convenient distances within the hole, are then coated in epoxy cement, deployed to depth into the pilot hole on flexible installation rods, and inflated with air pressure until the epoxy cement has cured. Up to three completely independent instruments can be installed in the same hole with the cables and air lines from the deeper instruments passing through the hollow centre of the shallower instruments.
3. An in situ pressure test is conducted by incrementing the air pressure to induce strain changes in the rock that are small enough not to significantly disturb the rock but large enough to provide confidence in the measurement of the elastic shear modulus and any variations that may occur as a result of stress concentration effects around the borehole.
4. For monitoring, the instrument cable is connected to a logging system and monitored over time at intervals ranging from a few seconds to many hours depending on the application. The properties of the rock, elastic modulus, Poisson's Ratio, and rock strength are also determined from laboratory testing of core recovered from the pilot hole at the location of each instrument.

SCT Operations Pty Ltd manufacture the ANZI strain cell in a range of sizes that can be deployed in boreholes ranging in diameters of 29, 38, 48, and 58-60 mm. However, most of the stress change monitoring is done with the 57 mm version of the instrument which has been found to be robust and convenient to use in the field. The instruments are supplied as part of a service.

2.2 Development history

The ANZI strain cell has been developed over the last three decades through incremental improvements that have gradually increased its capability over time. The original Auckland New Zealand soft inclusion (ANZSI) strain cell (Mills & Pender 1986) was developed from 1980 to 1983 at the University of Auckland for the purpose of measuring three-dimensional in situ stresses in coal. The instrument was primarily designed to reduce the tensile stresses generated in soft rocks at the borehole wall. The ANZSI strain cell was 38 mm in diameter and carried nine strain gauges. The instrument was successfully used to measure in situ stresses and monitor stress changes in coal mines in New Zealand, Australia, and the United Kingdom as well as at several hard rock civil sites in New Zealand.

In 1990, the instrument underwent a significant upgrade and a name change. The diameter was increased to 57 mm diameter and manufactured on a hollow, tubular body. The number of strain gauges on each instrument was increased to 18, and the name was changed to the ANZI (Australia New Zealand Inflatable) strain cell reflecting the instruments combined development history and essential mode of operation.

From 1996 to 1998, a 29 mm diameter version of the instrument was developed, also with 18 strain gauges. This instrument can be overcored using a BQ core barrel giving a 45 mm diameter overcore. The smaller size was aimed at reducing the time taken to drill to depth. In coal mines, these instruments are able to be installed at 10-15 m from an underground roadway within two hours of the start of drilling. However, the smaller drilling gear does not allow sufficiently good core recovery during drilling of the pilot hole to identify the optimal location where the instrument should be installed and the system has been found to be too delicate for use with conventional drilling rigs. Nevertheless, this version of the ANZI strain cell is useful in specialist applications such as measuring bending stresses in thin diaphragm walls by offsetting gauges along a single instrument installed into the wall.

Since 2001, ANZI strain cells have been deployed for monitoring the growth of full scale hydraulic fractures and have been found to provide useful information on fracture orientation, fracture growth, and stress changes induced by hydraulic fractures (Mills & Jeffrey 2004; Mills et al. 2004).

Since 2008, a standalone, battery powered logging system has also been developed for remote logging applications. This system has the capability to read all 18 strain gauges together with stable reference gauges embedded in the instrument at intervals ranging from a few minutes through to 90 hours depending on the application. The logging system is typically deployed at the collar of the borehole and concealed below the surface to limit disturbance and vandalism. The logging system is capable of deployment with twice daily readings for periods of up to six months without need of a battery recharge.

Further developments are underway to allow remote monitoring in hazardous zones within underground coal mines where intrinsically safe equipment is required.

2.3 Pressuremeter design

The pressuremeter design allows a pressure test to be conducted in situ after the instrument has been installed to confirm the operation of all the strain gauges prior to overcoring. The pressurised length of the ANZI strain cell membrane is designed to be four times the diameter of the borehole so as to generate near plane strain conditions during the in situ pressure test (Laier et al. 1975).

Air pressure is applied to inflate the instrument during installation typically at a pressure of about 200 kPa above any background water pressures in the borehole. Most of the epoxy cement applied to the recessed surface of the membrane prior to installation is extruded following inflation leaving the strain gauges pressure bonded directly to the surface of the rock with 0.2-0.4 mm of residual epoxy cement between the gauge surface and the rock. Curing time for the specially formulated epoxy cement varies with rock temperature but is usually less than 6-12 hours, typically overnight.

During the in situ pressure test, air pressure is increased to about 2,000 kPa above background typically in increments of about 200 kPa to confirm that all the strain gauges respond linearly to the applied pressure.

The results of the in situ pressure test provides a measure of not only the elastic properties of the rock but also how well the in situ rock material can be approximated as a linear elastic, isotropic, homogeneous material for the purposes of calculating stress changes from the measured strains. The pressure test also provides confirmation that the instrument is properly installed and all gauges are well bonded to the borehole wall. Repeats of the pressure test conducted from time to time confirm the continued operation of the instrument and allows any gauges that have ceased to operate, as a result of borehole breakout for instance, to be identified.

The ability of the ANZI cell to operate as a pressuremeter has allowed significant advances in understanding of in situ rock behaviour as well as confirming the correct operation of the instrument. For instance, in vertical boreholes, variation in the elastic modulus of rock strata caused by differences in horizontal stress concentrated around a borehole are frequently reflected in the differential response of the circumferential gauges during the pressure test. This difference provides an independent indication of the in situ stress direction and sometimes the magnitude of the stresses as well. This characteristic is convenient as an indication of the in situ stress field that exists prior to the commencement of monitoring in circumstances where it is not possible to conduct an overcoring stress measurement and as a check on any changes in stress direction that occur during the period of monitoring.

2.4 Strain gauge configuration

Eighteen electrical resistance strain gauges are arranged in six rosettes of three gauges each. The gauges are facing outward flush with the outer surface of a polyurethane membrane in a configuration that means the strain gauges and electrical components are waterproof while the strain gauge are in direct contact with the rock strata.

The six rosettes of three gauges each are oriented at 60° intervals around the circumference of the cell to improve statistical confidence in stress changes measured (Gray & Toews 1974). Each rosette has one gauge oriented in a circumferential direction. This combination gives 12 degrees of redundancy and two or more independent measurements of most of the individual strain components.

The strain gauges used on the ANZI cell are typically 5 mm long, 120 ohm electrical resistance strain gauges. The gauges are 5 mm long to reduce the potential for strain averaging around the borehole circumference in circumstances where the strain gradients are high such as in stress fields, where one of the stresses perpendicular to the borehole is much larger than the other. Longer gauges can be used to average out non-homogeneous rock composition but, in a small diameter hole such as the pilot hole, 10 mm long gauges are found to significantly underestimate the measurement of strain at a point when the stress gradients are high. Shorter gauge lengths are also used from time to time in specific applications, but the 5 mm gauge length has been found to give a good balance for routine use on the 57 mm diameter version of the instrument.

In monitoring applications, one or more reference gauges is deployed in each instrument to check for measurement system induced variations such as those caused by surface temperature changes that might affect the loggers. The reference gauges are isolated from any strain changes so that they should remain constant over time. Instrument orientation, water pressure, and temperature can also be monitored depending on the application.

Strain gauges and other sensing elements are monitored via a cable from the instrument at each pressure increment of the in situ pressure test and post overcoring biaxial pressure test, and continuously at approximately one second intervals during overcoring. Strain gauges are monitored as single ended gauges using a Wheatstone bridge completion circuit located at the surface. The bridge completion is switched sequentially across each gauge with each gauge arranged in a three wire configuration. The measurement electronics has been specially designed to eliminate cross-talk between gauges as they are switched.

Desensitisation of the gauges caused by long cable lengths are compensated for when determining strain changes so that strains measured during field measurements can be directly compared with strains derived from laboratory tests.

2.5 Analysis

Strains associated with stress changes are analysed in much the same way as for overcoring measurements. Stress changes are determined from the measured strains using the technique described by Leeman and Hayes (1966) and variously enhanced by others. A minor correction can be made during analysis to include the effect of epoxy cement layer formed between the membrane and the rock using the analysis described by Duncan-Fama and Pender (1980), but for the ANZI cell the effects of this correction are slight. For all practical purposes, the strain gauges can be considered bonded directly to the borehole wall. The elastic properties of the rock mass are determined independently during the in situ pressure test and laboratory tests on core recovered from the pilot hole.

3 Case studies of ANZI strain cell monitoring

In this section, three case studies of using the ANZI strain cell are presented. These include an example of measuring the stress changes at the fracture tip of a full scale hydraulic fracture, and two examples of stress change monitoring about longwall operations in underground coal mines, one of which captured a mining-induced step change event inferred to be a microseismic event.

3.1 Stress changes at the tip of a full scale hydraulic fracture

Hydraulic fracturing has long been used to induce fractures in rock strata. However, it is relatively unusual to have the opportunity to measure the actual stress changes induced in the rock mass by full scale hydraulic fractures. Mills and Jeffrey (2004) describe one of several field measurement programs where ANZI strain cells have been used to measure the changes in stress in a rock mass as a hydraulic fracture approaches and passes an instrument. At a site in a copper mine in Chile, ANZI strain cells were installed in two BQ holes drilled downward some 45 m at 59° from horizontal from an underground roadway as shown in Figure 2. These two monitoring holes were located either side of the main fracture injection hole. The hydraulic fractures were initiated between 60-75 m below the collar of the injection hole and grew upward past the monitoring cells some 10 m from the monitoring cells.

Figure 3 shows one of the instruments in a two instrument string being prepared and lowered into the hole.

All strain gauges were logged at about 15 second intervals through the hydraulic fracture treatments with signal noise reduced using a moving average function to achieve a resolution of the order of 1 microstrain.

In this application, the resolution indicated by the stresses calculated from multiple gauges is of the order of 0.01 MPa in rock with an elastic modulus of 60 GPa.

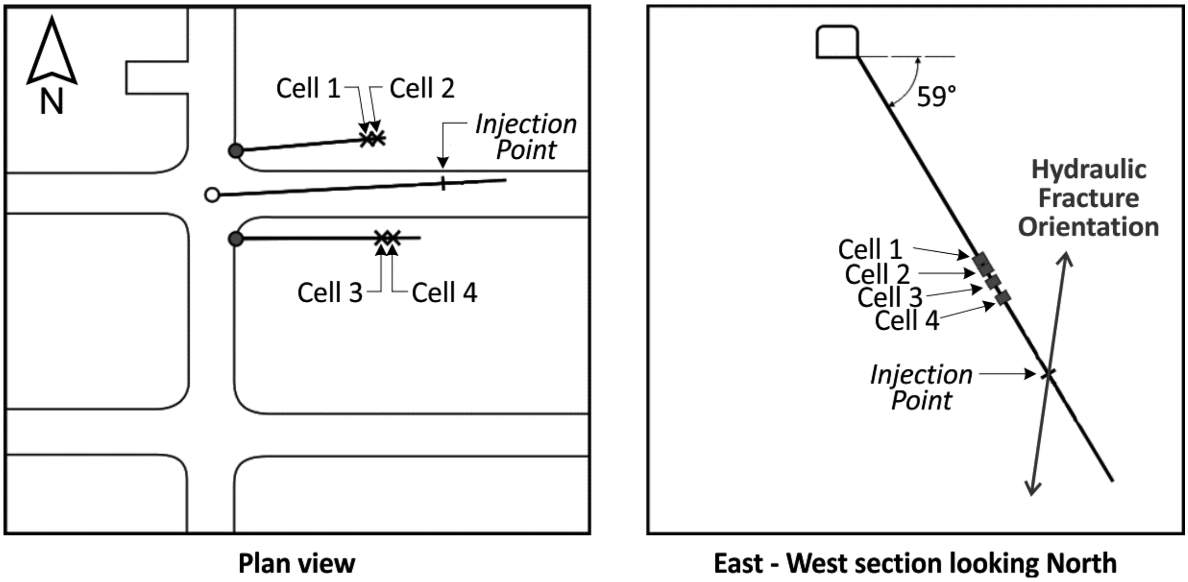

Figure 2 Location of ANZI monitoring cells relative to a full scale hydraulic fracture

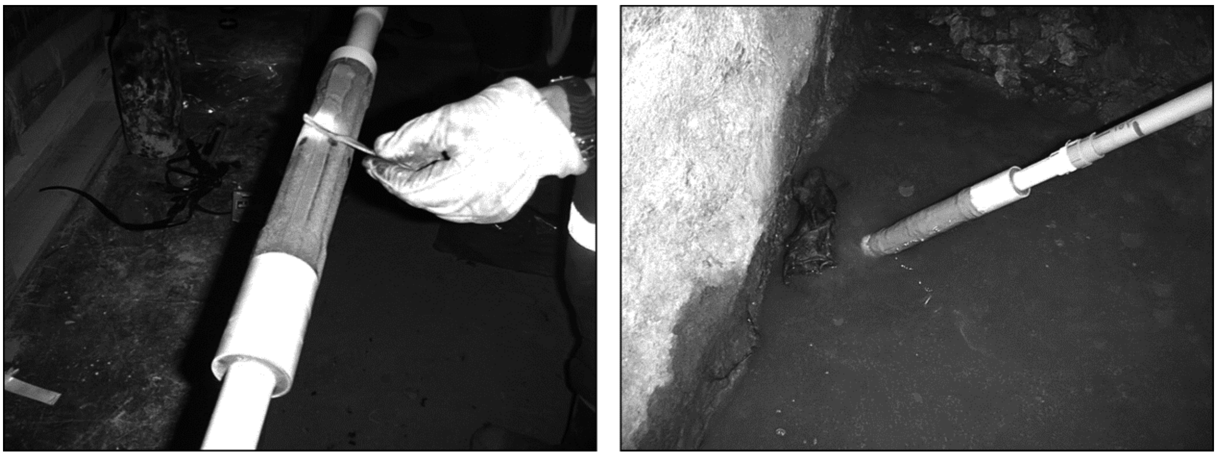

Figure 3 Photographs of installing ANZI strain cells for monitoring hydraulic fracture growth

Figure 4 shows a summary of the strain measurements observed during one of the ten hydraulic fracture treatments conducted at the sites together with the flow rate injected into the fracture and in the plot below the pressure maintained in the fracture and the stress measured normal to the fracture plotted on the same time base. The correlation between the individual strain gauges on the instrument is very close with pairs of opposite gauges responding similarly. The correlation with events associated with the hydraulic fracture treatment is also very close. As the hydraulic fracture is forming, the strains and stress normal to the fracture increase to reach a peak when injection stops (shut-in), and then gradually decrease with a step when pressure is released from the fracture (flow-back).

One interesting result of the measurements is the observation of the stress changes during the early stages of hydraulic fracture growth as the fracture tip grew past the location of the ANZI strain cells. Figure 5 shows a summary of these stress changes resolved onto a plane parallel to the plane of the hydraulic fracture. As the fracture approaches the instruments, the stress changes are tensile going consistent with the rock being stretched ahead of the fracture tip and then as the fracture tip passes beyond the instruments the stresses become compressive in response to the pressure within the hydraulic fracture.

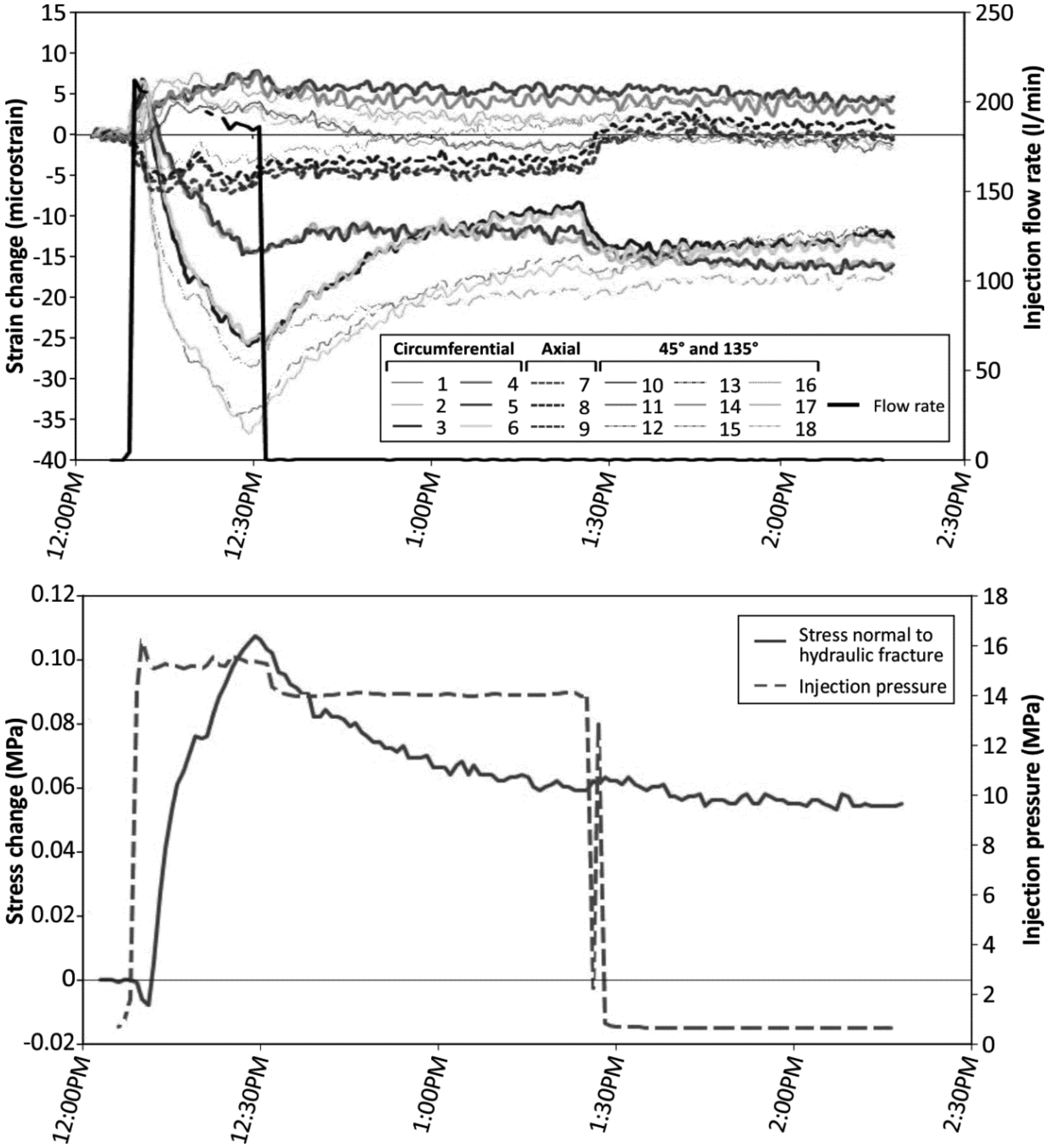

Figure 4 Strain changes measured during hydraulic fracture treatment and stress magnitude calculated normal to the fracture

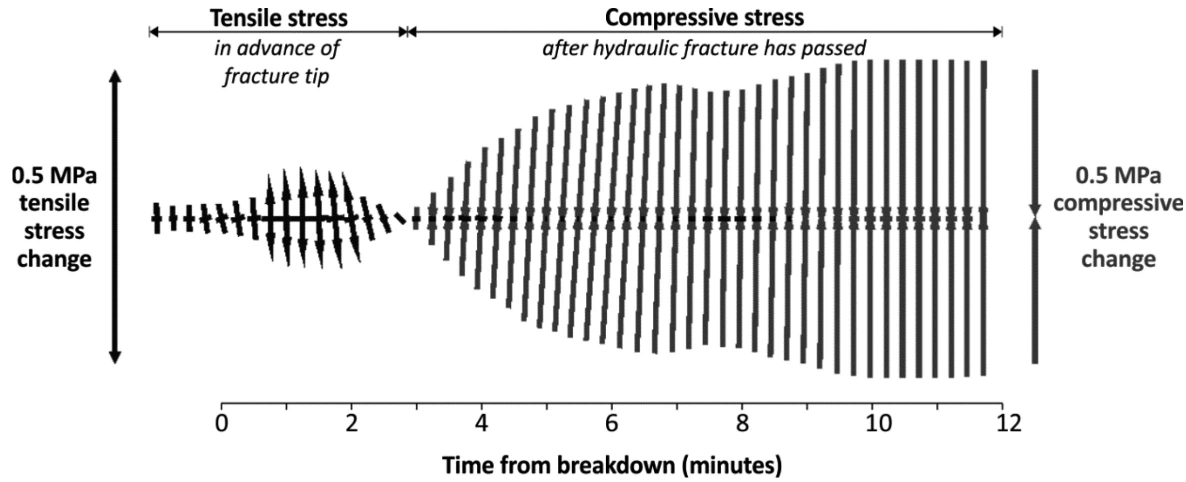

Figure 5 Stress changes measured normal to the plane of a hydraulic fracture as the fracture tip passes the instrument

In this application, the ANZI strain cells were able to monitor low level stress changes (<0.01 MPa) within the rock mass with a high level of confidence. These measurements helped define the orientation of the hydraulic fracture, the growth rate, and the peak and residual stress changes locked into the formation as a result of the hydraulic fracture treatment.

3.2 Mining-induced stress changes

Longwall mining activity is often conducted in areas where there are surface rock formations that require protection from the impacts of mining subsidence. These features include cliff lines, overhanging waterfalls, river channels, as well as archaeological heritage sites such as rock shelters and grinding groove sites. A second case study relates to longer term monitoring at a sandstone outcrop containing a large number of Aboriginal grinding grooves. Conventional surveying is typically not sensitive enough to detect the low level ground movements that precede perceptible impacts. However, stress change monitoring is several orders of magnitude more sensitive than conventional surveying and has been successfully used to provide early indication of the nature and magnitude of ground movement.

The site discussed in this section is located above a longwall panel approximately 700 m from the start of a panel and 80 m from the edge. The overburden depth to the coal seam is approximately 245 m. A double ANZI strain cell was overcored to determine the initial state of stress in the rock strata. A single monitoring cell was then installed in a vertical hole 12.9 m below the surface. This instrument was installed, and monitoring began, when the longwall had just started having retreated about 40 m.

Figure 6 shows the records of 18 independent strain changes measured during retreat of the longwall panel. The strain changes are plotted against time and against face position. Strain changes are plotted in Figure 6 rather than stress changes because changes in strain are easier to relate to the effects of mining activity that are the focus of this section. The stress changes have been calculated but these are less amenable to interpretation and have not been presented in this paper due to space constraints.

For the first 100 m of longwall retreat, the progression of goaf fracturing upward through the overburden strata is apparent in the strain change record. Once the goaf fracturing reaches the surface, and subsidence begins to occur, the rate of change of strain observed at the grinding groove site increases.

The longwall face was delayed for several weeks on two occasions due to adverse mining conditions underground. These delays are clearly evident in the strain readings plotted against time even though the instrument is located some 400 and 110 m respectively from the longwall face for the two events and some 230 m vertically above the mining horizon.

An outcome of these measurements is the observation that, for the first stoppage, the strain changes at the site are entirely a function of the geometry of the approaching longwall as evidenced by the absence of change when plotted against face position. The response is essentially elastic. When the longwall approached within approximately 150 m of the site, the strain changes no longer continued to build at the same rate as previously. The strain changes reached a plateau at this point and did not increase further. The first signs of perceptible fracturing were observed some time later, soon after the site was directly mined under. The large changes in strain observed during the period when the longwall face is 60 m past through to about 240 m past the site are consistent with the ground movements that are routinely measured by conventional subsidence monitoring techniques.

The high resolution of this type of strain monitoring provides a method to provide early warning of strain changes reaching a peak value well before perceptible impacts are observed. This approach has been successfully used at other sites.

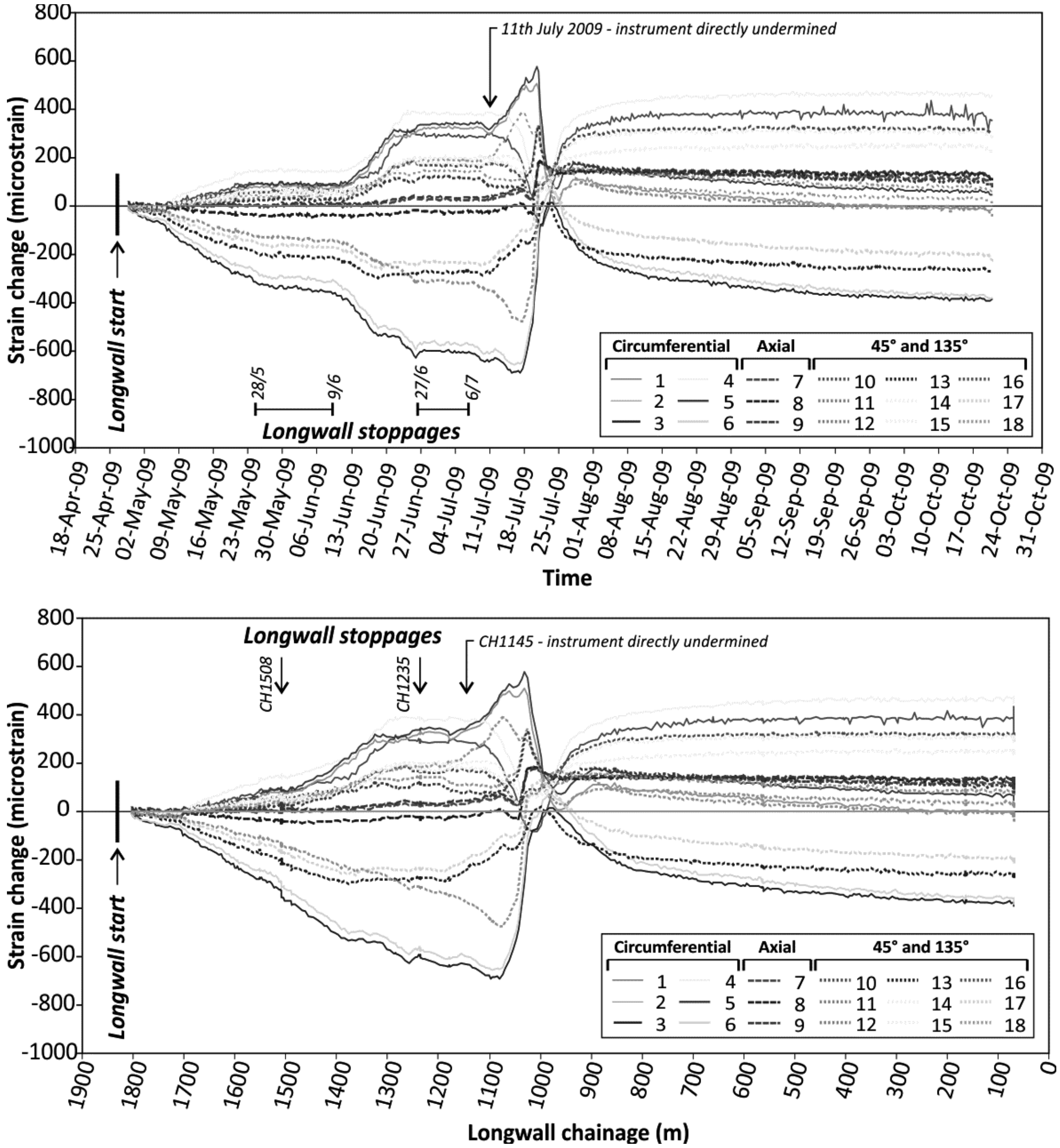

Figure 6 Strain changes measured by ANZI cell located in near surface sandstone strata above a longwall panel

3.3 Monitoring of a mining-induced step change event

A third case study relates to a site where three longwall panels were mined parallel to a prominent 48 m high sandstone cliff formation that was required to be protected from the impacts of mining subsidence. The stand-off distance of the nearest longwall panel from the cliff was the primary control to prevent impacts to the cliff, but ANZI strain cells were part of a program of monitoring used to confirm that changes in horizontal stresses were of a low enough level not to impact the cliff formations consistent with expectations. During the monitoring, a step change event, inferred to be a micro-seismic event, was captured in the monitoring at the northern monitoring site. Monitoring of this event is the focus of this case study.

Figure 7 shows a photograph of the cliff formation and Figure 8 a plan of where the ANZI monitoring sites were located between the longwall panels and the cliff at two pinch points. The instruments were installed at depths of approximately 42 m below the surface and 50 m back from the edge of the cliff. The location of the middle longwall panel is shown at the time the step change event was captured in the monitoring record. The orientation of the stress changes observed during the step change event is also shown.

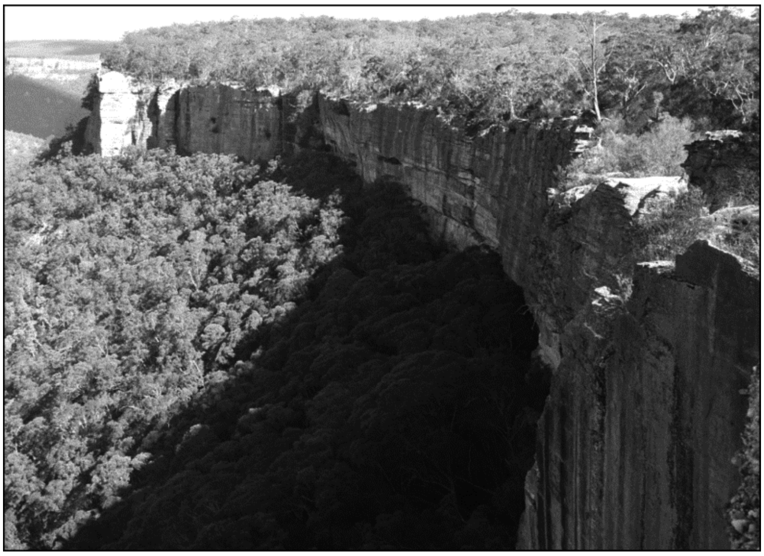

Figure 7 Photograph of major cliff formation required to be protected from mining-induced subsidence effects associated with longwall mining

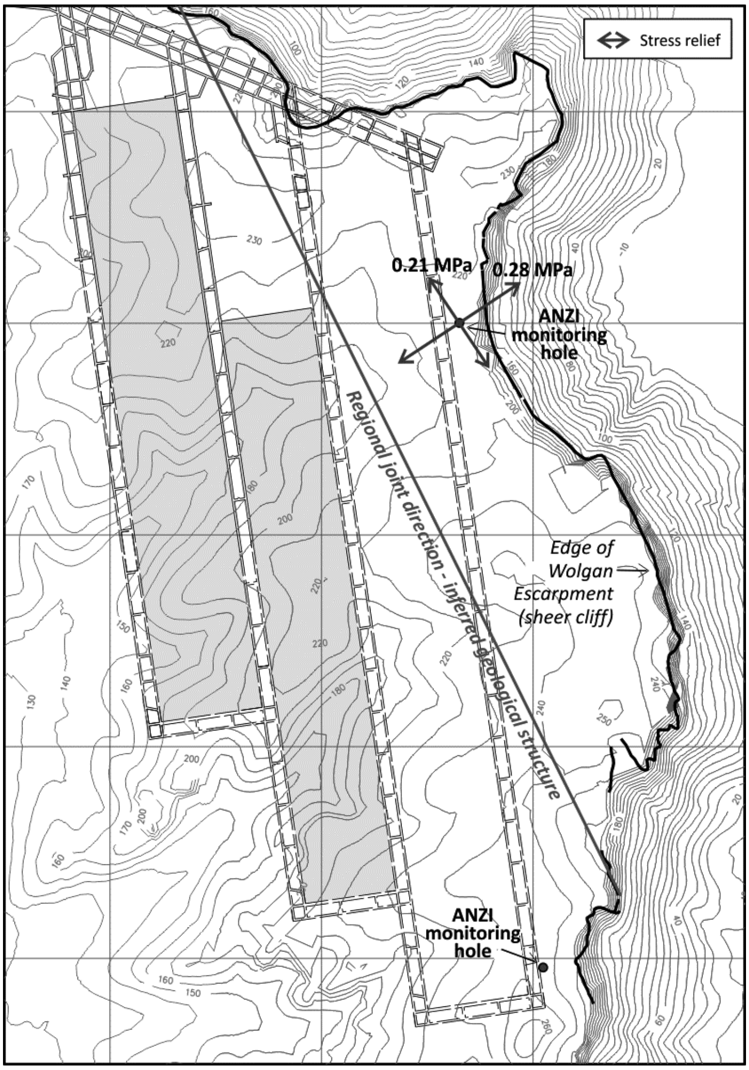

Figure 8 Plan showing the locations of ANZI monitoring cells relative to three longwall panels, the location of mining at the time of a step change event, and the orientation of the stress changes (stress relief) observed during the step change event

Strain changes were monitored at 10 hour intervals using automatic recording remote loggers installed at the top of each hole. The strain changes associated with general mining were gradual, low level, and oriented as expected. At the completion of the final longwall panel closest to the cliff, horizontal stress parallel to the cliff formation had increased by 0.78 MPa from a background of 2.3 MPa measured prior to mining and horizontal stress perpendicular to the cliff had increased by 0.11 MPa from a background of close to 0 MPa measured prior to mining. On 1 December 2010 in the interval between 0430 h and 1430 h, a step change occurred in the recorded strains as shown in Figure 9. The strain changes are shown here to illustrate the nature of the change. The stress changes are shown in Figure 8. The general monitoring resolution of the long term remote monitoring system is of the order of ±5 microstrain. The internal correlation between independent strain gauges on the instrument for this event is 0.994 on 12 degrees of freedom and indicates the very highest confidence can be placed in the measurement as an indication of stress change at the point of measurement.

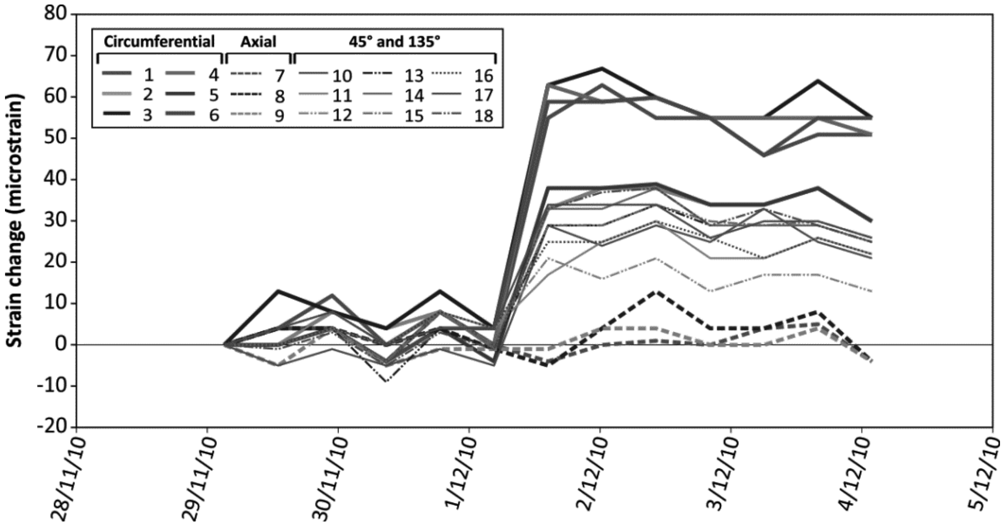

Figure 9 Strain changes observed before and after the step change event

The event caused a sudden release in horizontal stress of 0.28 MPa perpendicular to the cliff face, a release of 0.21 MPa parallel to the cliff face, and an indicated release in vertical stress of 0.18 MPa.

This event coincided with the second of the three longwall panels mining up to and through a regionally oriented vertical geological joint structure that also passes close to the monitoring site. The magnitude of this change in stress is significant in the context of the changes observed during the later stages of mining that were otherwise gradual and generally compressive in nature. The measurement has been interpreted as indicating slip on a bedding plane that became freed up when the longwall passed through a vertical joint set.

The observation of this event, the high confidence that can be placed in the stress changes observed, the relatively large magnitude of the stress changes, and the coincidence with mining intersecting a geological structure indicate a significantly different mechanism to the gradually increasing stresses observed at other times during the monitoring.

4 Conclusion

The ANZI strain cell has been found to have characteristics that can provide high confidence, three-dimensional stress change measurements in a range of applications remote from underground openings and deep below the surface.

The various operational features and analytical simplicities have enabled stress changes to be successfully monitored in a wide range of rock types and applications over the last three decades. Examples of stress change monitoring are presented to show the way that the instrument has been deployed and how the results allow the development of understanding of rock behaviour on both a large scale across entire longwall panels and at a somewhat smaller scale around the tip of a hydraulic fracture.

The high levels of redundancy in both the number of strain gauges and the measurement technique provide a measure of the confidence that can be placed in each result.

The capability to deploy three-dimensional stress change monitoring ANZI strain cells to distances of up to several hundred metres from the surface or underground openings enables multiple instruments to be located into areas of interest that may be remote from access points.

The capability to record strain changes in remote locations over extended periods of time enables the monitoring of longer term, large scale strain changes for subsidence impact assessment and general understanding of the ground behaviour. Strain changes associated with longwall mining have been monitored for significant distances well before they become detectable by conventional subsidence monitoring techniques.

The capability to record strain changes at high frequency offers the potential to monitor microseismic events in stress space with improved understanding of the effects that such events have on the rock strata.

Acknowledgement

The development of the ANZI strain cell has benefited from the support and ideas of many people, including many of the pioneers of in situ stress measurement in Australia and New Zealand. The development has also been strongly supported by the commercial and research projects funded by the underground coal mining industry, particularly in Australia. The authors wish to acknowledge the contributions of both individuals and the industry as a whole to the endeavour of developing the ANZI cell to provide high confidence measurements of three-dimensional measurements of stress changes in rock in locations remote from easy access.

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