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FLUID PRESSURE MONITORING IN DEEP CEMENT GROUTED BOREHOLES

Bruce Neels and Ian Gray

ABSTRACT: The installation of pressure transducers in deep boreholes is a key feature of determining the effectiveness of gas drainage and the effect of mining on the groundwater regime. This paper covers the work undertaken to ensure reliability of data obtained from deep formation monitoring boreholes for both coal seam gas and groundwater. Cementing technology has enabled strings of transducers to be installed at greater depths with reliable zonal isolation between close sensing points. However the behaviour of grout at depth can be problematic with the effect of filtration, consolidation, skin and dehydration of the grout rendering the installation only partially effective. A review of cementing grouts and additives was undertaken and mix designs developed, to suit the requirements of deep borehole monitoring. Techniques were developed to mitigate the vicissitudes of grout and ensure both zonal isolation and connectivity of the transducer to the formation. The paper also reviews the automated data acquisition systems used for monitoring installations.

INTRODUCTION

It is extremely important for many purposes to be able to monitor the fluid pressure existing in the ground. These range from the effect that fluid has on effective stress and hence failure of a soil or rock mass, the movement of groundwater, and the production or drainage of hydrocarbon fluids.

In the coal mining context all of these aspects are important. Failure of coals, and in particular outbursts and the energy release associated with them, are a direct function of the sorption pressure of the gas contained within the coal. The effectiveness of the drainage of water, methane and carbon dioxide is best determined by the use of long term pressure monitoring. The use of such pressure monitoring has the advantage over spot gas content measurement in that it provides a potentially continuous source of information on the drainage process rather than a single measurement. It is very cost effective as it does not require a hole to be re-drilled to obtain a coal sample for gas content measurement. Indeed, pressure measurement may be considered to be a more useful measurement for all these purposes than gas content alone, provided that the relationships between reservoir pressure, sorption pressure and gas content are understood.

The installation of pressure monitoring transducers for this purpose however needs to be undertaken carefully, with techniques to ensure that the correct values of fluid pressure are being measured, and with an adequate rate of response to pressure changes. This is particularly important where any transient testing is being used to determine reservoir properties.

HISTORY OF INSTALLATION PRACTICES

Transducers

The history of ground fluid pressure monitoring goes back to the measurement of the water level in hand dug wells. It was followed by the use of open stand pipe piezometers. Initially these were in connection with the entire formation through which they passed, and therefore they provided unreliable estimates where multiple heads existed. Later permeable tips were fitted to the open impervious tube. These were usually placed in a gravel or sand pack sealed above by bentonite, and grouted in place. In all cases these open tube devices could be monitored by hand dipping or later by the use of bubbler systems, where the pressure of the compressed air causing bubbles to be emitted from a tube was measured.

Point pressure monitoring without standpipes was developed for use in fill dams and embankments. Here installation was achieved between layers of compacted fill. Because electronic pressure transducers were not reliable enough in the long term, the transducers developed used compressed air to open an elastomeric valve to return air flow when the pressure reached that of the groundwater.

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These required a twin tube system and accurate gauges on the surface. These were inherently very accurate systems, some of which are still in use after many decades.

Because of the drift characteristics of early strain gauge based Wheatstone bridge type transducers, and more importantly the lack of stable electronics to get the signal from the bridge up a cable to the surface, an alternative was developed. This alternative was the vibrating wire pressure transducer. It has a diaphragm which is in contact with the fluid which is to have its pressure measured. Attached to the diaphragm is a steel wire which is stretched between it and a fixed end. Changing pressure alters the tension in the steel wire. To produce a measurement, the wire is vibrated by the use of a swept frequency series of electrical pulses through coils which are wrapped around a magnet and cause the wire to vibrate. This vibration settles down to become the natural harmonic of the wire under the load induced by wire pre-tension and fluid pressure. The same coils that were used to excite the wire pick up the signal and enable it to be transmitted up the connecting wire. Such transducers may be made to be essentially drift proof. The digital nature of the signal (a frequency) means that the signal does not degrade until it becomes so faint that electronics can no longer isolate it from background noise. The reduction in signal comes with time after the swept frequency excitation, and with increased cable length and deterioration of its properties. Signal deterioration comes with extended length of cable and is caused by capacitance and resistance. It may also come from cable deterioration leading to current leakage between cables.

In the last two decades electronics have improved dramatically to reduce drift, and bridge type transducers can now be used to monitor fluid pressures. The limitation is how the signal is transmitted from the borehole. The measurement of voltage directly from a bridge or even from an amplified bridge is subject to the behaviour of the cable. This also applies to current loop transducers where leakage between the conductors will lead to an incorrect reading. The only reliable way in which to get data from such transducers is to digitise it and send the digital signal to the surface. Digital signals can take many forms such as a frequency or pulse width output. More usually it involves a standard form of data transmission such as an RS485 signal.

In recent times the most precise forms of transducer are considered to be the resonant quartz devices. These are incorporated into an electronic circuit and change their natural frequency of vibration as a function of the pressure applied to them. They are however expensive and the additional accuracy they afford is often not warranted.

All modern pressure transducers have diaphragms that move very little over their pressure range. This has important consequences for installations in low permeability grouts or rocks as very little fluid volume is required to actuate them. This is in contrast to an open standpipe which has a high volumetric requirement to fill the pipe.

Borehole installations

The use of the standpipe type piezometer has obvious limitations not least of which is that it is unsuitable for formations in which the fluid is a gas, as this would escape unless sealed in by a packer. It is also difficult to install multiple standpipes in a single hole due to space restrictions. This applies particularly where each standpipe tip or pressure transducer has to have placed around it a porous sand or gravel pack which is then isolated by bentonite and grout.

Early work by Penman (1961) demonstrated that the development of gauges utilising low vibrating wire technology enabled direct placement in clay soils or in bentonite plugs within a well. Penman demonstrated, in accordance with sound soil mechanics theory, that clay will respond to a change in stress by an equivalent change in pore pressure. This work was further developed by Vaughan (1969) and McKenna (1995), in quantifying the relationship and requirements between the borehole backfill using bentonite grouts and the surrounding ground, and in doing so established the suitability of the new sensor technology for ground water monitoring.

Mikkelsen and Green (2003) demonstrated the use of Portland cement to stabilise bentonite grouts and improve placement. They also demonstrated the effectiveness of grout for zonal isolation, and quantified permeability and transducer response times for various grout mixes. This work was for shallow wells used for monitoring soil. It should be noted that the early work by McKenna (1995) used cement to stabilise bentonite slurries, and later bentonite was used as a viscosifier to stabilise cement slurries. The practice of cementing multiple pressure gauges in a cement grouted borehole grew, and was taken up by the oil and gas industries, with transducers attached to the outside of casing which would be cemented into a well (borehole). In the coal seam gas industry a number of transducer installations have been made in specific monitoring wells. Unfortunately this rush to install single or multiple transducers in cement grouted boreholes has not been without its failures. As suppliers of equipment (transducers and data acquisition systems) Sigra Pty Ltd has been in a good position to gain feedback on installation successes and failures. This information has assisted in development of systems for reliable installation.

The problems observed by Sigra in transducer installation include:

1) Improper location of transducers. This particularly applies to the cases where transducers are connected to polyethylene pipes which are dimensionally unstable and tend to float in water, and do so to a greater degree when cement grout is pumped into the borehole.
2) Damage to the transducer string or failure to reach the correct depth due to collapse within the borehole.
3) Gas movement to surface within the cable sheath.
4) The use of high water content cement grouts, without correct admixtures, which then exhibit excessive separation within the borehole (bleed). These are usually used as they are easy to pump.
5) The use of bentonite, which raises the cement grout viscosity, causing pumping difficulties at suitable mixtures.
6) Excessive heat generation on cement grout hydration causing failure of the transducer or cable.
7) Channelling of the cement grout caused by gas bleed or water movement, leading to interconnection of zones.
8) Loss of water from cement grout into the formation causing dense, ultra-low permeability zones within it, thus impeding the transducer's hydraulic connection to the zone where pressure is to be monitored.
9) The occurrence of hydrofracturing of the formation caused by the pressure of the cement grout within the borehole exceeding the minimum stress of the rock. This is primarily a function of the density of the grout and the depth of the hole.
10) Excessive cement grout pressure causing a shift in transducer calibration.

Some of these problems were observed closely, some were discovered by experience, and others were obtained anecdotally. The exact number of failures in installation is not known but it is estimated that most installations conducted in the coal seam gas and mining industry are less than ideal and therefore unreliable. For these reasons special installation and grouting systems for transducer installation have been developed.

Cement grout behaviour

Cement grouts are a mixture of water and Portland cement with various admixtures so that they develop the correct properties. The process of setting involves the hydration of the cement and the development of bonds between the hydrated particles. In a cement water paste with just enough water for hydration the void volume left after setting will be approximately 18% (Neville and Brooks, 1987). Excess water will lead to the filling of this space with water. As additional water is added the void space will increase. However additional dilution leads to a dispersed mixture of particles, and in water which will ultimately settle in the borehole, either before or late in the hydration process. If the latter occurs the cement will be weak. In both cases the density of cement grout will be greater in the lower levels of the hole as will its strength, while its permeability will be lower at the base of the hole.

In an endeavour to suspend the cement particles in the water and prevent this effect it is necessary to increase the viscosity of the mixture. Increasing its viscosity however causes problems as the pressure losses associated with pumping the cement grout down a pipe into the hole may increase significantly. There is thus a need for a shear thinning cement grout so that it is pumpable.

Cement grout columns in boreholes during the fluid state suffer from sedimentation (consolidation) of the cement where the coarser grains settle more quickly. This effect may be improved by reducing the cement particle size by high energy mixing. However this is offset in part by particle agglomeration after mixing and pumping. The grout also undergoes a change of state in its transition from a fluid, which provides hydrostatic pressure to the borehole, to a solid which has inherent structural strength. During this transition the grout becomes unstable and is susceptible to gas ingress into the internal capillary pores of the cement paste formed by the chemical hydration of the cement. This is exacerbated by the effects of consolidation and its resulting pockets of fluid. Bleed pathways can be linked together by the seam gas to form channels which will migrate naturally to these void spaces. This can affect the isolation of monitoring zones or in the worst cases even create pathways to the surface. Prevention of consolidation, with its resulting fluid pockets, is critical where a seal is required. The addition of colloidal (very fine) additives to the mix is designed to mitigate this phenomenon by maintaining the mix in a colloidal state to offset the segregation of cement grains. Gas channelling is thus resisted by the interlocking grains of cement in its fluid state until initial set occurs. Cement grouts are also susceptible to pressure filtration. A cement grout will exhibit filtration behaviour when it is being forced through any orifice be it a constriction in the pump line or a cleat in coal. This means that the thicker material remains behind and a more watery mix is passed.

In extreme cases, this will result in the formation of a skin of cement around the periphery of the borehole. This leaves behind a grout with insufficient fluid for full hydration. The process is then reversed as formation pore water is drawn back into the dehydrated zone to reach a chemical equilibrium and hydrate the remaining cement. In extreme cases this reversal can take several months or years to stabilise. If this has occurred at a transducer location the result is a zone of very low permeability around the sensor with the transducer exhibiting long stabilisation and slow response times. This effect is shown in Figure 1. The long term pressures of the aquifer being monitored show complete stabilisation, however this took three months.

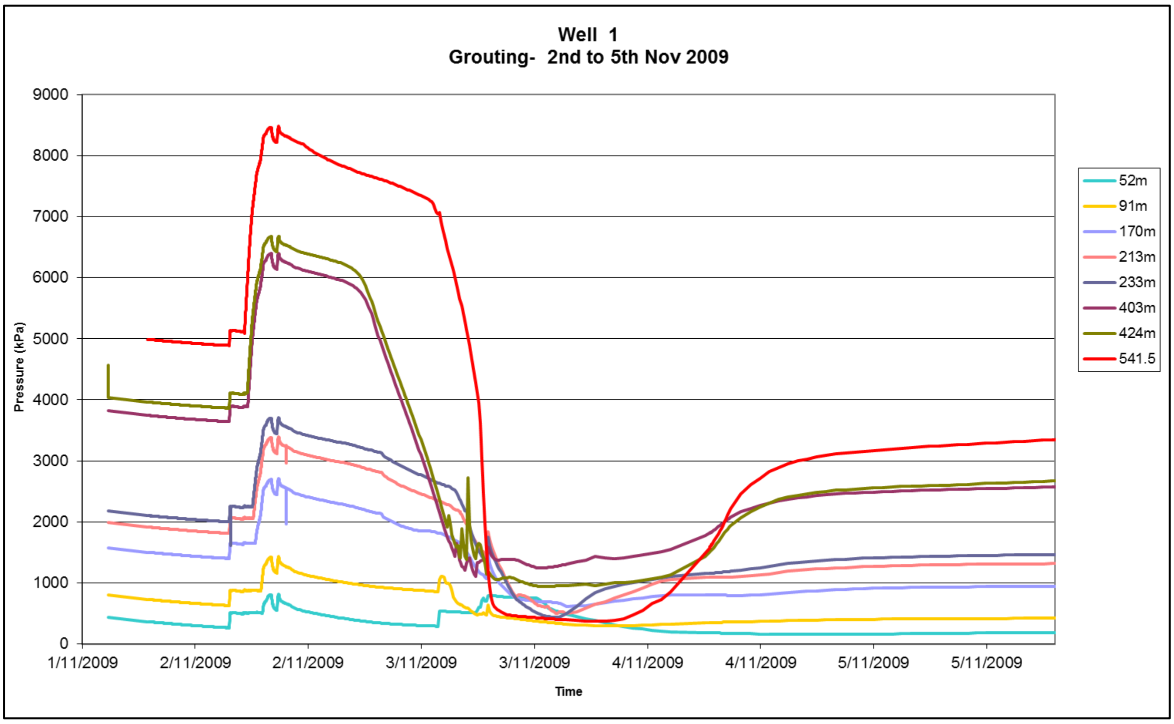

Figure 1 - Piezometric head plots showing hydrostatic head, grout head and post grouting change of state of grout, dehydration with slow recovery on deeper transducers

To minimise filtration, the cement grout needs to exhibit cohesion. Cohesion is essentially the shear stress of the cement grout at a very low shear rate.

The fluid grout is also susceptible to washout from aquifers. The grout is therefore also required to exhibit filtration to plug the washout zone. This characteristic is contrary to that required to minimise filtration behaviour.

It can be seen that grout for transducer monitoring wells, requires a complex set of engineering properties in both the fluid and set phase of the mix. It must have the correct rheology to be pump-able without segregation, remain in a suspension in its fluid state, be dense to displace drilling fluids and isolate zones, remain porous for permeability when set, resist filtration to prevent dehydration, resist consolidation and formation of bleed pockets, remain cohesive to prevent gas migration, able to plug up washout zones and have a predictable set control for the given *in situ* conditions.

After extensive grout testing a suitable thixotropic (shear thinning) mix with set control which controlled most of these requirements was developed. However grout dehydration was the one aspect that could not be eliminated due to the unpredictability of the interaction of the grout with the formation. This was determined to be critical to the relevance of the data and focus shifted to eliminate this uncertainty from the transducer installation.

NEW INSTALLATION TECHNIQUES

When making a new installation the following matters should be considered**:**

1) Improper location of transducers. The use of steel tubing enables the transducer string to be located precisely. Where coal seams exist that may need to be mined in the future, the steel is substituted by fibreglass tube.
2) Damage to the transducer string or failure to reach the correct depth due to borehole collapse may be prevented by installing the tubing and transducer string through an HRQ drill string and then withdrawing the drill string over the top of the transducers.
3) Gas movement to surface within the cable sheath. This may be readily prevented by the use of gel filled cable. Alternatives are the use of geophysical cable or Tubing Encapsulated Cable (TEC). The cost of the latter option is seldom justified.
4) A correct cement grout mixture requires an adequately low density, good pumping characteristics, and will remain in suspension in the borehole until it sets. This cement has a low heat of hydration to avoid overheating the transducers.
5) Channelling of the cement grout, caused by gas bleed or water movement and leading to interconnection of zones, is prevented by preventing segregation from the mix, maintaining a colloid in the borehole.
6) Loss of water from cement grout, and mitigating dehydration and filtration effects into the formation causing dense, ultra-low permeability zones within it. This problem is overcome by the use of a positive means to connect the transducer to the formation that involves water injection into the partially set cement grout around the transducer. The cement grout then sets and the connection between the transducer may be tested by injecting further water into the zone and observing the decay of pressure. The system for undertaking this is shown in Figure 2 and the results of its operation are shown in Figure 3.
7) The occurrence of hydrofracturing of the formation. This is caused by the pressure of the cement grout within the borehole exceeding the minimum stress of the rock and excessive cement grout pressure causing a shift in transducer calibration. These problems must be overcome by ensuring that the hydrostatic pressure of the cement grout mixture remains within adequately low limits. This gets to be more problematic with deeper holes. The solutions are to keep the density of the cement grout as low as possible, and the adoption of staged cement grouting operations. The cement grout's density can only be modified to a certain degree by the use of non-filling additives, and beyond this the use of lightweight filling additives such as hollow glass beads (cenospheres) needs to be adopted. Stage grouting involves cement grouting a lower portion of the hole, waiting for that to gain some strength and then cement grouting above this level. Figure 2 shows the inclusion of a stage cementing valve in a cementing pipe.

Figure 2 shows the fluid line to the transducer location. This is used to pressurise the grout after its initial set. This achieves a pathway from the filter tip of the transducer to the formation by fracturing the weak grout. This pathway is permanent and can be checked by re-pressurisation if required. The response of the transducer will not be affected by any filtration or dehydration of the grout. The cement displacement technique was trialled and the results are shown in Figure 3. Pressurisation of the fluid lines was carried out the morning following grouting. The fracture pressure spike and fall off is clearly seen.

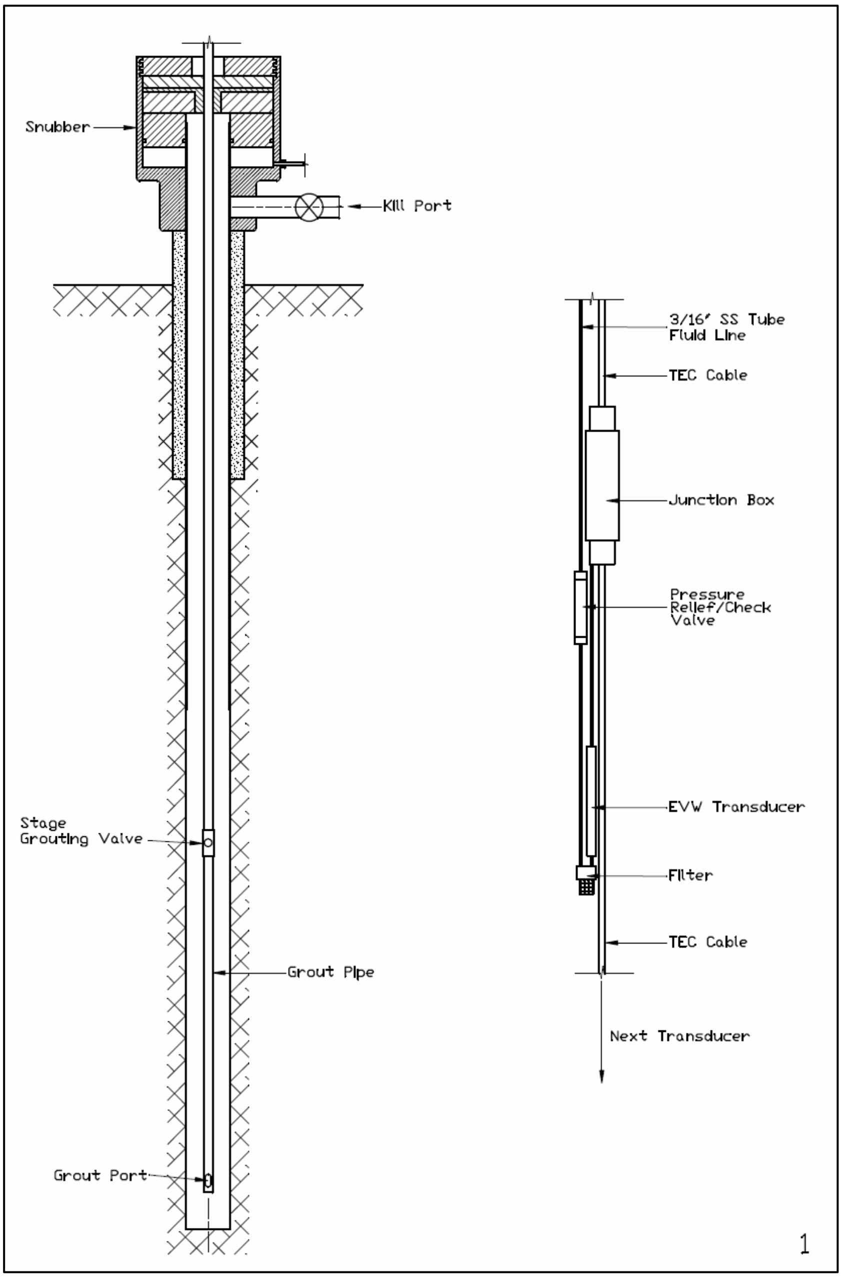

Figure 2 - Stage grouted cemented transducer installation with details of transducer system for cement displacement on right

THE MONITORING SYSTEM

Monitoring pressure transducers, generally of the vibrating wire type, are connected to a data logger. The frequency of monitoring needs to be tailored to suit its intended purpose and the predicted speed at which changes may occur. The frequency may vary, from recording daily for monitoring a stable aquifer, to seconds for transient testing. To reduce the amount of data recorded it is desirable to set the data acquisition system to measure frequently but record on change with a minimum recording rate (say once per day) to ensure that the system itself can be monitored and to confirm it is working.

DATA ACQUISITION

Sigra provides its own data acquisition equipment. This is based on a building block which will read multiple kinds of sensor and communicate with other devices through a variety of systems including cable, radio and the cell phone network. These devices have the ability to record on change, send messages when instructed or turn devices such as pumps, on and off.

These units can communicate with each other in a mesh or array. This array is frequently connected to a master unit that communicates with the cell phone network. This automated delivery of data can be further enhanced with access via a secure web based server, with data in its raw form and/or managed with graphics interface. The system can also be used with manual download of data by cable or radio. The installed units are inherently weatherproof in instrumentation cabinets with solar cells, modems and rechargeable batteries contained in the one box for security. Atypical installation is shown in Figure 4.

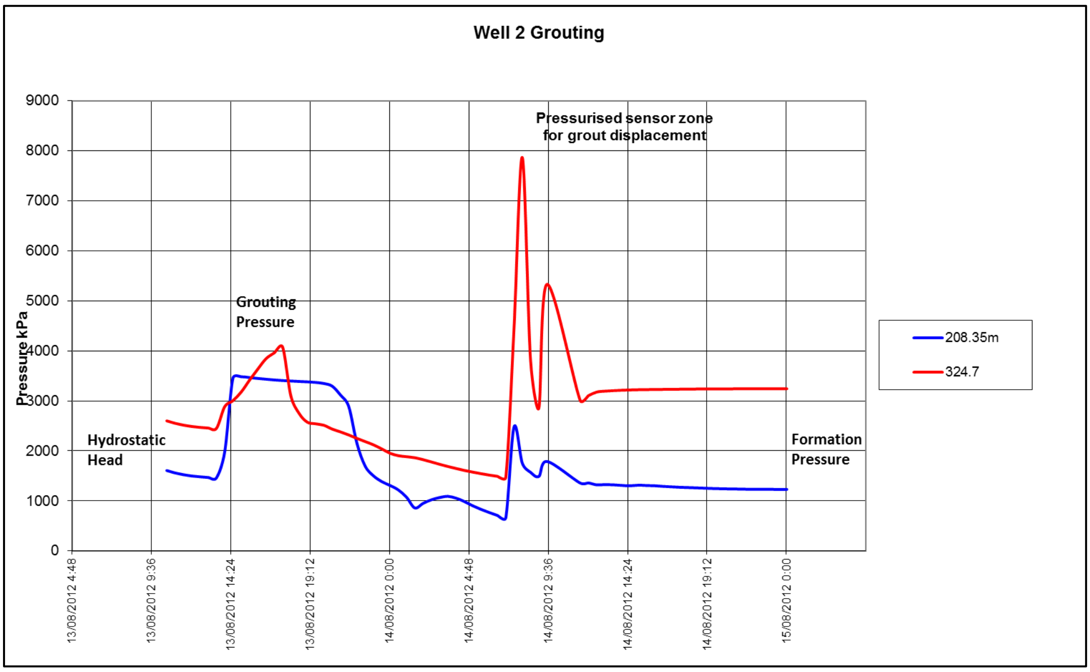

Figure 3 - Plot of post grouting displacement of cement to achieve connectivity to the formation

Figure 4 - Data acquisition system with logger box and modem

CONCLUSIONS

A review of pressure sensing hardware and the engineering practice for installation and cementing of transducers in relatively shallow ground water monitoring wells was carried out. This revealed the suitability of both vibrating wire transducer technology and the use of cement grouts for monitoring soil formations. However, it was found that this success did not readily transfer across to deeper wells or for monitoring coal seams. Poor installation and cementing techniques resulted in suspect or no data.

Research into installation methodologies was undertaken and extended to understand both the chemistry and rheology of cement grout. A grout was developed and tested to address the criteria for cementing transducers, namely pumpability, grout consolidation, and prevention of gas migration and channelling from coal seams. This technology had been applied to coal seam gas monitoring wells with some success, although evidence was found that grout dehydration could occur, resulting in long recovery times for transducer response.

The mechanism within grout columns such as consolidation, filtration, dehydration and gas channelling, which would result in poor transducer response, was revealed through the review of the chemistry of hydration of Portland cement in boreholes. It was found by close examination of current transducer data that the critical problem of grout dehydration needed to be addressed.

Laboratory testing was carried out on a range of mix designs and additives. A thixotropic grout mix design performed best to address most of the engineering requirements, but transducer response remained at the mercy of the fickle formation / grout interaction. A method for providing a direct connection to the seam at the transducer location was developed and tested in the field. This method effectively solves the problem of grout dehydration affecting the transducer response. For deeper or highly gaseous wells, staged cement grouting techniques are required to prevent hydraulic fracturing of the formation.

Technological developments in electronic data logging can now provide real time data acquisition from remote sites using either mobile dial up or radio telemetry. This ensures the user is only an iPhone, iPad or web-link away from the current data download and its integrated graphics interface. Some of the installation techniques described in this paper are the subject of patent applications.

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