Practical Application and Design Considerations for Fully Grouted Vibrating Wire Piezometers in Mine Water Investigations.

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Abstract Fully grouted vibrating wire piezometer sensors have proven to be particularly useful in mine water investigations where the use of traditional standpipe piezometers may have practical drawbacks, such as low conductivity of the formations, depth, borehole diameter and inclination. Design considerations are presented for implementation of the method to many applications in mine water investigations.

Keywords Fully grouted vibrating wire piezometers, design considerations, piezometeric head

Introduction

In-situ measurement of groundwater levels and piezometric pressures is an important part of many mine water investigations. In order to collect accurate and representative data, it is essential that the design of the monitoring instrumentation is individually adjusted to the actual site conditions. The traditional standpipe groundwater monitoring well design has the disadvantage that a finite volume of water must flow into or out of the borehole to register a change in water level. This creates a time lag between the piezometric pressure in the strata and the monitoring well. In strata of low hydraulic conductivity the equilibration rate may be too slow to provide useful information within a reasonable time.

Since the 1980s the standpipe piezometers have been replaced for some applications with vibrating wire pressure (VWP) sensors. These sensors respond to groundwater pressure changes, at the sensor location. For early applications VWP design included a sand pack around the sensor, similar to the conventional standpipe design. However, in the last two decades the "fully grouted" installation method has been developed, where multiple VWP sensors are set in a low permeability grout within the borehole, without a sand pack.

Considerable experience in installation and monitoring has been gained with this type of instrumentation in the mining industry since this methodology was first developed, but some questions remain over the installation requirements and technical limitations.

This paper provides a review of the general installation methodology, and the conditions when this type of instrumentation can offer advantages over the traditional design. A project case study is presented to describe challenges associated with the installation of the fully grouted piezometers. This discussion is intended to be useful for mine water practitioners planning groundwater investigations in complex hydrogeological conditions, particularly where strata of low hydraulic conductivity are present.

Development of Rapid Response Piezometer Methods

The traditional form of groundwater monitoring piezometer comprises an open tube (termed a standpipe) with a perforated section to allow water to enter the well at the depths of interest (Fig. 1a). These piezometers in strata of moderate to low permeability will respond slowly to changes in pore water pressure, because a finite volume of water must flow into or out of the piezometer to register the change in pressure. This leads to a 'time lag' between changes in water pressure in the strata and the registering of that change in the piezometer. The time lag is greater in strata of lower permeability, and is greater for piezometers using larger diameter tubing, where larger volume flows are needed to register pressure changes.

To avoid the time lag problem various 'rapid response' piezometer instruments were developed. In the 1960s hydraulic and pneumatic piezometers were developed, where the movement of small volumes of fluid (water or air, respectively) in closed systems inside the instrument was used to balance external water pressure, allowing external groundwater pressure to be determined. Unfortunately these instruments were difficult to set up correctly and intolerant of extreme field temperatures.

Since the 1980s and 1990s the vibrating wire pressure transducer (often known as a vibrating wire piezometer or VWP) is widely used for monitoring of hydraulic pressures and water levels. These instruments contain a metal diaphragm in hydraulic connection with the groundwater. Inside the instrument a taut wire is stretched between the diaphragm and a stable datum. The wire is activated by passing a controlled frequency electrical pulse along it. The wire resonates at a frequency related to its tension which can be related to the deflection of the diaphragm, and the water pressure on the diaphragm.

When VWP instruments were originally applied for field use, each instrument was typically installed in a discrete filter sand response zone in a similar way to a standpipe piezometer (Fig. 1b). This approach is effective but difficult, and time consuming. In the 1990s an alternative approach, known as the 'fully

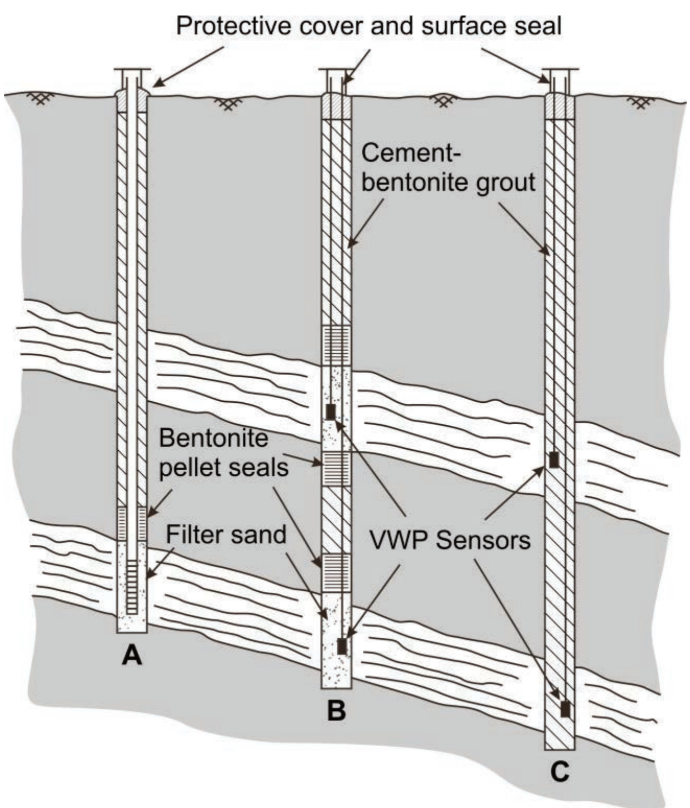

Fig. 1 *Monitoring Wells Designs: (a) Standpipe Piezometer; (b) VWP Sensor in Borehole with Response Zone; (c) VWP Sensor in Fully Grouted Borehole.*

grouted method' (McKenna 1995) was developed where the VWP instruments are installed in the borehole surrounded by cement-bentonite grout (Fig. 1c). This method is possible because VWP instruments require only a very small volume equalisation (10^{-6} to 10^{-7} m^3) to respond to water pressure changes, and an appropriate cement-bentonite grout is able to transmit the pressure change over the short distance which separates the VWP instrument from the ground around the borehole.

Guidance for Installation Requirements and Technical Limitations

VWP sensors can be installed within boreholes in both soil and rock and therefore suit all applications where pore pressure monitoring is desired. The sensors register the pore pressure at the location of the VWP diaphragm. This creates a specific point at which the pore pressure can be monitored, rather than monitoring the average pore pressure across a screened interval within a standpipe piezometer or sensor installed within a sand pocket. This allows the design of very specific response zones, for example to target discrete fractured zones in fractured rock systems, or in complex soil and rock lithologies where pore pressures are expected to vary across short distances.

Given the ability to target specific locations for pore pressure measurements, the greatest benefit from sensor placement comes when a good understanding of the lithology has been developed. For this reason it is most beneficial in ground investigations to install the sensors within a cored borehole where the recovered core can be used to identify the specific target lithologies for sensor installation, or where reliable geophysics has been used. This is particularly true when VWPs are used in ground investigations where the exact nature of the target materials may be unknown prior to the sensor installation as opposed to dam and embankment applications.

Field and laboratory tests of hydrodynamic response times of VWP sensors in fully grouted installation have been shown to be very quick. Contreras *et al.* (2012) report responses of less than two minutes in a 100 mm diameter borehole backfilled with a water:cement:bentonite grout (1:2.5:0.3); Mickelson and Green (2003) present similar results.

Suitable Applications for Grouted VWP Sensors

Given the nature of VWP sensors, fully grouted methods are best suited for use in the following applications:

- monitoring within low hydraulic conductivity formations where a short hydrodynamic time lag is desired;
- monitoring at locations that could be affected by surface freezing conditions (Contreras *et al.* 2012), provided the sensors are installed below the ground freezing depth;
- deep, inclined, or horizontal installations in which a discrete sand pack interval might be difficult to place;
- artesian or flowing borehole conditions in which discrete sand pack intervals and bentonite pellets might be difficult to place; and
- small diameter boreholes where multiple monitoring points are desired. Multiple sensors can be placed within a single borehole where space might limit the number and amount of standpipe piezometers which can be installed within a single borehole.

There is a practical limit on the number of sensors which can be installed within a single borehole. This is generally much greater than the number of standpipe piezometers, however the number of practicable installations depends on the borehole and sensor diameter, and support design used to place the sensors in the borehole. It is the authors' experience that in general installations of three to four sensors in 75.8 mm (NQ) diameter boreholes, and four to five sensors in 96 mm (HQ) diameter boreholes are practicable.

Overview of Installation Methods

The VWP sensors are positioned downhole attached to cables which run from the sensor to surface where they can either be connected to a datalogger or can be read with a portable unit. Fully grouted VWP sensor installation procedures are described in detail by Mikkelsen and Green (2003). The sensors are often installed attached to a support structure such as a sacrificial tremie pipe which supports the weight of the installation, and allows for placement of the grout from the bottom of the hole up. If a grout plant is not available, the grout is prepared in a drum or mud tank and mixed either by separate mixer or by circulating the mixture with the driller's pump using a suction hose and jet nozzle. Once suitably mixed, the grout is pumped in place through the tremie pipe/hose filling the borehole to surface and allowed to cure. A suitable surface housing should be installed to protect the cables and/or dataloggers at surface.

VWP Sensor Installation Design Considerations

Key factors in the design of installations of fully grouted VWP sensors include:

1. Choosing the appropriate VWP sensors;
2. Structural support of the installation;
3. Design of the grout mixture;
4. Placement of the grout;
5. Additional Installation challenges; and
6. Installation costs.

Choosing the Appropriate VWP Sensors

Sensors should be chosen based on the range of pressure that the sensor is expected to measure when installed, with sufficient range to withstand the additional pressure applied during grouting. When the expected pressure is unknown it can be approximated based on the installation depth. As with most commercially available pressure transducers, the greater the sensor range the greater the potential systematic error in the readings. Therefore for the most accurate readings, sensors should be chosen to have the lowest appropriate range that can still withstand the pressure applied during grouting.

The nature of VWP sensors allows for the length of cable to be adjusted without any degradation of the signal. Most manufacturers will supply easy to use splice kits which can be used to extend the cable length, and similarly the cables can be easily cut and shortened. This means that materials can be procured in advance of the investigation based on expected installation depths and adjusted based on conditions encountered.

Structural Support of the WVP Sensor String

VWP sensors can be installed by hanging them within a borehole or by guiding them into place using a support structure such as a driller's wireline or a tremie-pipe/hose. The purpose of the support structure is for depth control as well as support of the installation to avoid cable stretch or damage. During installation, care must be taken not to damage the cables. Installation on the outside of a tremie-pipe is useful in inclined or horizontal boreholes where gravity alone cannot be used to place the sensors. The tremie pipe can be left in place for the dual purpose of sensor support, and then be used to deliver the grout from the base of the borehole to surface.

The use of sacrificial tremie pipe may not be appropriate for use in soft ground where a large amount of vertical compression is expected. Contreras *et al.* (2012) has shown that the behavior of the fully-grouted installation using a sacrificial grout pipe in soft ground is adequate when the amount of vertical compression expected is less than 15 %.

Design of the Grout Mixture

When using the fully grouted method, sensors should be placed within a grout that is matched to the permeability of the surrounding formation (Mikkelsen and Green 2003). Cement-bentonite grout mixtures for fully grouted VWP applications have been investigated and described in detail by Mikkelsen

(2002) and in field and laboratory experiments by Contreras *et al.* (2008, 2012) with recommended mixtures presented below in Table 1.

The amount of bentonite required will vary depending on the type of bentonite, the amount of mixing, and the water quality such as pH and temperature (Mikkelsen 2002). Mikkelsen (2002) describes the grout consistency as "drops of grout should barely come off a dipped finger and should form "craters" in the fluid surface."

Control of the water-cement ratio is essential when designing the mixture as it controls the compressive strength and void ratio of the grout and thus the permeability (Contreras *et al.* 2008). Bentonite is added to assist with suspension of the cement, to control shrinkage and bleeding, and therefore grout component separation on setting. The ability to pump the grout is also a contributing factor in the design.

Contrary to the original theoretical work done by Vaughan (1969) which suggested that grout should be no more than one order of magnitude greater than the permeability of the surrounding formation, Contreras *et al.* (2008, 2012) have shown that grout permeability can be up to three orders of magnitude greater than the surrounding soil and rock without inducing significant error in the measured pore water pressure. This leaves a significant amount of flexibility in the properties of the grout mixture for most applications.

It is the authors' experience that the grout mixture presented in tab. 1. for use in hard soils is suitable for use in most fractured rock systems. Additional information on the permeability and properties of cement-bentonite mixes can be found in Contreras *et al.* (2008).

	Hard To Medium Soils		Soft Soils	
Material	Weight	Ratio by Weight	Weight	Ratio by Weight
Cement	40 kg	1	40 kg	1
Water	100 L	2.5	264 L	6.6
Bentonite	12 kg	0.3	16 kg	0.4

Table 1 *Recommended Cement-Bentonite Grout Mixtures (after Mikkelsen 2002).*

Placement of the Grout

Cement-bentonite grout can be placed into the borehole through the drill string or a tremie pipe. Tremie pipe should typically be fitted with ports in the lower section of the pipe through which the grout can escape when it is pumped downhole. Grouting the borehole from the bottom up to surface using the tremie pipe is preferred to ensure that the grout is consistently placed with no voids or separation. Factors to consider when placing the grout are:

- ensure the tremie pipe contains sufficient ports for grout delivery;
- check the suitability of the tremie pipe to withstand grouting pressures and support the weight of the instrumentation;
- check the back pressure within the tremie pipe or rods when pumping the grout;
- check the suitability of the grout pump to handle the pressures required to place the grout;
- where several batches of grout must be delivered, can they be delivered quickly enough to avoid partial setting or separation of the previous batches; and
- can the pumping pressure be controlled to avoid overpressuring of the VWP sensors.

It is recommended that the VWP sensors are monitored during grout placement to ensure the grouting pressure does not cause significant overpressuring of the VWP sensors, and that the grout has been placed properly. Overpressuring during grouting is one of the key causes of VWP sensor malfunction (Marcil 2006). Downhole grout pressures can be minimized by slowing the delivery of the grout.

Other Installation Challenges

There are several additional challenges commonly encountered when performing VWP installations which can be accounted for in the installation design.

1. Borehole stability issues. Where possible, sensors should be lowered into place within the drill string which will support the borehole during installation and can subsequently be removed leaving the sensors in place.
2. Damaged cables during sensor placement. In addition to testing of the VWP sensors on surface, a robust quality assurance and quality control ("QA/QC") procedure should require testing of the VWP sensors once they are in place in the borehole, but before grouting activities commence. It is possible that VWP sensor cables become cut or damaged during placement. If this is identified during the QA/QC check prior to grouting, the installation could be removed and the damaged cable removed and repaired prior to grouting.
3. Difficulty in attachment of the sensors and cables to the support structure under high temperature and depth conditions. For shallow installations (less than 300 m), it is normally sufficient to attach sensors to the support structure using tape. However in conditions where high temperature or greater depth is expected, the tape may not be strong enough to support the weight of the cables, and a more robust attachment method should be considered.
4. Strength of the tremie pipe or support structure. Care must be taken to ensure that the tremie pipe used is robust enough to support its own weight and the weight of the instrumentation as well as the expected grout pressures. This is particularly relevant for deep vertical installations.

Cost Considerations

The cost of the materials should be considered when designing a VWP sensor installation (costs below are 2013 costs): Sensors typically cost $US350–500; sensor cable typically costs $US4–6 per metre depending on type; support structures such as PVC tremie pipe cost $US5–10 per 3 m length; grouting materials such as cement cost $US7–10 per 25 kg bag, bentonite cost $US10–15 per 25 kg bag and water; and dataloggers or readout units necessary to collect the data typically cost approximately $900 USD per unit depending on type.

Installation of VWP sensors by the fully grouted method is often quicker than the placement of sand and bentonite for traditional standpipe piezometers, thus limiting drill rig support costs.

Case Study – Deep VWP Installation for Mine Water Investigation

The following case study presents an example of the application of the fully grouted method to illustrate the challenging conditions that can be expected in mining investigations.

A hydrogeologic investigation was undertaken in a vertical, 155.6 mm diameter exploration borehole designed to investigate a coal bearing formation of alternating sandstone, siltstone, and mudstones from 500 to 1200 m depth below ground surface. Single well pressure response testing using borehole packers equipped with a shut in tool was undertaken over depth intervals from 665 to 1670 m. Calculated hydraulic conductivities were of the order of 5×10^{-11} m/s. Borehole stability and the potential for the generation of coal gas limited testing times to 12 h before the borehole had to be reconditioned with drilling muds. This was sufficient testing time over which hydraulic conductivities could be estimated, however it was not always long enough to allow the pressure within the system to equilibrate to the average interval pore pressures.

A VWP sensor string was installed to determine equilibrated pore pressures within different lithological units in support of the testing program, and to be used for long term monitoring. A typical setup at the drill rig during installation activities is depicted in Fig. 2.

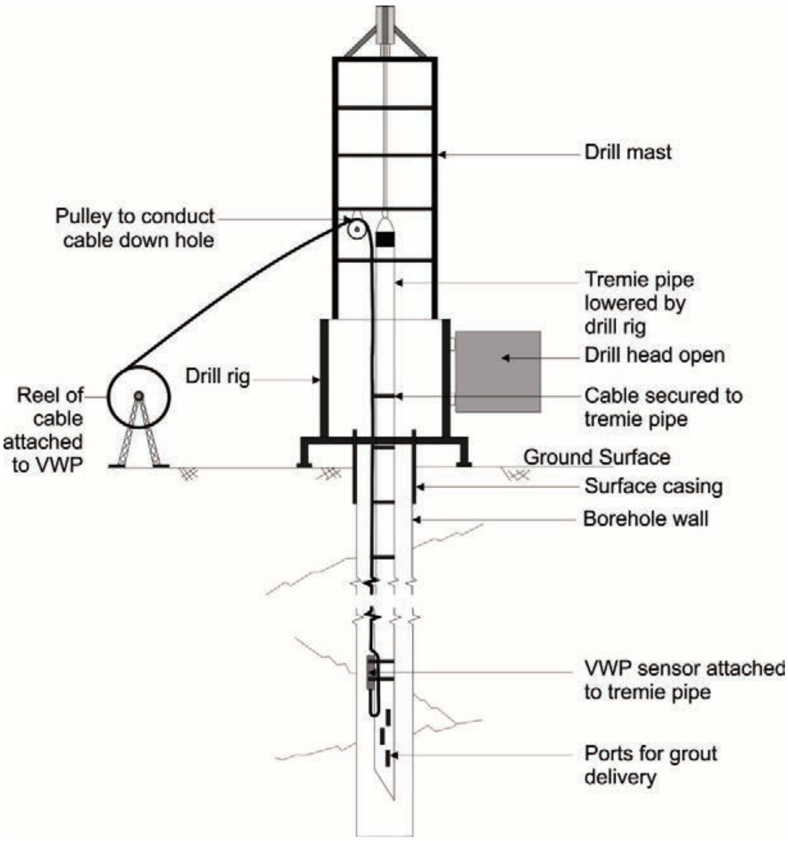

Fig. 2 *Site Set up During VWP Installation.*

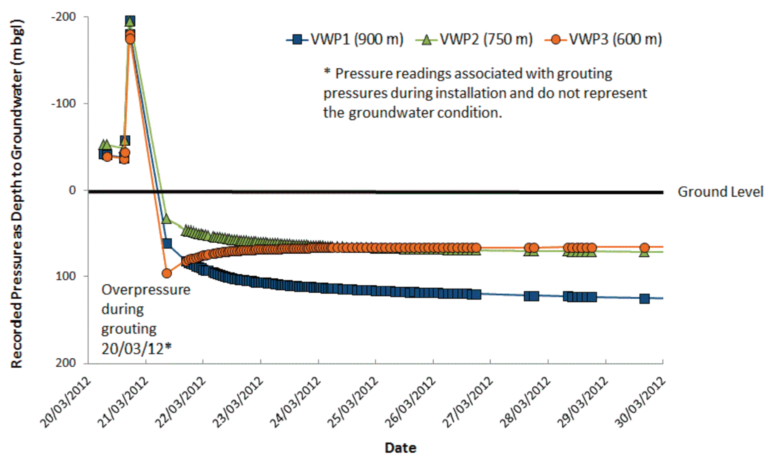

Fig. 3 *VWP Sensor Readings During Placement and Setting of the Grout – expressed in metres below ground level (m bgl)*

Challenges to the installation included borehole stability, the depth of the installation, and the high formation temperatures, measured at depth from 32 °C to 50 °C. These challenges were overcome by designing the installation using robust steel rods to support the increased weight of the installation and expected grouting pressures. Metal banding was used to secure the cables and sensors to the tremie pipe to withstand the increased temperature and weight. A dedicated high performance pump was used to inject the grout through the pipe and backfill the borehole from depth to surface. The grout placement was undertaken by pumping several batches of grout in series within a short enough timeframe to allow placement before the grout had set. Fig. 3 depicts VWP sensor readings during grout placement and stabilization of piezometric levels as the grout is set.

VWP sensors were successfully installed to depths of approximately 600 m, 750 m and 900 m below ground surface and subsequently measured piezometric heads of approximately 50 m, 80 m and 190 m below ground surface respectively. The results were comparable with a second installation undertaken in the same formation from approximately 650–1000 m depth approximately 3 km away. These sensors have been functioning well since their installation in mid 2012.

Conclusions

Monitoring boreholes installed with fully grouted vibrating wire piezometers can have significant advantages over conventional standpipe wells. This paper has discussed installation and design methods, and used a case study to highlight typical installation challenges.

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