STANDPIPE PIEZOMETER INSTALLATIONS - LESSONS LEARNT

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ABSTRACT

Standpipe piezometer installations are frequently commissioned as part of site investigations to monitor groundwater levels and chemistry. On a recent site investigation for a large tunnel infrastructure project in Sydney, Australia, 15 standpipe piezometers were installed and developed. Some of the well screen depths exceeded 100 m below ground surface. Several of these wells, especially the deeper ones, returned unexpectedly high pH values after development and sampling. The values were potentially misleading for the assessment of infrastructure durability and environmental impacts.

A hypothesis for these high pH readings was the potential ingress of the cement-bentonite grout in the annulus to the standpipe piezometer via the bentonite seal and/or the casing threads. The latter was confirmed by borehole imaging. Following this observation, a literature review and trials were carried out to investigate the impacts of typical well construction methodology and materials on the pH of the groundwater sampled. In particular, threads from several PN18 nominal pressure rated casing were tested, with their elastomeric joints, at different confining pressures. The effectiveness of the bentonite seal above the screened section was also tested by varying curing time and seal thickness for different overburden pressures. This paper discusses the results of these trials and describes measures to reduce the risk of groundwater contamination induced by cement-bentonite grout leakage.

1 INTRODUCTION

Well installations are frequently commissioned as part of site investigations to monitor groundwater levels. These usually take the form of standpipe or vibrating wire piezometers. Standpipe piezometers constructed with 50 mm internal diameter (DN50) casings are particularly common as they are economical and enable both instrumented groundwater level monitoring and sampling.

During a recent site investigation for a large road and tunnel infrastructure project in Sydney, Australia, Terratest Pty Ltd (Terratest) and AECOM Australia Pty Ltd (AECOM) installed standpipe piezometers following standard industry practice. Terratest is an experienced site investigation contractor and has installed more than 10,000 wells in Australia in the last 20 years. AECOM's ground engineering, hydrological and environmental teams have delivered many large geotechnical and environmental site investigations that have included monitoring well design and installation.

Most of the piezometers installed as part of this project were screened within the Hawkesbury Sandstone, a medium to coarse Triassic sandstone, with the base of the screens varying from 20 m to 140 m below ground surface. Groundwater quality was tested in the field during piezometer development and during the monthly groundwater contamination sampling regime. Several of these wells, especially the deeper ones, returned pH (potential of Hydrogen) readings well in excess of the 5 to 8 range expected. A hypothesis for the high pH values measured in the sampled water was the potential ingress of the cement-bentonite grout in the annulus to the standpipe piezometer via the casing threads and/or the bentonite seal. Ingress via the casing threads was confirmed by borehole imaging. Subsequent trials and a literature review were conducted by the authors to investigate the impacts of typical well construction methodology and materials on the pH of the groundwater sampled.

This paper presents current well design and installation practices in Australia, and then describes project-specific groundwater quality testing results. Measures to reduce the risk of groundwater contamination induced by cement-bentonite grout leakage are then presented.

2 TYPICAL WELL DESIGN AND INSTALLATION PRACTICE IN AUSTRALIA

2.1 TYPICAL WELL DESIGN

An example of a standpipe piezometer is shown in Figure 1. The standpipe is typically made of unplasticised Polyvinyl Chloride (PVC-U), and is a continuous casing which is locally slotted to form a well "screen" along the section of aquifer of interest. The annulus adjacent to the screen is filled with a filter pack of uniform gravel or sand to allow the water of the targeted aquifer to rise hydrostatically in the standpipe. Above and below the filter pack, bentonite seals can be constructed to avoid contact with the annulus grout and isolate the target formation. The annulus section above is backfilled with cement-bentonite grout until close to the surface, where a bentonite seal typically avoids surface water ingress. A sump can be constructed under the screen with a PVC cap and a blank casing riser to capture fines without blocking the slotted screen.

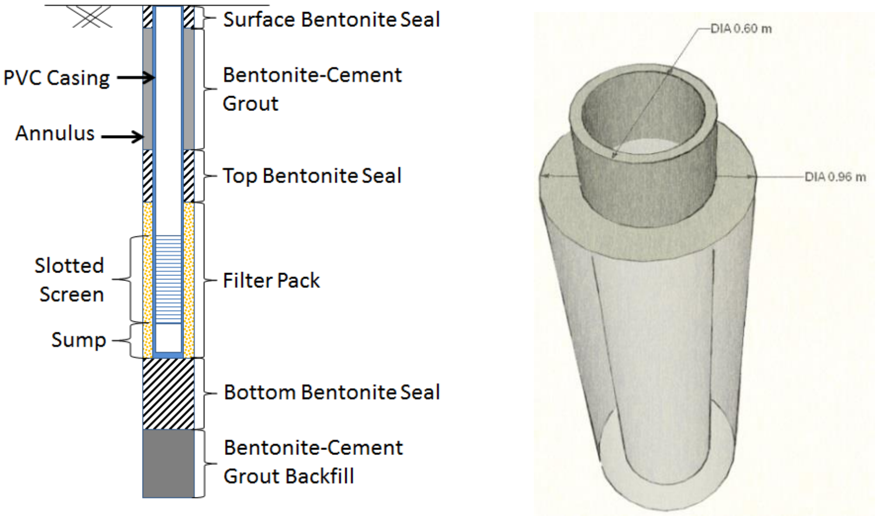

Figure 1: Typical 50 mm internal diameter (DN50) standpipe piezometer in 96 mm diameter (HQ) hole

2.2 STANDARD REQUIREMENTS

Boreholes and monitoring wells in Australia are typically constructed in accordance with the methodologies and practices outlined in NULDC 2012. Selected mandatory requirements of particular relevance to this paper are:

- PVC-U casing must comply with AS/NZS 1477:2017 (AS1477)
- The casing and casing joints shall "withstand the pressures imposed during the installation and operation of a water bore" and "all casing joints shall be aligned, secure and leak-proof"
- The cement grout annulus should have a minimum annular thickness of 15 mm (20 mm if artesian) above the maximum diameter of the casing to provide "adequate clearance"
- Bentonite pellets/chips shall only be used below the fluid level when sealing the annulus.

Additionally, the casing should be centred in the hole by means of centralisers at the top and bottom of screen and at a maximum spacing of 6 m for "long lengths". The annular thickness must be greater than four times the graded size of the filter sand or gravel. There is no specific requirement for bentonite seals.

2.3 TYPICAL MATERIALS AND INSTALLATION METHODOLOGY

The initial step is to drill and flush the borehole. Geotechnical drilling typically consists of non-destructive drilling, augering above the water table in soil, rotary non-core with casing advance below the water table in soil, and coring in rock. Environmental drilling often uses direct push drilling techniques instead of augering to avoid mixing contamination. Rock is typically cored with triple-barrel wireline HQ3 (96 mm hole diameter). Once the drilling is complete, the hole is flushed by pumping fresh water into the hole until clean water runs from the top of the borehole to reduce the likelihood of contamination of the groundwater by drilling chemicals, polymer and sediment.

The well installation methodology then consists of backfilling the base of the hole (if required), installing the PVC casing and backfilling the annulus. Typical materials and installation methodology are summarised as follows:

2.3.2 Casing

Casing is usually AS1477 Series 1 white DN50 PVC-U rated to a nominal pressure of PN12 or PN18, corresponding to respective nominal internal working pressures of 1200 kPa and 1800 kPa at 20° C.

This casing is typically installed in 3 m long sections, which are clamped and assembled during the installation down the hole. AS1477 describes two types of moulded spigot and socket (bell) joints for Series 1 casing: solvent cement jointing (SCJ) and elastomeric seal joints, also called rubber ring joints (RRJ). In practice, typical piezometer casings joints are however Male/Female (M/F) threads with an O-ring, rather than moulded joints (Figure 5).

Centralisers are rarely used. Depending on the contractor, the drilling rig availability and the casing length, the casing either rests at the base of the hole or is suspended from the ground surface. Once the PVC casing is installed, the annulus is backfilled with a filter pack, bentonite seals and cement-bentonite grout.

2.3.3 Filter pack

The annulus adjacent to the screen is filled with a filter pack that is usually composed of uniform coarse sand and fine gravel ranging from 2 mm to 4 mm. The maximum size of the particles is limited by the (radial) annular thickness and the grainsize of the aquifer. The filter pack usually extends 0.5 m to 1.0 m above and below the screen, creating a buffer zone, to avoid swelling of the bentonite seal in the slotted screen and allow for settlement of the filter pack. Filter socks, which slide over the screen to keep out fines, are generally not used due to the risk of clogging by algal growth.

2.3.4 Bentonite Seal

Subject to well design, a bentonite seal can be installed in the annulus above and below the filter pack to create a relatively impervious barrier between the cement-bentonite grout and the filter pack. Compressed bentonite pellets or chips are used as bentonite powder is not appropriate to create a seal (Mikkelsen 2002). When hydrated, these swell and can reach hydraulic conductivities of 10^{-10} m/s (Mikkelsen 2002). Pellets used for bentonite seals are generally coated to retard the start of the hydration so they can reach the intended depth of the seal prior to swelling. In practice, the bentonite seal is typically 0.5 m to 1.0 m thick where present and left to hydrate from 45 minutes to 1.5 hours. Frequently, no water is added down the hole to help hydration, unless water loss occurred during drilling.

Pellets are usually placed in the annulus by hand from the surface (gravity method) or poured down a polypropylene pipe. The hand installation is often far quicker but can lead to bridging off of the pellets in the annulus above the intended depth of the seal, even if coated (Kaempffer 2003). Once bridging has occurred, there is no option but to redrill (Mikkelsen 2002).

Dropping the pellets via a tremie pipe to the required depth mitigates the risk of annulus bridging and is often used below 30 m or in challenging installation environments (e.g. artesian flow). To limit pipe blockage, the pellets must be placed slowly. A pump can usually clear pipe blockage. The tremie pipe diameter typically exceeds the annular space and has to be flattened as it is lowered. To place the tremie pipe at the correct depths, it is often secured to the PVC casing during installation, about 2 m above the target depth. The tremie pipe is usually removed after installation of the seal to avoid acting as a conduit for gas or water.

2.3.5 Cement-Bentonite Grouting

Cement-bentonite grouting is typically carried out in the annulus above the screen section/bentonite seal, but also in the annulus below the screen section/bentonite seal in the case of a sump. If the base of the borehole is substantially deeper than the depth of the screen, the bottom grout is left to set overnight prior to placement of the standpipe.

The grout typically comprises water, cement and bentonite powder. The cement increases the compressive strength of the grout and reduces the swelling of the bentonite. The bentonite quickly decreases hydraulic conductivity of the grout, increases the viscosity of the mix and also its stability by preventing segregation of the cement particles (“bleeding”) (Mikkelsen 2003). The grout can have highly variable properties depending on the proportions of the constituents and the mixing process (Bruce 1997). Typically, drillers use a bentonite/cement mass ratio ranging from 3 % to 5 % for borehole and annulus backfilling. However, this ratio can reach 30 % when proportions of 2.5 (water) to 1 (cement) to 0.3 (bentonite) are used, as proposed by Mikkelsen 2003 for fully grouted piezometers.

Two approaches can be used by the drillers to prepare the cement-bentonite grout. Mixing bentonite and water first, then adding cement, is more economical (Mikkelsen 2002) and enables an ideal pH range for bentonite hydration (Kelessidis *et al*. 2007). Mix ratios presented in NUDLC, 2012 are based on this method. However, hydrating and shearing the bentonite early increases viscosity, which decreases pumpability and limits working times. The typical approach is therefore to initially mix cement and water, which enables to control the stiffness and strength of the grout first and then adjust the hydraulic conductivity and viscosity by increasing the quantity of bentonite (Mikkelsen 2002).

Ideally, a colloidal mixer should be used to quickly produce a homogeneous mix. However, common practice is to use a flexible drive pump suction line and output in the same tank. An additional positive displacement pump can be used to deliver the grout to the hole via the tremie pipe. Tremie pipes should be slightly raised during each batch volume to keep pumping pressures as low as possible (Mikkelsen 2002) and rinsed prior to retrieval to avoid grout smearing.

2.4 TYPICAL WELL DEVELOPMENT METHODOLOGY

Groundwater monitoring wells are usually developed using either disposable polyethylene bailers, submersible pump or by air lifting. Submersible pumps are generally suitable for well development above 30 m, but air lifting methods should be preferred when significant amounts of sediment are expected. Compressed air can be used effectively when the casing is connected to a PVC T-piece to divert the purge water down to a drum and the air pressure is slowly increased until a steady stream of purge water is lifted. The wells should be purged until returned groundwater is sediment-free. However, often the wells are bailed dry and left to recharge until three well volumes are completed.

3 PROJECT GROUNDWATER QUALITY TESTING

3.1 BACKGROUND

The Hawkesbury Sandstone in Sydney is a medium to coarse grained quartzose sandstone of the Triassic period. This 200 m thick formation acts as a semi-confined dual porosity regional aquifer typically varying from acidic to slightly alkaline (pH of 5 to 8) and is probably influenced by leakage from the saline groundwater present in the overlying Wianamatta Group shales and mudstones, where present (Hawkes *et al*. 2009, McLean & Ross 2009).

3.2 METHODOLOGY

Along the project alignment, 15 standpipe piezometers were installed in HQ3 boreholes by two highly experienced and licenced groundwater drillers under the direction of experienced field engineers. Of the piezometers, 12 were screened in the Hawkesbury Sandstone, while the others were screened in fill and alluvium. The piezometers were installed using standard monitoring well installation techniques and the materials below:

- Casing: DN50 PN18 PVC-U manufactured by Waterscreens Pty Ltd in 3 m or 6 m long M/F threaded sections with an O-ring, machine slotted to 0.5 mm
- Filter pack: 2 mm Boral Blue Circle Specialised Sand extended by 0.5 m to 2 m above and below screen
- Cement-bentonite grout: bentonite/cement mass ratio varying from 5% to 30%. Boral Blue Circle General Purpose Cement and Halliburton Aquagel bentonite powder
- Bentonite seals: 6.35 mm Pel-Plug TR30 natural sodium bentonite pellets, mined in Texas, single-coated in order not to stick together for up to 30 minutes when poured in standing water.

Bentonite pellets were dropped by hand for wells shallower than 40 m and tremied for deeper wells. No water was added for hydration. Centralisers were installed at 9 m intervals in some of the initial deeper wells (BH1, BH4, BH5) but only two were placed above and below the screen in the other wells following issues with lowering the tremie pipe.

Development by air lifting and pumping was carried out until three well volumes of water were removed from the monitoring well. Due to consistently slow recharge conditions in most wells across the alignment (no level changes within 10 minutes during slug testing except in BH7), multiple development rounds were required over several days.

3.3 GROUNDWATER QUALITY TESTING RESULTS

Groundwater samples were retrieved with a bailer and field parameters including Electrical Conductivity (EC) and pH were measured using a calibrated and decontaminated water quality meter. The field-testing of 8 of the 15 piezometers, described in Table 1, indicated higher-than-expected pH values. Figure 2 shows the pH evolution for these piezometers. With the exception of BH1, elevated pH values remained high, even months after the end of development.

Table 1: Installation Details and pH and EC results

Well	Length (m)	Screen Section (m below ground level)	Backfill (below sump)	Seal thickness (m)		After development		Long-term	
				Top	Base	pH	EC (mS/cm)	pH	EC (mS/cm)
BH1	66.5	62.5 – 65.5	Pellets	1.0	n/a	9.6	1.42	5.5	1.35
BH2	49.7	45.7 – 48.7	Grout	2.1	1.0	11.2	1.75	n/a	n/a
BH3	137	121.0 – 127.3	Pellets	0.5	0.8	9.3	0.62	n/a	n/a
BH4	103.5	99.5 – 102.5	Grout	0.5	None	11.3	0.47	n/a	n/a
BH5	52.2	48.2 – 51.2	Grout	1.0	None	11.6	1.27	n/a	n/a
BH6	65.0	59.0 – 64.0	Pellets	4.1*	n/a	11.9	3.46	11.4	1.22
BH7	29.0	24.0 – 27.0	Pellets	2.0	4.0	9.6	1.43	11.3	0.80
BH8	139.0	135.0 – 138.0	Pellets	1.0	n/a	9.0	0.52	n/a	n/a

*left to cure for 12 hours

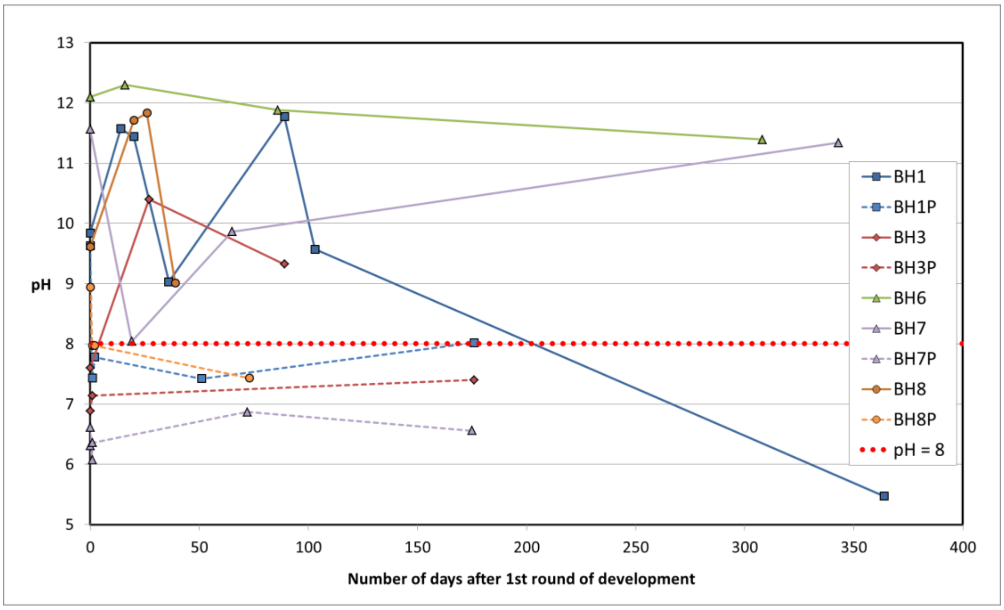

Figure 2: Groundwater pH readings during and after development

3.4 TELEVIEWER RESULTS AND REDRILLING

The elevated pH readings were not expected to reflect aquifer conditions but rather to be caused by direct or indirect contact with the installation materials. Nielsen 1991 states that even hard set grouts can bleed very alkaline water down into the well screen area. Cement contains calcium hydroxide, which has a pH of about 12.4, and is therefore expected to be the most likely material to impact the pH readings. Based on the absence of water-bearing discontinuities in the rock between the annulus grout and the screen in the eight piezometers, the most probable contact mechanism between the grout and the sampled groundwater is either an absent or ineffective bentonite seal, or ingress inside the casing from the annulus via the threads or a fissure in the casing.

To investigate potential grout ingress, Terratest completed post-development downhole optical televiewer imaging inside the PVC casing in BH3 and BH6. The imaging in BH3 (Figure 3) suggests a breach of casing thread by dark material, expected to be cement-bentonite grout from the annulus, at 65.2 m and 68.4 m below top of casing. The quality of the water did not enable confirmation of leakage via the deeper threads. The casing also seemed full of grout from 112 m to 120 m. The imaging in BH5 showed material from 62.8 m to the base of the casing. The annulus was backfilled with grout only above 55 m, suggesting leakage from either a shallower thread or the bentonite seal.

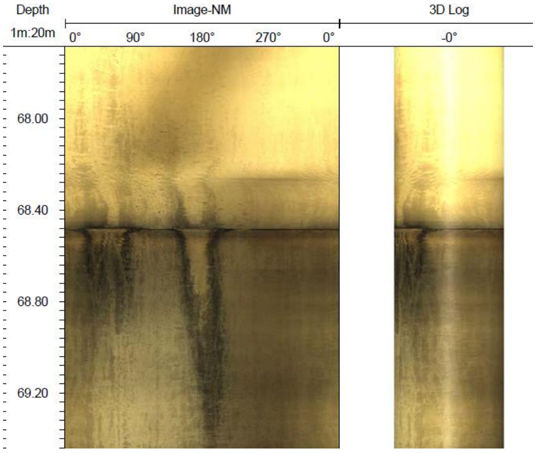

Figure 3: Evidence of material ingress through PVC thread in BH3

Four selected wells were redrilled at about 10 m from their original position and extended about 1 m below the required screen depth. The filter pack was installed from the base of the 1 m sump interval to at least 2 m above the top of the screen. A 2 m thick bentonite seal was installed above the filter pack and left to hydrate for at least 2 hours. The remaining annular space was sealed with bentonite pellets installed in multiple batches of maximum 30 m thickness, each allowed to hydrate for at least 2 hours. No bentonite-cement grout was used.

These wells are labelled with a “P” suffix on Figure 2. Despite similarly slow recharge compared to the original wells, the measured pH stayed within a 6 to 8 range after development, confirming that the high pH of the original wells did not reflect true aquifer conditions and were likely to be due to contact with bentonite-cement-grout.

Whilst this methodology was apparently successful, the approach of replacing the cement-bentonite grout with pure bentonite pellets is time-consuming, can create substantial external pressures on the PVC casing due to swelling, and can cause issues if intersected during construction (e.g. tunnelling blowout). Pure bentonite is not volumetrically stable (Mikkelsen 2002) and can be affected by the water chemistry, even after curing. Trials were therefore carried out and lessons learnt are presented in the following section.

4 FIELD TRIALS AND LESSONS LEARNT

The impact of the piezometer installation methodology on the pH of the sampled groundwater was investigated both through a literature review and trials. The tests were completed using the project materials listed earlier and are relevant to single standpipe piezometers. The findings were not correlated with the project-specific results due to the number of unknowns and the variability of the readings.

4.1 IMPACT OF DRILLING ON WELL PERFORMANCE

4.1.1 Drilling diameter

The external diameter of DN50 casing varies from 60.2 mm to 60.5 mm. DN50 PN18 casing requires a wall thickness of about 5 mm, leading to an average internal diameter of 50.5 mm. Assuming that the casing is centred, the resultant annular thickness is only 18 mm in an HQ borehole. Despite fulfilling NUDLC 2012 requirements, this annular thickness can impede annulus backfilling by preventing the lowering of the tremie pipe and increases the risk of bridging. Besides, using 6.35 mm diameter bentonite pellets in such an annular thickness exceeds the recommendations from DEP 1992 to limit pellet size to a fifth of the annular thickness. Installing DN50 in HQ borehole also precludes the use of moulded spigot and socket joints due to the increase in external diameter at the socket.

Most available guidelines recommend a minimal annular thickness of 50 mm or 60 mm (e.g. EPA 2013, DPI 2010). For a M/F threaded DN50 casing, this would require reaming the borehole diameter to 160 mm. If this is not practicable, we recommend reaming boreholes to at least 123 mm (PQ) diameter if the screen base exceeds 30 m.

4.1.2 Borehole depth

The difficulty of successfully installing a well increases with borehole depth. Standpipe piezometers are often installed in existing geotechnical boreholes which are deeper than the target zone, requiring backfilling of the base with cement-bentonite grout. The economy of using an existing hole compared to redrilling an adjacent well terminating at the base of the target zone should be balanced against the risk of grout ingress along the walls of the borehole during backfilling, the grout curing time (unless a plug is installed) and the additional flushing required. As outlined above, reaming the borehole prior to well installation should also be considered in deep wells.

4.1.3 Flushing

Insufficient flushing is common and negatively impacts optical televiewer imaging and well development. As well as installing the surface casing deep enough to avoid material ingress, it is recommended that at least 1000-2000 L of clean potable water are available and that the well installation is carried out at least two hours after water pressure testing if the losses exceed one Lugeon. Flushing should be completed before and after any bottom backfilling.

4.1.4 Construction records

As-built details cannot be checked post installation and should be recorded during each installation stage and signed by the drillers. Whilst the thicknesses of the backfilling sequence are usually measured at each stage, the details of the installation methodology are often not recorded. These should include type and brand of all materials used, position of any centralisers, bentonite seal installation methodology and curing time, grout mix proportions and mixing methodology and a comparison of calculated and actual material quantities to identify potential bridging.

4.2 IMPACT OF BACKFILLING MATERIALS

The filter pack and bentonite are in direct contact with the aquifer and were investigated to assess if these materials could have impacted the pH of the groundwater drawn into the casing.

4.2.1 Filter pack

The Safety Data Sheet for the Boral Blue Circle Specialised 2 mm Sand states that the quartz content is more than 60% but no information could be found on the potential other constituents or the pH range. The addition of 100 grams of sand to 250 cm^3 of tap water was found to increase the pH from 6.7 to 7.5 in 10 minutes, decreasing to 7.4 after 3 hours. Six tests on three different batches of sand also confirmed that the sand is only slightly alkaline. This suggests that the sand is not likely to have caused the high pH measurements.

4.2.2 Bentonite

Na-bentonites are alkaline due to the formation of sodium hydroxide (NaOH) in water. The typical pH range of natural Na-bentonites is 9 to 10 and the material data sheet for the Pel-Plug TR30 used on the project reports a pH ranging from 7 to 11 in a 0.5% solution (PDS 2017). Na-bentonites were found to increase the pH of a solution for at least several months, even in relatively small concentrations (Muurinene & Clarsson 2013). The evolution of the pH was recorded after adding 15 grams of Pel-Plug TR30 pellets to 225 cm^3 of tap water. Results are presented in Table 2 and show a significant pH increase within the first hour, followed by stabilisation. Similar proportions of Na-bentonite in various solutions increased the pH from about 8.2 to more than 9 even after 3 months (Melamed & Pitkanen 1996).

Table 2: Impact of Pel-plug TR30 bentonite on solution pH

Time after addition	0 s	30 s	1 min	5 min	10 min	20 min	1 h	24 h	48 h
pH	6.14	6.23	6.38	8.05	8.80	9.19	9.53	9.74	9.35

The recorded increase in pH could explain the wells with a slightly alkaline pH but does not explain the pH>11 occurrences. Bentonite seals are in direct contact with the filter pack in most wells and further testing would be required to assess the impact of a real-scale hydrated bentonite seal on the pH of the sampled water pH at various recharge rates.

4.3 PERFORMANCE OF BENTONITE SEAL

4.3.1 Lack of bentonite seal

Well designers do not often require a bottom bentonite seal between the cement-bentonite grout and the filter pack. To investigate the impact of the lack of a bentonite seal, a vertical 4 metre long piezometer was constructed within a Class 12 DN100 PVC-U casing (representing the hole) using the project methodology and materials presented previously but with no bentonite seal. The filter pack was saturated with tap water with a pH of about 6.5. Within an hour, the pH of the water sampled reached 11.9, reflecting the pH of the calcium hydroxide contained in the cement-bentonite grout.

Bentonite pellets should typically only be placed below groundwater level (NULDC 2012) due to hydration and desiccation. Neat cement or bentonite-cement grouts can have sufficiently low hydraulic conductivities compared to the aquifer to act as a seal. However, we recommend the systematic placement of bentonite seals between any cement-containing grout and the filter pack to limit surface contact between the cement and the water in the screen. WRP 1993 recommends installing a 150 mm thick bentonite seal above the filter pack if the screen if above the water table.

4.3.2 Bentonite seal hydration

As discussed above, bentonite chips or compressed pellets are used to form seals above and below the filter pack. Often, water is not added down the annulus to hydrate the bentonite, unless water loss occurred during drilling. However, the water levels in the annulus at the time of placement might not be sufficient to hydrate the seal. This section summarises why the addition of soft water during installation is usually required to successfully create a seal.

The hydraulic conductivity of the bentonite decreases with swelling (Pusch *et al.* 2010). The expected swelling mechanism of bentonite is described by Savage 1999, Tripathy 2004, Morodome & Kawamura 2009, Ferrage *et al.* 2010, Hensen & Smit 2002, Svensson 2015, Ahmed *et al*. 2015.

The swelling behaviour of bentonite is explained by its mineralogy. By definition, the main component of bentonite is montmorillonite, which is an aluminium phyllosilicate clay mineral with a 2:1 structure: each clay platelet comprises one aluminium octahedral sheet sandwiched between two silica tetrahedral sheets. Isomorphic substitutions in the octahedral and tetrahedral sheets (Lavikainen, 2016) create a negative charge along the surface of the platelet. This charge inequality is balanced by cation exchange in an interlayer between the clay platelets.

The first type of swelling to occur, called "crystalline" swelling, is an increase in the thickness of this interlayer due to the adsorption of water molecules in the interlayer. The thickness of the interlayer increases in steps with moisture content and can double when four layers of hydration are reached.

Once the interlayer has reached a certain thickness, another process called "diffuse double-layer" swelling is expected to occur. This swelling is caused by the difference in concentration between the cations close to the surface particles and of the solution, creating an osmotic pressure. Importantly, the thickness of the diffuse double-layer decreases with the electrolyte concentration of the water solution and the valence of the cations. The first point entails that to enable swelling, the bentonite should be hydrated with soft water. The second is that Na-bentonite, containing mostly monovalent sodium Na^+, will, at a given water content, swell more than Ca-bentonite, containing mostly divalent calcium Ca^{2+}. Na-bentonite is therefore typically used to create seals.

Na-bentonites can be natural or sodium activated. Natural Na-bentonites are mined and rarely monoionic. PDS Pel-plug TR60 (similar to TR30 but with double-coating) cations were found to be 60% sodium and 30% calcium (RWM 2016). Alternatively, Ca-bentonite can be activated by adding sodium to improve the swelling properties by exchanging Ca^{2+} for Na^+. In a similar process, contact between the Na-bentonite with material containing divalent cations, such as hard water present in the ground or cement from the grout, can greatly decrease the swelling and increase the hydraulic conductivity of the seal. This ion exchange will occur even after bentonite hydration, for the life of the seal (Benson & Meer 2009, Melanmed & Pitkanen 1996). Hydration with soft water is therefore essential for good seal performance.

Hydration is also influenced by the thickness of the bentonite layers. RWM 2016 tested hydration of bentonite pellets placed in columns and found that the swelling occurred mainly in the top 50 mm to 100 mm. This is expected to be due to the limited access to water for the underlying pellets following the swelling of the top pellets. We therefore recommend to place and hydrate bentonite pellets in batches, for instance 0.5 m thick.

4.3.3 Groundwater Salinity

Despite not being usually checked prior to piezometer installation, groundwater salinity can have a detrimental effect on the performance of the bentonite seal.

In Sydney, the salinity of the Hawkesbury Sandstone aquifer is typically higher in its upper part, particularly where it is overlain by the Wianamatta Group shales. Measured Electrical Conductivity (EC) readings can be as high as 1.7 mS/cm but typically decreasing with depth to about 0.3 mS/cm (McLean & Ross 2009). The shales from the Wianamatta Group are generally saline and in the range of 5,000 to 50,000 mg/L – total dissolved solids (McNally 2009) which corresponds to approximately 8 mS/cm to 80 mS/cm. However, much higher values can be expected when the aquifer is hydraulically connected to saltwater, such as in joint swarms associated with faulting close to Sydney Harbour.

As discussed previously, the diffuse double-layer swelling decreases with the valence of the cations and the electrolyte concentration in the water solution. This swelling can be suppressed in relatively saline solutions (Rao *et al*. 2013, Shirazi *et al*. 2011). With a compressed or inexistent diffuse double-layer, attractive forces cause the clay particles to flocculate, effectively disintegrating the pellets and increasing the hydraulic conductivity of the seal.

Dispersion and flocculation depend on the soil's Electrical Conductivity (EC) and Sodium Absorption Ratio (SAR). The SAR is the ratio of the Na^+ concentration divided by the square root of the Ca^{2+} and Mg^{2+} concentration (in mmol/L). The bentonite will flocculate if the SAR decreases but also if the EC increase. Even a soil with a SAR higher than 13 will tend to flocculate if the EC is more than 4 mS/cm (EMU). A study on bentonite pellets by RWM 2016 concluded that the EC has a greater influence on the stability of the clay than the SAR.

The coating from coated bentonite pellets was found to slow but not suppress flocculation in various saline solutions (RWM2016). After 10 minute exposure in an 0.1M (about 10 mS/cm) solution, Pel-plug uncoated pellets were almost completely disintegrated. Single coating coated pellets (Pel-plug TR30) were highly disintegrated in a 1M (about 100 mS/cm) solution after 10 min. Even double-coated pellets were highly disintegrated in a 0.1M (about 10 mS/cm) solution after 30 min. Disintegration of the pellets reduced their sinking speed, increasing the risk of bridging.

We therefore recommend measuring the groundwater salinity after borehole flushing and recharge. If the salinity is high enough to compromise the effectiveness of the bentonite seals, neat cement can be used as a seal at certain water/cement ratios (NUDL 2012) but the groundwater pH readings will be affected. A similar approach should be taken in contaminated sites, as certain chemicals such as hydrocarbons are known to affect bentonite (Nielsen 1991).

4.3.4 Bentonite seal thickness and hydration time

Typically, bentonite hydration times varied from 45 minutes to 1.5 hour on the project. However, Pel-plug recommends a minimum of 4 hours (PDS 2017). This recommendation is not generally displayed on the containers or bags but can be found on an online data sheet that only a few suppliers provide on their website.

The curing duration should conservatively start after the pellets have reached the base of the hole. The average sinking rate of pellets in water is 0.30 to 0.45 m/s (RWM 2016).

To assess the impact of the thickness of the top bentonite seal and its curing time, a vertical steel or PVC-U HWT (102 mm internal diameter) casing with pressure sealed end caps was packed with 2 mm diameter wet sand. A bentonite seal of varying thickness was installed (Figure 4). The bentonite seal was hydrated and allowed to cure for various durations before cement-bentonite grout was added and pressurised for a nominal duration of 25 minutes to simulate overburden.

A sample of the water from the filter pack was then analysed in the field with a water quality meter. Results are presented in Table 3.

Figure 4: Bentonite seal testing (Left, Middle); PVC thread testing (Right)

Table 3: Bentonite Seal Pressure

Seal thickness (m)	Seal Curing time (min)	Grout Pressure	Equivalent grout head (assuming 14 kN/m^3)	Breaching comments (original water pH: 6.8)
0.5	45	760 kPa (110 psi)	54 m	No breach observed (pH = 8.8*)
0.5	120	1240 kPa (180 psi)	89 m	Breach (pH = 11.2)
2.0	120			No breach observed (pH = 8.1*)

*expected to be due to the Na-bentonite

More testing would be required to characterise the behaviour of 0.5 m and 2 m thick bentonite seals at a range of pressures. However, this preliminary testing suggests that even after curing for 2 hours, a 0.5 m thick bentonite seal does not resist an overburden of 1240 kPa, corresponding to a grout head of 89 m. As a result, we recommend a top seal thickness of at least 2 m with a minimum curing time of 2 hours for depths of screen base in excess of 50 m.

4.4 PERFORMANCE OF PVC CASING

4.4.1 Standard requirements

As discussed previously, AS1477 Series 1 DN50 (50 mm) PVC-U casing is typically used. AS1477 describes two types of moulded spigot and socket joints, rubber joints (RRJ) or solvent cement joints (SCJ).

SCJ exist in a wide range of nominal diameters and ratings and require Type P (for Pressure) solvent cements compliant with AS/NZS 3879. However, solvent cements are usually proscribed as some of the solvents can migrate in the groundwater and affect its chemistry for months despite development (Barcelona *et al*. 1983). More testing would be required to confirm that the cement solvents used become inert once fully cured. AECOM observed no change in pH within an hour of adding 100 grams of solvent cement Type P in 250 mL of water with a pH of 6.6.

RRJ do not require solvents, but are typically manufactured to DN80 upwards and can require a lubricant and bactericidal fluid, potentially affecting hydrochemistry. Also, the annulus thickness, already reduced by the spigot, is further reduced by the thickness of the ring cavity. Rubber rings should comply with AS 1646.

As a result, casings are usually AS1477 DN50 PN18 or PN12 which is then threaded straight Male/Female and supplied with an O-ring, instead of moulded spigot and socket joints. The compression of the ring is meant to create the seal (fastening thread) since the threads are parallel to each other. NUDLC, 2012 recommends the use of a sealastic or flexible sealant for threaded PVC so that the joints are watertight. This is, however, not expected to be applicable to fastening threads.

AS1477 only briefly mentions threaded joints and states that the threads need to be of Whitworth form, and require a minimum number of fully engaged threads. For 50 mm diameter fastening threads, at least 4 full threads should be engaged. Reference is made to AS1722:2 for fastening threads in terms of type and dimensioning. AS1477 refers to various parts of AS1462 for testing joint performance, most of which are however relevant to socketed joints.

4.4.2 Manufacturing

Two major Australian casing manufacturers were approached. One manufacturer mentioned that, despite being widespread, the cutting of threads on PVC casings (without a moulded thread adaptor) is not an acceptable practice due to performance issues. As a result, they only provide moulded spigot and socket joints. Another manufacturer confirmed verbally that although their casings are rated to AS1477, they did not manufacture the threads and O-rings to any particular standard.

Threads from several manufacturers were counted and measured and were found to be inconsistent. The male thread varied in length across four DN50 casings by a total 4 mm deviation for a same manufacturer. The number of fully engaged threads was typically less than the minimum of 4 required by AS1477 for DN50 casing with fastening threads.

4.4.3 Trials

A 1.5 m long section of M/F threaded DN50 PN18 PVC-U casing was tested for both water and cement-bentonite grout breaching under varying external pressures. This casing section comprised one M/F threaded joint in the middle, with the 1.7 mm annular diameter O-ring supplied and two end caps. Primer and cement solvent was used to seal the end caps only. The caps were tested separately at 1725 kPa to ascertain that potential breaches would happen via the middle thread and not the end caps. The same operator applied torsion to the threads for consistency; however the torsion was not measured.

This casing section was placed in a horizontal custom-made steel pressurised HWT (102 mm internal diameter) casing. The annulus between the DN50 casing and the HWT casing was filled either with water with a blue dye, or cement-bentonite grout. The grout comprised 27.5 L of water, 20 kg of cement and 1 kg of bentonite (5% bentonite), yielding a 34 L mix with a unit weight of 14 kN/m^3. The pressure was applied to the water or the grout to a nominal 3 or 10 minutes.

The inside of the DN50 PVC casing was left empty: neglecting viscosity effects, the pressure applied to the middle joint was therefore equal to the pressure applied to the water or grout in the annulus.

Breaching examples are shown in Figure 5. The results in 00 m with a PVC full of water. To reduce the likelihood of a breach, it is recommended that the PVC casing should be filled with water during well installation until the annulus backfill has set.

Table 4 show water and cement grout consistently breaching between 795 kPa and 830 kPa, corresponding to a grout head of about 60 m with an empty PVC casing and about 200 m with a PVC full of water. To reduce the likelihood of a breach, it is recommended that the PVC casing should be filled with water during well installation until the annulus backfill has set.

Table 4: Water and grout breaching trials

Pressure applied to water in annulus	Pressure applied to grout in annulus
795 kPa (115 psi) for 10 min – NO BREACH OBSERVED	795 kPa for 10 min – NO BREACH OBSERVED
830 kPa (120 psi) for 10 min – BREACH*	830 kPa for 10 min – BREACH, grout solids visible
860 kPa (125 psi) for 10 min – BREACH	930 kPa for 10 minutes – BREACH, no solids
135 psi, 150 psi, 175 psi, 220 psi for 10 min – BREACH	1725 kPa for 10 minutes – BREACH, grout solids visible
1515 kPa (220 PSI) for 3 min – BREACH*	
1725 kPa (250 PSI) for 3 min – BREACH	

* water only on threads past O-ring, not in casing

Figure 5: M/F thread with O-ring: Water breach (Left); Grout breach (Middle, Right)

4.4.4 Use of centralisers

NULDC 2012 recommends centralisers above and below the screen at a maximum spacing of 6 m for “long lengths”. However, pipe buckling under its own weight when resting on the base of the hole could lead to contact between the casing and the side of the borehole even above the screen, causing backfilling issues, which could compromise the integrity of the well and connect different aquifers. AECOM estimated the quantity of centralisers required due to self-buckling of a vertical DN50 PN18 PVC casing. Euler’s critical load for a long slender column was calculated assuming a uniform modulus of elasticity of 3000 MPa and a unit weight of 13.6 kN/m^3. Results suggest that intermediate centralisers are required for casings longer than 11.5 m. The longer the pipe, the higher the axial loads and 50 and 100 m long casings would require a respective maximal centraliser spacing decreasing to about 5 m and 3 m at their base.

The conclusion of this theoretical exercise is that centralisers are required if DN50 PN18 PVC casing longer than 10 m is resting on the base of the hole, and that their required frequency increases substantially with casing length. The recommendation is to install one centraliser above and below the screen but also systematically suspend the casing from the ground surface until the annulus backfill has set.

5 SUMMARY AND CONCLUSIONS

Unexpectedly high pH readings of groundwater sampled in standpipe piezometers during a large infrastructure project triggered a review of current standpipe piezometer installation practice and identified potential issues with the manufacturing of PVC casing threads and areas of improvement for future installations. These recommendations are summarised in the table below.

Table 5: Standpipe piezometer installations - hazards and recommendations for future installations

Item	Hazard	Recommendations
Hole	Incorrect piezometer type selection	- Install fully grouted vibrating wire piezometers instead of standpipe piezometer unless groundwater sampling is required.
	Insufficient annular thickness	- Aim for 50 mm annular thickness if feasible - For DN50 PVC casing, ream HQ boreholes deeper than 30 m to PQ diameter (30 mm annular thickness) as a minimum
	Lack of flushing	- 1000-2000 L of clean water to be available on site - Flush before and after any bottom backfilling - Observe cleanliness of water return not just well volume
Casing	Leakage via M/F threaded joints	- Request evidence from casing supplier/manufacturer of M/F threaded joint compliance with existing standards and evidence of testing for leakage when submitted to a appropriate range of pressures - Fill casing with freshwater to decrease overburden via threads - Do not place clamp on thread - Use 6 m casing sections where feasible to limit number of joints
	Casing not centralised	- For lengths > 11 m, suspend PVC casing until the grout has set
Tremie	Smearing of grout along screen	- Rinse tremie prior to retrieval
Filter pack	Lack of specified pH	- Seek confirmation from supplier or check pH of filter pack
Bentonite	Bridging	- Use coated Na-bentonite pellets - Use tremie pipe to install pellets in holes deeper than 30 m
	High pH	- Be aware of the potential impact of Na-bentonite on pH
	Poor hydration	- Add soft water in the annulus during bentonite seal installation - Install seal in 0.5 m thick layers, hydrated separately
	Insufficient curing time or thickness	- Curing time of at least 2 hours and 2 m thick seal below 50 m - Install even above groundwater table
Groundwater	Groundwater salinity (and chemistry)	- Check groundwater salinity prior to well installation - Use alternative materials such as neat cement in saline environments
Records	Lack of information	- Record full installation methodology, not only as-built details

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