The Fundamentals of Piezometer Installation

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ABSTRACT: How a piezometer is installed really matters. It is quite possible to use an incorrect installation method that will give erroneous results. This paper discusses the various installation methods, their shortcomings and advantages. It addresses such problems as false indications of perched water tables which are a function of the piezometer installation method. It presents some new approaches to cement grouted installations so as to get reliable information from piezometers and which are also testable, something that is generally lacking. The different types of piezometer required for soil or fractured rock are considered with particular attention being paid to the piezometer response time.

KEYWORDS: piezometer, grout, packer, ground fluids, pressure.

1 INTRODUCTION

The purpose of a piezometer is to determine the fluid pressure at a point in the ground. The reason for doing this includes:

1. The determination of fluid pressure changes related to flow behaviour and storage characteristics such as measured in pumping tests.
2. The determination of the fluid component of effective stress as it affects stability in slopes, excavations, tunnels etc.
3. The determination of fluid flow and storage changes in the ground.
   - To understand aquifers and aquicludes in water supply
   - To understand ground water inflow into an excavation
4. The determination of leakage characteristics from storage caverns.

All of the above applications require the ability to monitor fluid pressure changes. This is essential for the first case, important for the second, especially where changing groundwater pressures may lead to slope failure and it also matters in the third and fourth cases.

It is therefore important to have a piezometer installation that does not modify the pressure that it is supposed to measure. This means it should respond to changes without a time lag. It should also measure pressure at a point and not attempt to average the measurement by connecting different zones.

2 HISTORY OF PIEZOMETER INSTALLATION

The requirements of not modifying the pressure nor affecting the time response of the piezometer have been conflicting requirements.

Traditionally the piezometer is a standpipe tube which requires a volume change of fluid to cause the water level within it to change. This water must come from the ground, and the normal process used to enable an adequate fluid connection was to fill a section of the hole with sand or gravel surrounding a filter tip at the bottom of the standpipe. Hopefully, but not always, the installation was then completed by sealing the top of the sand with bentonite and the hole above was then cement grouted. The measurement of the water level in these standpipes was normally achieved by running a dipper into the standpipe and registering the level of the water within it. In some, tubes were inserted into the standpipe, compressed air was pumped down these and the pressure required to achieve flow was measured by a pressure transducer arrangement at surface.

With the advent of suitable pressure transducers, these could simply be placed in the standpipe to monitor the changing head. This did not change the behaviour of the standpipe with respect to its connection to the ground. Such use also meant that the pressure transducer could be checked by pulling it up and down within the standpipe and measuring that the pressures indicated matched the change in height. In the event of a transducer failure, it could be readily replaced.

The next development in piezometer installation was to omit the standpipe and simply install the pressure transducer in the sand pack with the normal completion by bentonite and cement grout. The problem with this kind of installation is that a transducer calibration cannot be checked and if it fails, it cannot be replaced.

In 1961 Penman showed that it was possible to measure fluid pressure in London Clay without the use of a sand pack.

Where multiple levels of pressure measurements are required in a borehole, the use of standpipes became a limiting factor. Practically, only two could be installed in a typical site investigation borehole of 100 mm diameter. The difficulty with such installations is getting the filter pack in place, the time involved in this and the double cement grouting operation. This made piezometer installation very expensive. Deep installations were particularly time consuming and difficult.

The next development was the idea that if the pressure transducer had near zero volumetric change to operate its sensing diaphragm, then it could be cemented directly into the ground. This type of installation requires some means to protect the diaphragm from being locked in place by the cement grout. It also requires a suitable connection between the transducer diaphragm and the ground, via the cement grout. This meant that the cement grout must be permeable. The usual process was to use a cement grout that was relatively low in cement with a high content of bentonite. The immediate apparent benefit of such an installation is that multiple transducers might be installed within a borehole. All that was required was a pipe to enable the cement grout to be pumped to the bottom of the hole and for transducers to be hung in the hole or strapped to the grout pipe to enable the installation to take place.

The problem with this approach is that having a permeable cement grout means that there is intra-connection within the borehole. The argument presented against this is that this intra-connection is minor compared to the connection to the ground which is much closer to the transducer as it is the borehole wall. This argument is dependent on the permeability of the ground, compared to that of the cement grout and also the way in which the cement grout may penetrate into the ground, thus sealing the pores and fissures adjacent to the borehole. The problem that the pressure transducer is neither checkable nor replaceable in such installations remains.

3 REAL PIEZOMETER INSTALLTIONS

The three installations covered in this section are from the Authors' direct experience.

3.1 *Po Shan Drainage Works*

In 1986-1987 the Hong Kong Government undertook a study of the slope adjacent to the Po Shan landslide site of 1972 in which three tower blocks were destroyed and 69 people died. The site investigation involved the installation of multiple piezometers which were installed carefully using the traditional approach of a sand pack, bentonite pellet seal and cement grout placed around a conduit. These were mostly monitored by air bubbler systems. The ground was colluvium overlying volcanic rock below. While a number of these piezometers were installed below the permanent water table, some were installed above this in an area that was thought likely to suffer from perched water tables. There was concern that these perched water tables would suffer rapid pressure rises during heavy rainfall and this would lead to landslides.

These piezometers subsequently showed a rapid response to rainfall and it was decided to install a horizontal drain system to control the water pressure in these as well as that in the permanently saturated ground below. The horizontal drains that penetrated the apparent perched water tables failed to flow, even in the heaviest of rainfall, while those in below the main water table flowed reliably.

The conclusion drawn from this was that the perched water tables did not exist and that what was measured was an artefact of the piezometer installation method. Water had entered the sand pack and had partially or fully filled it generating a saturated column therein. This was a function of the differing permeability of the sand pack and the ground. It should be appreciated, that water that is freely flowing under gravity through a uniform porous medium, does not generate pressure. This is important from the viewpoint of understanding the fluid pressure component of effective stress.

3.2 *Cut 3 Investigation, Centennial Highway, SE Queensland*

In 2008-2009 a detailed hydrogeological investigation was undertaken of a moving cut slope adjacent to a new highway. The slope was one of highly fractured trachyte and basalt overlying sedimentary deposits up to 60 m below surface. The movement was of the order of 1 mm per day and accelerated during the wet to 3 mm per day, Gray et al (2013).

The purpose of the hydrogeological study was to determine whether drainage could be used to slow the movement. The fractured nature of the rock meant that it was completely impractical to attempt to cement grout piezometers into the rock mass, as the grout would not only be lost but would penetrate the fractures, thus changing the permeability and connection to the borehole and the piezometer. The piezometers were therefore installed conventionally using a slotted tube surrounded by a sand pack to near surface and the remainder of the hole filled with a sand -cement mortar.

The installation worked well with automatic piezometric monitoring being used to record pumping tests and then the response to rainfall events over many years.

3.3 *Deep Piezometer Installation to Monitor Groundwater, Metropolitan Colliery, Illawarra Region, NSW*

In 2010-2013 a large number of piezometers were installed into 600 m deep boreholes through coal measure formations and the overlying sedimentary strata. The purpose of these installations was to determine the effects of longwall mining on piezometric response with specific relation to the effect that mining would have on surface reservoirs.

These piezometers were installed by what was then becoming the popular method of simply cement grouting the piezometer into the borehole. In this, the pressure transducer was strapped to the grout pipe and its tip was protected by grease. The hole was then filled with cement grout. The grout then went through the hydration process and the pressure at each of the piezometer tips dropped to a few hundred kPa, despite the static ground water pressure being from 1500 to 4000 kPa. The pressure recovered substantially after two days but then required three months to reach equilibrium.

The drop in pressure was certainly due to hydration. However, a drop in this magnitude would not have been expected with the water-cement ratio. Neither should the local permeability have been lost to this degree. It was deduced that the cement grout had lost substantial water into the rock around the borehole and that it had become extremely impermeable.

Another problem faced in similar installations, is that of the grout pressure, during installation, is sufficient to cause fracturing of the borehole wall.

4 CEMENT GROUT INSTALLATIONS

Vaughan (1969) suggested that grouted in piezometers could operate with a cement grout up to two orders of magnitude greater permeability than the surrounding ground. Contreras, Grosser and Ver Strate (2008) revised this to three orders of magnitude. The basis of this was numerical models with vertical flow.

What these models have failed to take into account is the behaviour of cement grout on the inside of the hole. If the pressure of the cement grout in the hole is greater than fluid pressure in the ground, there will be a tendency for an outward flow of liquid into the ground with plugging of pores and fractures. This then leaves a cement grout near the hole wall that is of much lower water cement ratio than that designed and hence much lower permeability. This effect was well demonstrated by the last field example.

A practical and quite testable analogue of this is the process of casting lean concrete against a filter cloth in the hope that a permeable structure will be created. All that happens is a cement smear clogs the filter cloth, making an effective water barrier between the ground and the concrete.

The work by Mikkelsen and Green (2003) focuses on very lean cement grouts with water cement ratios that are greater than two and with substantial bentonite fractions. These are permeable and quite unsuited for permeability measurement in lower permeability ground even without filtration effects.

If the cement grout does not have a pressure that is higher than that of the ground fluids, then inflow can take place. Channelling will take place in the cement grout with the result that an imperfect seal is created. This is also the case if there is shrinkage of the cement grout. The result of either of these is that there is intra-connection within the borehole. This is seldom detected because pressure transducers within the hole show a pressure that approximates to hydrostatic and the result is considered to be normal and is not questioned.

An alternative approach to cement grouts is to make them as impermeable as possible. This removes concerns about what the permeability is as it is close to zero. This is the approach used by the author. What it does however require is a definite connection from the transducer diaphragm to the surrounding ground.

If cement grouts with a water/cement ratio of around 0.6 are used they have very low permeabilities. They can be made to be pumpable with superplasticisers and a very small quantity of bentonite (1%) keeps the cement in suspension so that segregation in the borehole is avoided. This sort of cement grout is quite suitable for use in rock and also for soils that will not shrink or expand. Alternatively, more plastic grouts can be made using higher bentonite contents but care needs to be taken to test any cement bentonite mixture, because it is quite dependent on the actual cement and bentonite used. These are not uniform materials but depend on the individual sources of supply.

Where low water/cement ratio grouts are used, their densities will become higher. A cement grout with water/cement ratio of

0.6 will have a density of approximately 1700 kg/m^3 This can lead to pressures that are well above hydrostatic, and may in many circumstances, be above the horizontal stress in the ground with the consequence that hydrofracturing occurs. This can be prevented by cement grouting in stages, or by the use of cenospheres. These are very small hollow spherical ceramic bubbles which are frequently incorporated into cements used in oilfield applications to reduce their density.

4 ALTERNATIVE CEMENT GROUT PIEZOMETER INSTALLATION PROCEDURES

The approach of a near zero permeability cement grout requires that some mechanism can be used which enables the diaphragm of the pressure transducer to be connected to the ground. The method chosen is called cement displacement. This installation can be used with or without a local pressure transducer, depending on the ground fluid and its pressure.

Such an installation procedure is shown in Figure 1. In schematic A, the pressure transducer is shown hanging in the borehole adjacent to a grout pipe, though in reality it will be strapped to it. The transducer is connected to an electrical cable. The pressure transducer's diaphragm is connected to a manifold. The manifold has a pressure relief valve connected to it and above this is an injection tube which runs to surface. The action of the pressure relief valve is to support the water column in the injection tube.

The manifold is connected to the borehole by a filter. In the first stage, shown in schematic A, the filter is pumped clean. In schematic B, the borehole is grouted. In schematic C, a small amount of water (100 ml) is pushed through the injection tube, past the pressure relief valve, into the manifold and out through the filter to ensure that the filter is not blocked by cement grout. In schematic D, the cement grout is displaced from around the filter by more water (1000 ml). The cement grout is then permitted to set.

Following the setting of the cement grout, more fluid may be pumped through the injection tube. This raises the pressure in the pressure transducer which should dissipate as it drains away. This is how this system is tested.

The system is eminently suitable for multiple piezometer installation and has been used in successfully in tens of boreholes of 300 to 600 m depth. Testing in these cases also permits the detection of any intra-borehole connection. This has generally been very good and in the case shown in Figure 2, piezometers S2 and S3 are located 4 m apart, at some 360 m depth with a 300 mm thick tuff band in between. Pumping in either of these shows no effect on the adjacent piezometer and shows suitable leak off into the formation. The slight pressure rises are due to the expansion of the nylon tube used as an injection tube. The nylon tube can be replaced by a stainless steel tube in deeper holes. Normally a 3 metre separation ensures no intra-hole connection with perfectly good connection to the ground.

The system described has the pressure transducer cement grouted into the borehole. It is therefore impossible to replace it if it fails. A variant of this is to cement a conduit into the hole and conduct the cement displacement process at its end. The conduit may then be fitted with a packer and a pressure transducer. Here the packer stops the need for a changing volume of water to generate a pressure head within the conduit. The packer and transducer are also removable for servicing.

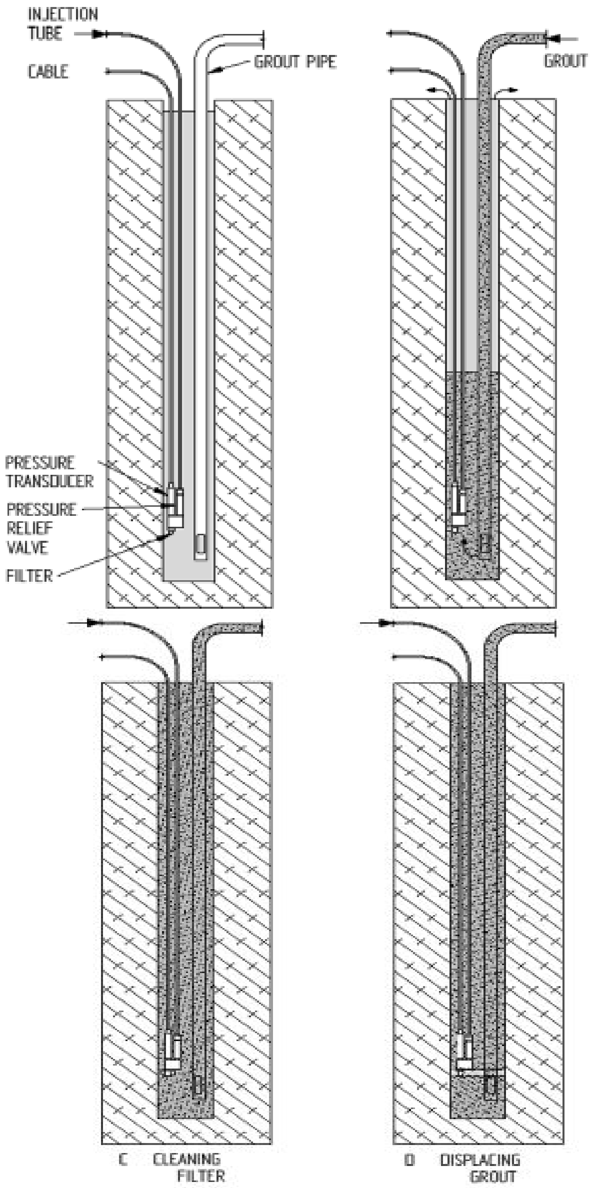

Figure 1. Cement displacement piezometer installation process

The conduit may be borehole casing or alternatively, a narrow tube (3 mm inside diameter) connected to a larger conduit in the upper levels of the borehole, so that a packer and pressure transducer may be installed therein. This latter system is only suitable if the fluid in the hole has a pressure that would cause it to rise into the larger conduit. Another advantage of this system is that it allows the use of lower pressure range, more accurate, pressure transducers to monitor pressure changes. In the event of some blockage occurring at the tip, it is also possible to remove the packer-piezometer and hydrofracture through the cement grout into the formation. Figure 3 schematically shows such an installation.

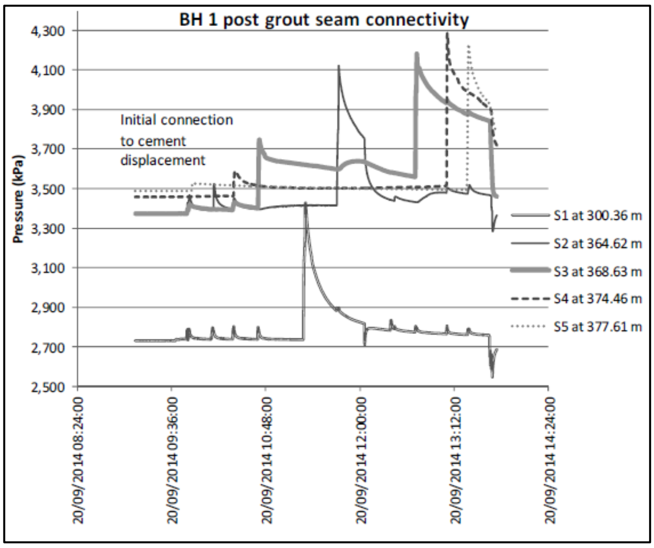

Figure 2. Pressure testing piezometers in a 380 m hole in coal measures.

The problem of hydrofracture caused by too high a cement grout pressure within the hole must be dealt with by either using a low density grout, such as that containing cenospheres, or grouting in stages. In a large enough borehole, it may be possible to run multiple grout pipes so that grouting may be accomplished in stages. Generally, this is not suitable though, and stage valves to permit multiple cement grouting levels within a single hole have been developed. In these the first volume of cement grout is pumped and at its end a dart is pumped down the grout pipe. This dart lands on a shuttle within a valve, closing the grout pipe below and opening a port above. Water is then circulated through the opened port to remove any cement grout and establish a clean return flow. The first stage cement grout is then permitted to set and a second stage cement grouting may be completed. Multiple stage valves may be used. It is standard practice to use one stage valve in cementing 400 m deep holes in sedimentary measures in eastern Australia to prevent the occurrence of hydrofracturing during cement grouting operations.

While reference is made here to deep piezometer installation, the cement displacement system is equally suitable to shallow piezometers.

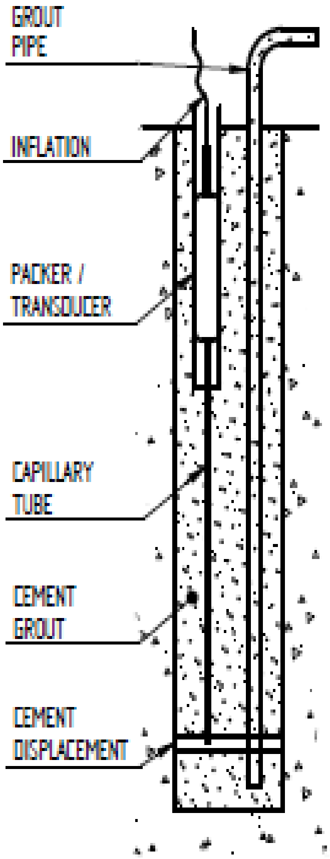

Figure 3. A capillary tube connected to the ground by cement displacement and attached to a larger tube containing a small packer and pressure transducer.

5 WHERE CEMENT GROUT INSTALLATIONS ARE NOT SUITABLE

Cement grout piezometer installations are not universally suitable. This is particularly the case where the ground is rock that contains substantial fractures or voids, such as solution cavities or vugs. The problem is that the cement will disappear into these. What is needed is a packer system to seal between zones within the borehole.

The kind of packers that may be considered are inflatable ones and those made of swellable elastomers. Swellable packers are used regularly in the oil and gas industry, usually to seal casing or tubing strings. They work by reacting with the fluid in the well and can withstand very substantial differential pressures and last for long periods. If the zone of a borehole in which a seal is made is always full of water, then swellable packers are a good choice. A suitable choice of swellable elastomer needs to be made so that the equipment can be run in hole before swelling locks the system in place. Different compounds may be made up by the manufacturers of swell packers.

In the case where the hole may be dry for much of the time, inflatable packers may be considered. They cannot however be regarded as permanent installations and will require pressure monitoring over time with the probability that some form of topping up of pressure will be required.

An alternative to inflatable packers is a reactive chemical seal. Some of the urethane resins are designed to react with water and form a closed cell foam that, with proper design, will form a seal. All packer installations require attention to their capacity to withstand absolute pressure and differential pressure across the packer element. This applies particularly to seals based on expanding foams as the pressure of the gas generated within the reaction and which holds the cells open may be inadequate for a particular sealing need.

Inflatable packers may be used to great advantage to seal within the casing of a water production well. Doing this eliminates the problems of well bore storage causing delays in piezometric response to testing in adjacent wells.

5 CONCLUSIONS

A piezometer installation has the task of measuring pressure at a point in the ground. It is not supposed to measure some sort of average pressure across a wide zone. To achieve this, the zone in connection with the ground, needs to be limited in size. Doing this means that there is a restriction on the length of borehole that can supply fluid to actuate the pressure measurement system. It should also be considered that long sand or gravel packs may act as collection chambers leading to false groundwater pressure readings. The extremely low volumetric requirements for diaphragm movement of pressure transducers, makes pressure measurement work with very little movement of fluid.

Despite this, the risk for cement grouted piezometer installations to have very poor connection to the ground leading to lags of some months is a reality. The present approach of cementing using cement grouts that can block the connection to the ground and where their permeability may lead to borehole intra-connection is real. That these installations are not testable is also considered to be unsatisfactory.

Rather than take the approach of using permeable cement grouts to achieve a connection between the transducer and the ground the approach recommended is different. It involves using a very impermeable cement grout that can be used so as to ensure there is no intra-connection within the borehole. This is then connected to the ground by the process of cement displacement which involves injecting water into the zone around the pressure transducer so as to locally clear it of cement grout. This has been shown to work in multiple installations. It is also testable. The high density cement grout also reduces the risk of shrinkage and channelling due to high ground fluid pressures and differential pressures between sections of the hole.

An alternative form of this installation, where the head of groundwater is adequate, is to use a narrow diameter tube reaching up from the point of measurement. This narrow tube is connected to a larger diameter conduit in the upper levels of the borehole. The hole is cement grouted using the cement displacement technique and the pressure is monitored by a high level pressure transducer located with a packer in the larger conduit. This is both a testable system and one in which the pressure transducer may be changed if it fails.

The risk of hydrofracturing the ground by excessive pressure of cement grout in the borehole is addressed by the use of stage grouting. This is facilitated by the use of stage valves which enable grout ports to be closed and other opened in the grout pipe.

There are still cases where grouted installations are not suitable. They are usually related to fractured rock. These may in some cases be fitted with gravel packs and pressure transducers. Where fracture groups are to be monitored, then these should be isolated with packers. The use of swell packers is recommended if the hole is always water filled. If the hole is for the most part dry, then inflatable packers or chemically seals need to be considered.

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