Piezometers in Fully Grouted Boreholes

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ABSTRACT: For decades it has been common practice in the geotechnical industry to install diaphragm piezometers (pore pressure sensors) in boreholes using methods developed for standpipe piezometers in saturated soil (Dunnicliff, 1988, 1993). Surrounding a diaphragm piezometer with a poured-in sand pocket and placing a bentonite seal above it is at best a laborious process and can in the worst case be so difficult that the installation becomes a total failure. This paper argues that traditional methods should be abandoned and that pneumatic and vibrating wire diaphragm piezometers can be more simply installed directly surrounding them with cement-bentonite grout in the borehole. The method is not only easier and faster, but has a much better chance of succeeding in measuring the correct ground water pressure. A review of key papers shows that this idea is not new, but that only recently have fully grouted diaphragm piezometers begun to be employed in practice. The fully grouted method also makes it feasible to install multiple piezometers and to install piezometers together with other instruments in a single borehole. A review of traditional practice is provided as a background for understanding why it is time to change. Note that the proposed fully grouted method of installation only applies to diaphragm piezometers installed in saturated soils and generally excludes conventional standpipe piezometers. Application to unsaturated soils, soils exhibiting positive gas pressures or large negative pressures (suctions) are beyond the scope of this paper.

1 INTRODUCTION

1.1 *Why use a sand pocket?*

Open standpipe piezometers shown schematically in Figure 1(a) rely on a sizable intake volume and a narrow pipe diameter to obtain a reading of piezometric head without significant time-lag (Hvorslev, 1951). The volume of sand surrounding the intake filter is a necessary, integral part of the piezometer. The larger the sand volume, the more rapidly water can be delivered to the standpipe to equalize pressure changes. The smaller the standpipe diameter the faster equalization occurs. In contrast, when diaphragm piezometers are utilized to measure piezometric head, only an infinitely small volume of water is required to activate the sensor diaphragm. For diaphragm piezometers such as vibrating wire and pneumatic types in current use, the sand pocket normally specified around the sensor is unnecessary and the time-consuming installation step of sand (and bentonite seal) placement can be eliminated. They can more simply and effectively be fully grouted into the borehole as shown in Figure 1(b).

1.2 *Why use a conventional bentonite seal?*

Proper isolation of the piezometer sensor intake along the length of the borehole is necessary in order to obtain a correct pore water pressure measurement. Sealing a conventional standpipe piezometer can still be achieved by fully grouting the borehole above the sand and eliminating the conventional bentonite seal shown in Figure 1(a). The grout itself forms an adequate low permeability seal. It is common practice to place a bentonite pellet or chip seal above the sand. The bentonite is allowed to partially hydrate before tremie-grouting the rest of the borehole. This practice should also be abandoned in order to simplify the installation procedure. The bentonite seal in Figure 1(a) is redundant, but is perceived to be necessary to protect the sand from being disturbed during grouting and being grouted. Assuming the sand zone to be saturated, grout with a creamy consistency would penetrate the sand only a few inches. Grouting directly above the sand can be done provided excessive initial pump pressures are avoided and the tremie is prevented from acting like a jet nozzle directly into the sand. Side port exits from the tremie will prevent this. An extra few feet of sand can also help.
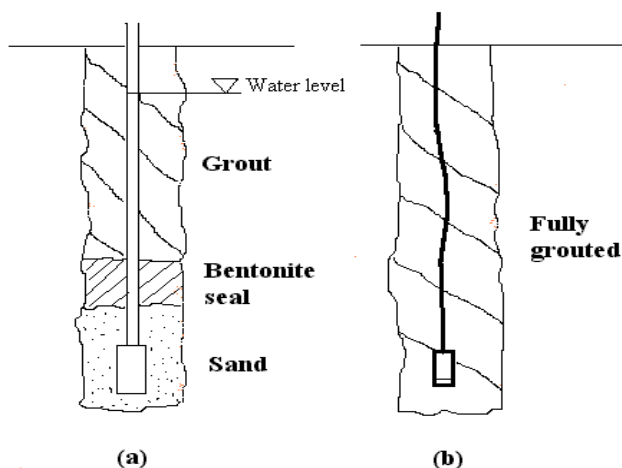

Figure 1. (a) Open standpipe piezometer. (b) Diaphragm piezometer

2 BACKGROUND

2.1 *Forgotten test results*

In 1961 Penman demonstrated the vast difference in response times between open standpipe, twin-tube hydraulic and diaphragm type piezometers. Various piezometers were pressed into reconstituted London clay with a permeability of 3.4×10^{-8} cm/sec, essentially the same as bentonite clay. Theoretical and experimental results showed how little time was required to equilibrate diaphragm sensors during 20 and 30 psi loading steps and that they responded in a matter of minutes or less (Penman, 1961). The significance of this paper has been largely overlooked with respect to piezometer installation in boreholes. Whereas pushing or embedding piezometers directly into compacted or soft clay without a sand-pocket is an accepted procedure, a borehole piezometer is not normally installed without a substantial volume of sand around it. Current worldwide practice for installing standpipes and diaphragm piezometers are essentially identical. Penman's 1961 paper demonstrates that diaphragm sensors are clearly different from open standpipes and twin-tube hydraulic piezometers. His studies demonstrated that a vibrating wire piezometer responds extremely rapidly if embedded directly in a clay material similar to bentonite. Surrounding a diaphragm piezometer in the borehole with a cement-bentonite grout with a similar low permeability is sound engineering.

2.2 *Ignored theory*

A diaphragm piezometer embedded directly in a low permeability saturated clay strata or a large mass of low permeability cement-bentonite grout should respond instantly to a pore water pressure change. Effective stress principles and consolidation theory are well understood and accepted in long-standing soil mechanics practice. A saturated clay layer initially responds to an applied stress increment, $\Delta\sigma$, by an increase in pore water pressure, $\Delta u = \Delta\sigma$ throughout the layer. Unfortunately the application of these principles to diaphragm piezometer equalization and appropriate installation details has been largely ignored.

   With the aid of Darcy's Law, Vaughan (1969, 1973) established that for very small diameter standpipe piezometers the grouted section of the borehole can have a permeability greater than one or even two orders of magnitude higher than the surrounding formation without degrading the measured pore water pressure. This is particularly significant in fat clays with a permeability of 10^{-8} cm/sec or less. Use of a higher permeability borehole seal is possible because of the much higher horizontal hydraulic gradients adjacent to the piezometer than the vertical gradients along the grouted borehole. As illustrated in Figure 2, radial pressure gradients from the borehole wall to the piezometer are normally one to several orders of magnitude greater than those produced vertically from the sensor to some point many feet above in another strata ($R_d \ll L_d$). Radial pressure gradients will control piezometer response. Piezometer A will correctly measure the pore water pressure in the adjacent silty clay and piezometer B will correctly measure the pore water pressure in the adjacent silty sand.
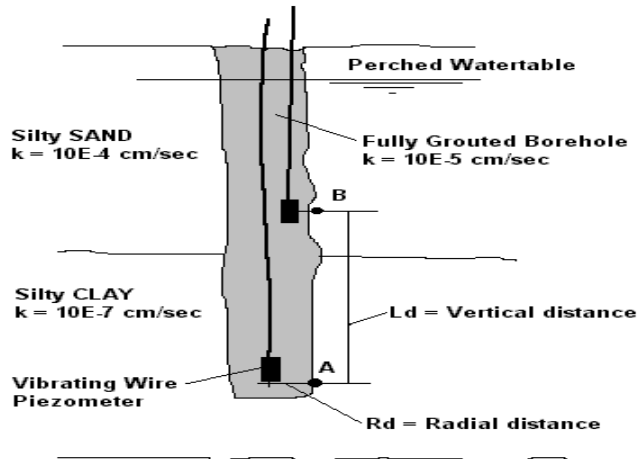

Figure 2. Multi-level piezometer installation.

3 CEMENT-BENTONITE GROUTS

3.1 *Basics*

A bentonite grout backfill consisting of just bentonite and water may not be volumetrically stable and introduces uncertainty about locally introduced pore pressures caused by the hydration process (Mikkelsen, 2002). Introducing cement, even a small amount, neutralizes the expansive properties of the bentonite component once the cement-bentonite grout takes an initial set. The strength of the set grout can be designed to be similar to the surrounding ground by controlling the cement content and adjusting the mix proportions. Controlling the compressibility (modulus) and the permeability is not so easy. Weaker cementitious grouts tend to remain much stiffer than normally consolidated clays of similar strengths. The bentonite solids content has the greatest influence on the permeability of cement-bentonite grout, not the cement content.

Cement-bentonite grouts are easier to use than bentonite grouts, provide a long working time before set and are more forgiving should the user deviate from the design recipe or mixing equipment and method. It is easier to adjust the grout mix in the field for variations in temperature, pH and cleanliness of the water. Pure bentonite grouts must be mixed and deployed by strictly following measured quantities and procedures that are not common among drillers doing test borings.

3.2 *Strength and deformation considerations*

The general rule for grouting any kind of instrument in a borehole is to mimic the strength and deformation characteristics of the surrounding soil rather than the permeability. However, while it is feasible to match strengths, it is unfeasible with the same mix design to match the deformation modulus of cement-bentonite to that of a clay for example. The practical thing to do is to approximate the strength and minimize the area of the grouted annulus. In this way the grout column would only contribute a weak force in the situation where it might be an issue.

Strength data collected informally from various sources over the years are summarized in Figure 3. A trend line drawn through the data points illustrates the decrease in strength with increasing water-cement ratio. The water-cement ratio controls the strength of the set grout (Marsland, 1973). Marsland's rule-of-thumb is to make the 7-day strength of the grout about one quarter that of the surrounding soil.
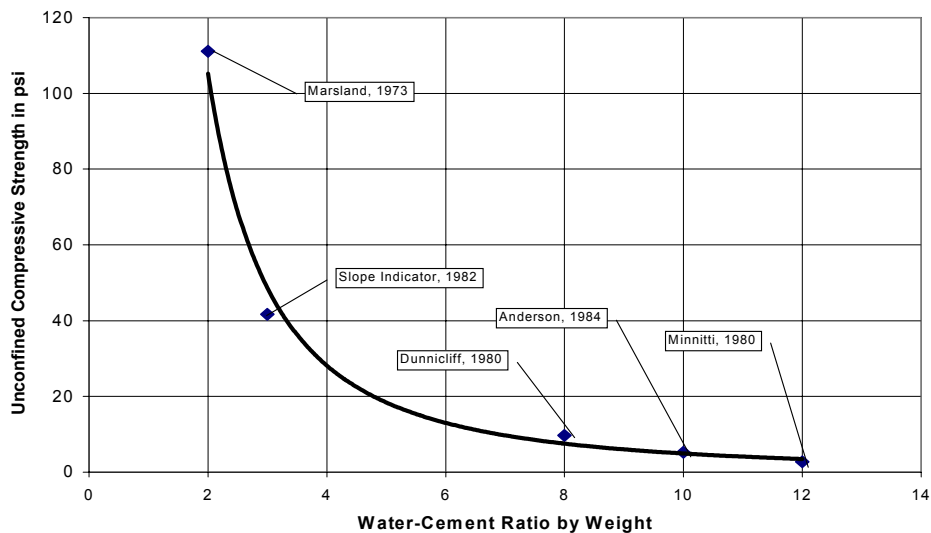

Figure 3. 28-day cement-bentonite grout strength vs. water-cement ratio. Data from authors personal files.

Water and cement in proportions greater than 0.7 to 1 by weight will segregate without the addition of bentonite or some other type of filler material (clay or lime) to suspend the cement uniformly. In all cases sufficient filler is added to suspend the cement and to provide a thick-creamy-but-pumpable grout consistency. The bentonite does not add significant strength to the grout. The background data for Figure 3 also suggests that the amount and type of bentonite or hydrated lime does not influence strength as long as the grout is non-bleeding and pumpable. If the grout bleeds the water-cement ratio decreases and strength increases. If fly ash were to be used as a substitute for cement the strength and modulus would be expected to drop. Fly ash has a smaller amount of cementing agents (calcium and gypsum).

3.3 *Mix design rules*

In order to keep field procedures simple the emphasis should be on controlling the water-cement ratio. This is accomplished by mixing the cement with the water first. When water and cement

are mixed first, the water-cement ratio stays fixed and the strength/modulus of the set grout is more predictable. If bentonite slurry is mixed first, the water-cement ratio cannot be controlled because the addition of cement must stop when the slurry thickens to a consistency that is still pumpable.

Making cement-bentonite grout in the field is a straightforward process. The most effective mixing is commonly done in a barrel or tub with the drill-rig pump, circulating the batch through the pump in 50 to 200 gallon quantities. The rig pump provides the kind of jet-mixing required to get the job done quickly. Any kind of bentonite powder used to make drilling mud combined with Type 1 or 2 Portland cement and water can be used, but the appropriate quantity of bentonite will vary somewhat depending on grade of bentonite, mixing sequence, mixing effort (agitation), water pH and temperature.

Grout mixes should be controlled by weight and proportioned to give the desired strength of the set grout. The conversion factors contained in Appendix H.10 in Dunnicliff (1988, 1993) are very helpful in mix design. Two mixes are given in Table 1 that varies in 28-day strength from 50 psi to 4 psi for water-cement ratios of 2.5 to 6.6 respectively.

Table 1. Cement-bentonite grout, water and cement mixed first.

Application	Grout for Medium to Hard Soils		Grout for Soft Soils	
Materials	Weight	Ratio by Weight	Weight	Ratio by Weight
Water	30 gallons	2.5	75 gallons	6.6
Portland Cement	94 lbs. (1 sack)	1	94 lbs. (1 sack)	1
Bentonite	25 lbs. (as required)	0.3	39 lbs. (as required)	0.4
Notes	The 28-day compressive strength of this mix is about 50 psi, similar to very stiff to hard clay. The modulus is about 10,000 psi.		The 28-day strength of this mix is about 4 psi, similar to very soft clay.	

3.4 *Example mixing procedure.*

A rig pump with one suction hose and a return hose fitted with a jet nozzle in a 50-gallon barrel are the minimum requirements for circulation batch mixing of grout. Paddle or high shear mixers can also be used. A measured quantity of clean water goes into the mixing tub/barrel first and pumping and circulation starts. Then the cement is gradually added to the water and mixed thoroughly. At this stage the mix is like gray water. Next, bentonite powder is slowly added into the jetting area of the barrel, slowly enough so clumps of bentonite do not form. This should be constantly checked by scraping the bottom with a shovel. When clumps form, slow down and do not add any more powder until they are dissolved. Keep adding bentonite until the watery mix transitions to an oily/slimy consistency. Observe the consistency while mixing and let the grout thicken for another five to ten minutes. Generally, the mix thickens some more with added mixing time. Add more bentonite as required. When it is smooth and like thick cream or pancake batter, it is as heavy as is it feasible to pump. Drips of the grout should then barely come off a dipped finger and form "craters" in the fluid surface. That is the correct consistency for pumping the grout batch down the tremie-pipe. When possible, withdraw the tremie after each batch an amount corresponding to the grout level in the boring to keep the pumping pressures as low as possible. When pumping grout 100 feet or more from the borehole, thinner consistency would be required, but at the risk of some bleeding.

Old habits die hard, so that some users will insist on mixing water and bentonite powder first as recommended by Dunnicliff (1988, 1993). This practice should be abandoned for instrument grouts. This is normally the way drilling mud is mixed and it yields more slurry per sack of bentonite than the above method. Also, use of hydrated bentonite with cement added last is common practice in grouting technology for ground improvement. Such mixes are highly thixo

tropic and rely on industrial type mixing plants and methods. The cement content is difficult to control under ordinary field instrumentation installation circumstances.

The amount of bentonite that is required for the above mixing procedure will vary due to factors mentioned earlier. The amount of bentonite shown in Table 1 should only be used as a guide and is also handy for estimating material quantities shipped to the site. With this method more bentonite is required than if water and bentonite was mixed first. This is an advantage from the standpoint of wanting a low permeability. When the bentonite solids content increases, the density increases and the permeability is lowered. It is another reason for mixing water and cement before adding cement. A lower permeability is generally preferred since cement-bentonites have a higher permeability than high-density bentonite grout or chip seals.

4 DIAPHRAGM PIEZOMETERS IN FULLY GROUTED BOREHOLES

4.1 *Recent experience*

Increasingly, both single and multiple vibrating wire and pneumatic pressure sensors are being successfully grouted directly into boreholes without sand pockets and bentonite seals. The idea is not new. Thirty years ago, Vaughan in London demonstrated that even grouted multiple small-diameter standpipes in clay were feasible (Vaughan, 1969). Tofani (2000) has used the procedure for 20 years in California for both pneumatic and vibrating wire piezometers. McKenna (1995) in Canada has adopted the fully grouted installation of piezometer sensors following extensive field testing and McKenna and others (1994) adopted combined inclinometer casing and diaphragm piezometers directly grouted into the same borehole as standard procedures. The US Army Corps of Engineers, Omaha District adopted fully-grouted vibrating wire piezometer installations and included them with deep inclinometer casing installations based on recommendations by the first author (USACE, 1999). But, because the geotechnical community seems to be so rooted in traditional thinking when it comes to sealing a piezometer in a borehole, it is counter-intuitive to most engineers to simply grout the sensors in the boring.

Grout is perceived as a sealant that would prevent the sensor from registering the correct pore pressure, should it get between the soil and the porous element on the piezometer tip. However, based on research 40 years ago (Penman, 1961), that perception is incorrect. Despite research in the 1960s that recognizes the feasibility of direct grouting, it remained largely unrecognized in 1988 when the "redbook" was first published (Dunnicliff, 1988).

4.2 *Grout permeability*

Cement-bentonite grout is a porous solid with a permeability that lies somewhere in the cement and bentonite range mentioned above. Typical published values of permeability are listed in Table 2. Vaughan (1973) quotes a coefficient of permeability for a pumpable cement-bentonite grout mix on the order of 5×10^{-8} cm/sec. For low bentonite solid contents the permeability can be expected to be close to 10^{-6} cm/sec and for higher bentonite solids content it would be close to 10^{-8} cm/sec. So the issue is really not if this method works, but how well does it work and what, if any, are the limitations involved with the use of vibrating wire sensors or pneumatic sensors.

Table 2. Permeability, k, of some grouts.

Grout Type	Characteristics	k (cm/sec)	Source
Neat cement	w/c ratio = 0.89 to 0.53	10^{-5} to 10^{-7}	Baroid
Bentonite chips	hydrated	10^{-8}	Baroid
Bentonite slurry	6 % solids	10^{-5}	Baroid
Bentonite slurry	20 % solids	10^{-8}	Baroid
Cement-bentonite	water/solids = 4 to 1	10^{-6}	Vaughan, 1969
Cement-bentonite	w : c : b = 4 : 1 : 1	5×10^{-8}	Vaughan, 1973

4.3 *Vibrating wire vs. pneumatic piezometers*

Response tests (Penman, 1961; Tofani, 2000; McKenna, 1995; Mikkelsen and Slope Indicator Co., 2000) all show that both vibrating wire and pneumatic sensors stabilize after a pressure change in a matter of seconds to several minutes. Examples of recent response testing on a vibrating wire piezometer embedded in cement-bentonite grout are shown in Figures 4 and 5 (Mikkelsen and Slope Indicator Co., 2000). However, it should be recognized that vibrating wire and other electrical sensors have an advantage over pneumatic sensors. The volume of fluid displaced at a vibrating wire diaphragm during a pressure change is extremely small, so that system equilibrium is rapid. During reading, no actual displacement of the diaphragm occurs. In contrast, the diaphragm of a pneumatic sensor has to displace a small amount of pore-fluid every time the sensor is activated to take a reading. Experience demonstrates that a small amount of undisolved air must be present in the intake area of the sensor for it to work properly in low permeability clay. A fully saturated pneumatic sensor embedded in clay must overcome the total soil pressure for initial movement of the diaphragm. Obtaining a stable, reliable pore water pressure reading is not only time-consuming, but also often nearly impossible to get. A pneumatic piezometer should be installed without any special effort to remove all the air outside the diaphragm. It is a necessary compromise with an obvious sacrifice in response in low permeability clay. In contrast, a vibrating wire piezometer should be installed upside down, fastened to its cable and flooded with water to discourage air from collecting against the diaphragm.
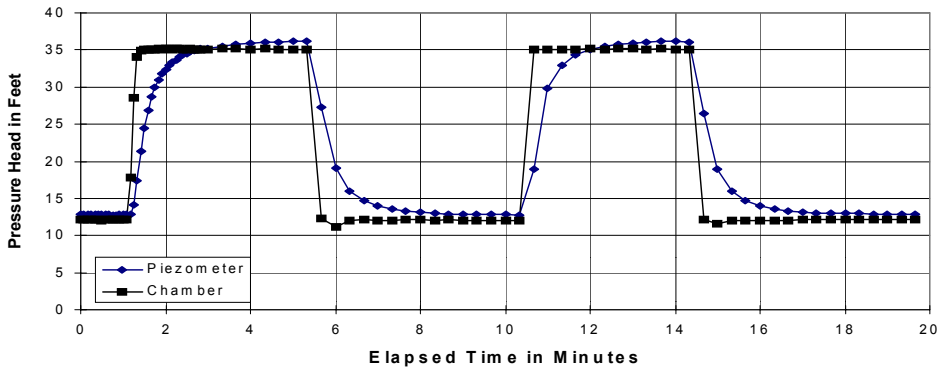
Figure 4. Vibrating wire piezometer response after 288 days cure. Piezometer embedded under 200 mm of cement-bentonite grout inside chamber. Pressure applied above grout surface and piezometer response recorded.
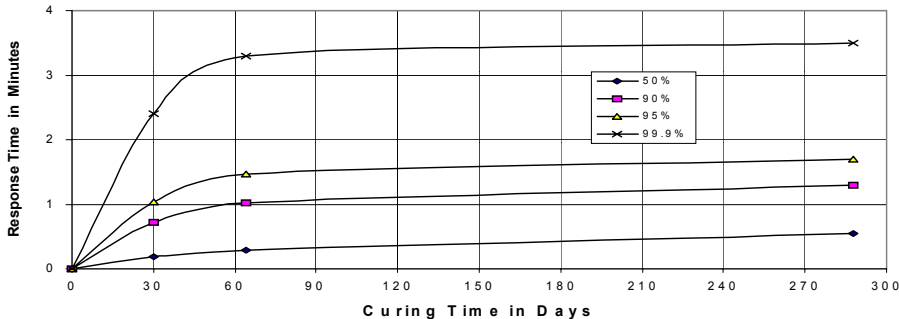
Figure 5. Vibrating wire piezometer response time vs. grout curing time.

As a practical matter, lowering a diaphragm piezometer down a water or mud-filled borehole usually requires added weight to keep the cable or tube straight and counteract buoyancy and borehole stickiness. A short length of re-bar can be attached. A better method, especially for the pneumatic sensors, is to enclose the sensor in a 1.5 to 2-inch diameter, sand-filled geo-textile (or

canvas) sock. This will encourage entrapment of a small amount of free air. Diaphragm piezometers can be directly attached to inclinometer casing during assembly without the re-bar or the sand-filled sock. As a final note, pneumatic piezometers are generally unsuitable for measuring negative (sub-atmospheric) pressure whereas the vibrating wire piezometers are quite capable of measurements to 7 psi (50 kPa) below ambient atmospheric pressure.

4.4 *Cement-bentonite as a high air-entry filter*

As a side issue, the cement-bentonite grout discussed herein also offers advantages of interest for pore water suction measurements in partially saturated soils. During the preparation of this article it was pointed out (Vaughan, 2001) that cement-based grouts have an air entry value up to about 100 psi, a property required for measurement of negative pore pressures. The grout, when set, becomes a perfectly saturated porous material, a far easier task than pre-saturating a high-air entry ceramic filter and deploying it down a borehole. A vibrating wire piezometer fully grouted within cement-bentonite grout can therefore be expected to measure negative pore water pressure or suction. Research is currently in progress in the UK on the role of grouts surrounding directly grouted-in piezometer tips designed to measure suction and the air entry value of grouts.

5 MULTIPLE PIEZOMETERS IN A BOREHOLE

5.1 *Simplicity and reduced cost*

The borehole is the highest cost component of an instrument installation, so that there is a great incentive to put more than one sensor or more instrument types for that matter, in the same borehole. Debate has surrounded this topic in the past, because of the perceived lack of ability to seal around multiple cables, pipes and tubes in one boring. It is the author's opinion that most difficulties arise from dealing with rigid standpipes and attempting to place multiple sand/bentonite seals. Elimination of multiple rigid pipes, poured-in sand-pockets, bentonite layers and opportunity for multiple down-hole measurements, are considerable benefits.

   The ability to reliably install two, three or more piezometers in one borehole has enormous attractions. Vibrating wire piezometer sensors in fully grouted boreholes practically eliminates the risk of installation failure. The sensors should probably be spaced no closer than 10 to 20 feet apart. An option exists for users who remain skeptical about introducing grout between the soil and the porous piezometer filter. An enlarged porous pad directly attached to the piezometer sensor can be pressed directly against the borehole wall by springs (Green, 2000). Mechanical and hydraulic jacks have been used in Norway to achieve direct contact and a spring-actuated system was used successfully on a very deep installation in Canada. Pneumatically released spring-loaded multi-level piezometers are now available from Geokon for installation in fully grouted boreholes. Whether or not the spring-actuated system is used should not detract from the data quality; its use may encourage skeptics to go fully grouted.

5.2 *Installation methods*

A number of basic installation methods can be successfully employed depending on drilling method, borehole stability and user preferences. Variations in these methods may be appropriate.

- Install piezometers one by one from bottom up in an open borehole. Grout and withdraw tremie pipe as grouting proceeds. Alternatively, attach piezometers to rigid tremie pipe and leave tremie pipe in place.
- Install piezometers one by one from the bottom up inside casing or hollow stem auger. Attach piezometers to rigid tremie pipe and leave in place while pulling casing or auger.

- Drill and grout hole and pull casing and auger. Install one by one from bottom up in grout filled hole. Add weight to each piezometer as required to overcome viscous resistance while lowering piezometer.
- Attach directly to outside of inclinometer casing midway between casing couplings.
- Attach directly to outside of corrugated polyethylene pipe (Sondex) or similarly attach to magnet/reed switch casing between magnet sensors so that pore water pressure and settlement are measured along the same borehole.
- Build a series of vibrating wire piezometers into a coupled 2-inch PVC pipe so that piezometers and cables are inside the PVC pipe, Figure 6. Useful in deep installations inside casing or augers to prevent cable damage during casing or auger rotation during extraction. Tremie-grout outside the PVC pipe. Telescoping couplings may be inserted to accommodate settlement.
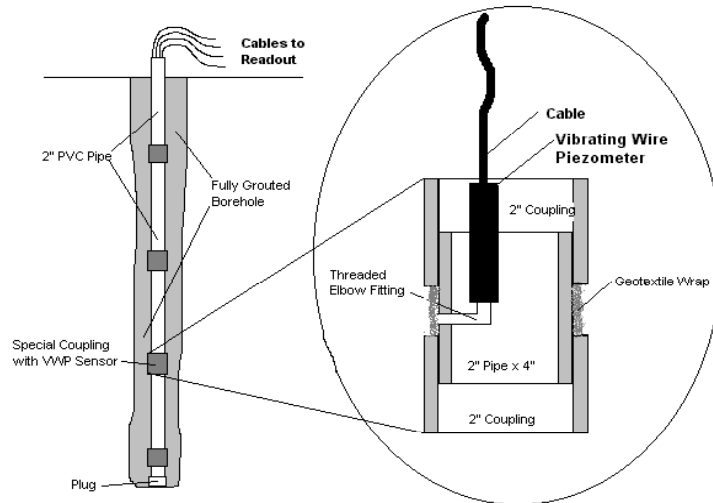

Figure 6. Multi-level piezometers in PVC pipe.

6 CONCLUSIONS

- Theoretically, fully grouted diaphragm piezometers should correctly measure the pore water pressure in the surrounding saturated soil. Effective stress concepts are well established and Darcy's Law helps us understand the significance of how the larger radial pressure gradient at a particular piezometer governs the measured pressure and that the smaller pressure gradients along a grouted borehole severely limits the effect of leakage along the borehole.
- Empirical evidence from Penman (1961) and Vaughan (1969), and more recently by McKenna (1995), Tofani (2000) and the first author, clearly demonstrate that grouted-in diaphragm piezometers should and do work reliably. It is time for fully grouted diaphragm piezometers to be adopted in general without further delay or pending further testing.
- A cement-bentonite grout mixture is the most reliable, versatile, easily mixed and readily pumpable grout for piezometer grouting seals. Poured in place sand pockets placed around the piezometer tip and sealed with compressed bentonite pellets or granular bentonite should be abandoned. Single component bentonite sealing grouts are too difficult to control during mixing, may set up too quickly and if thinned may remain too soft when set.
- A fully grouted diaphragm piezometer is simpler and easier to install and therefore is more reliable. It saves considerable field installation time and is less costly.
- Fully grouted installations facilitate placing multi-level piezometers in a single borehole and provide great savings in drilling and instrument installation cost. They are much simpler and less costly than other multi-level piezometer systems available (e.g. Westbay and Waterloo).

- Multi-level piezometer installations provide more details of pore water pressure/depth profiles in complex strata with irregular ground water regimes, often revealing unrecognized potential failure mechanisms or explaining previously unexplained field behavior.
- Fully grouted installations open up the opportunity to place multiple instrument types in a single borehole, e.g. inclinometers and piezometers.

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