The Use of the Fully-grouted Method for Piezometer Installation
Part 1

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Introduction

The fully-grouted method described in this article entails installing a piezometer tip in a borehole which is backfilled entirely with cement-bentonite grout. Part 1 of this article presents a detailed discussion of the fully-grouted method, including the installation procedure and theoretical background, as well as a seepage-model analysis used to evaluate the impact of the difference in permeabilities between surrounding ground and cement-bentonite grout. Part 2 describes laboratory test results for six cement-bentonite grout mixes and field examples of applications of the fully-grouted method. Both parts of this article are based on the paper, "The Use of the Fully-grouted Method for Piezometer Installation," presented at FMGM 2007: Seventh International Symposium on Field Measurements in Geomechanics, and are published in GIN with permission from ASCE.

A crucial parameter for the success of the fully-grouted method is the permeability of the cement-bentonite grout. Vaughan (1969) postulated that the cement-bentonite grout should have a permeability no greater than two orders of magnitude higher than the surrounding soil in order to obtain representative pore-water pressure readings. Unfortunately, there is limited published data on the permeability of cement-bentonite grout mixes.

Figure 1a shows the typical piezometer installation commonly known as a Casagrande or standpipe piezometer. With this installation, the tip of the piezometer (e.g., slotted PVC pipe or porous stone filter) is surrounded with a high permeability material, commonly referred to as sand pack. Above the sand pack is a bentonite seal typically consisting of bentonite chips or pellets. The installation is finished with cement-bentonite grout to the ground surface. This installation relies on a sizable intake volume and a narrow riser-pipe diameter to obtain a pore-water pressure reading in the riser pipe without significant time lag (Hvorslev, 1951).

With the development of diaphragm piezometers (e.g., pneumatic and vibrating wire), the method developed for standpipe piezometers was used for diaphragm piezometer installations (Dunnicliff, 1993). This has been a common practice for decades and the resulting installation is shown on Figure 1b. However, because of the

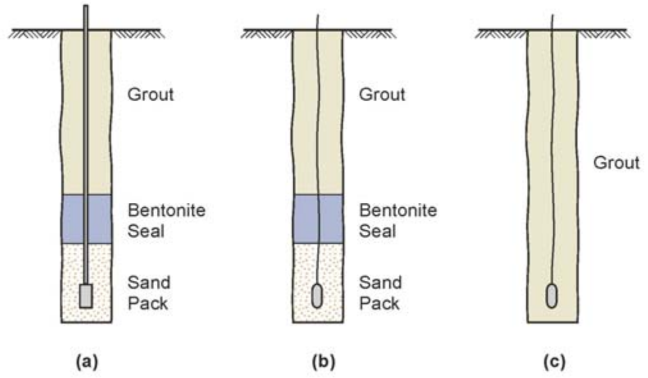

Figure 1(a). Traditional standpipe piezometer with sand pack.
Figure 1(b). Diaphragm piezometer with sand pack.
Figure 1(c). Fully-grouted piezometer.

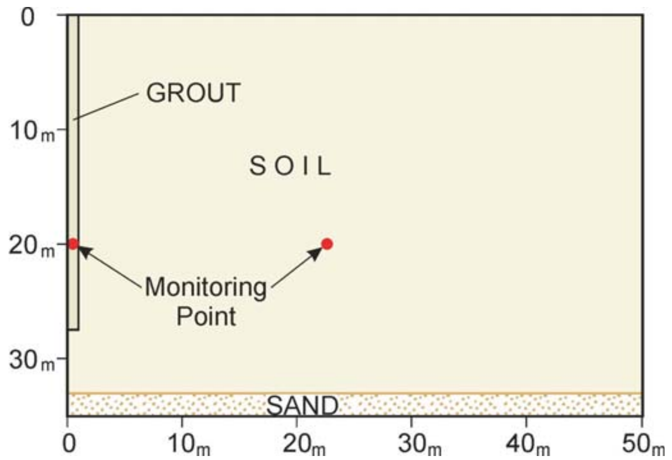

Figure 2. Schematic computer model to simulate seepage around a fully-grouted piezometer (borehole not to scale).

low-volume operation of diaphragm piezometers, the sand pack around the instrument tip is unnecessary, and the diaphragm piezometer can be installed in the borehole surrounded by cement-bentonite grout. This procedure is commonly known as the fully-grouted method (Mikkelsen and Green, 2003) and is shown on Figure 1c.

Fully-grouted Method

Figure 1c shows a piezometer installation using the fully-grouted method, in which a diaphragm piezometer tip is set in a drilled borehole and entirely backfilled with cement-bentonite grout. The following is a detailed description of the installation procedure for a vibrating-wire sensor tip in typical geotechnical boreholes (i.e., 140 mm), including preparation of piezometer assembly and materials, grout mixing, piezometer construction, and theoretical background.

Piezometer Assembly

Construction of the piezometer assembly commonly begins with attachment of the sensor tip to a sacrificial grout pipe. The sacrificial grout pipe, which can be either belled-end electrical conduit or threaded PVC well casing, is generally constructed or laid out on the ground in manageable lengths for handling. The piezometer location is selected by reviewing the soil stratigraphy. The sacrificial grout pipe will generally extend to the bottom of the borehole for support; therefore, it is possible to determine the location of the piezometer tip from the top or bottom of the borehole since the pipe is left in place.

After drilling a borehole, the piezometer tip is attached to the grout pipe at the appropriate location. For boreholes with a diameter of 140 mm, a typical grout pipe (such as 25.4-mm diameter PVC well casing) is used. Large-diameter or stronger grout pipe may be required for deeper installations with higher pumping pressures.

The sensor tip, which has been saturated following the manufacturer's directions, is typically set with the sensor in the upward position to minimize the possibility of desaturation. The cable connected to the sensor tip is attached to the pipe at approximate intervals along the grout pipe, leaving some slack in the line. The grout pipe, sensor tip, and cable are then lowered into the borehole with the grout pipe placed on the bottom for support. The piezometer tip is now located within the desired monitoring zone. The cable is brought to the surface where readings are taken with a readout device.

One advantage of the fully-grouted method is that it can be used for installation of nested piezometers. In a nested piezometer configuration, more than one piezometer tip is attached to the sacrificial grout pipe. The authors have successfully installed up to four piezometer tips in a borehole. During installation the drill casing should be removed carefully to prevent damage to the cables and the cables should be separated around the grout pipe to prevent a direct seepage path along a bundle of cables.

Another advantage of the fully-grouted method is the feasibility of using a single borehole to install more than one type of instrument. For example, the piezometer tips can be attached to an inclinometer casing, and a single borehole is used for measuring both deformation and pore-water pressures, resulting in reduced drilling costs. However, the inclinometer casing joints must be sealed. This technique has been used successfully by the authors on several projects.

Materials

The cement-bentonite mixes described in this article use Type I Portland cement and sodium bentonite powder such as Baroid Aquagel Gold Seal or Quickgel. The water used in the mixes should be potable water to prevent possible interaction of chemical constituents in the water with the cement-bentonite mixture.

Grout Mixing

The mixing procedure described in this article assumes the availability of a capable drill-rig pump and a high-pressure, jet-type nozzle attachment on the end of a mixing hose. In most cases, the drill-rig pump provides enough pressure for the jet-mixing required to obtain a desirable mixture. Other methods may use actual grout-mixing plants. Generally, the cement-bentonite mix is prepared in a barrel or mud tank using the drill-rig pump to circulate the batch with a suction hose and return line. Occasionally, a hydraulically-operated, propeller-type mixer is used. However, it has been the authors' experience that, in some cases (depending on the mix viscosity, pump operability on the drill rig, or grout volume), the use of a grout mixer/pump may be required. Typical batch sizes are 200 to more than 2,000 liters.

The mixing process begins with calculation of the amount of grout required to fill the borehole. A measured quantity of potable water is pumped into the mixing barrel first and circulation begins. During circulation, the water and cement are mixed first so that the water:cement ratio remains fixed and the properties of the grout mix are more predictable. The measured quantity of cement is gradually added to the water until both components have been thoroughly mixed. This is the most important step in the mix preparation and runs contrary to the common practice of mixing bentonite and water first. An initial measured quantity of powdered bentonite, based on a mix design, is added into the barrel near the jet stream to minimize the formation of clumps within the mix. Typically, additional bentonite is added as mixing continues to achieve a "creamy" consistency. Mikkelsen (2002) describes the consistency as "drops of grout should barely come off a dipped finger and should form "craters" in the fluid surface."

Piezometer Construction

At the completion of the grout-mixing process, and after measuring the final density of the mix, the piezometer tip assembly is lowered into the borehole. In shallow boreholes (e.g., typically less than 30 m deep), grout is then pumped into the borehole through the sacrificial grout pipe until it reaches the ground surface. In deeper boreholes, staged grouting using multiple grout pipes or multiple port pipes may be required so the piezometers are not over-pressurized during installation. In cased boreholes, the drill casing is slowly retrieved so that no gap is left between the top of the grout and the bottom of the casing. Typically, the entire process takes approximately one hour for a 30-m borehole. The hole is typically completed with concrete and a protective top.

The field engineer should take pressure readings during and immediately after installation. One benefit of vibrating-wire technology is that readings can be taken quickly. The readings obtained during grouting can be used to determine if the device has been over-pressurized during grouting. The measured pressures should approximately correspond to the pressure exerted by the column of grout above the tip, provided the sensor and grout are at nearly the same temperature, as temperature equalization may take several minutes. However, with time, this pressure decreases as the cement-bentonite mix sets up and pore-water pressure readings are taken at the tip locations. Typically, grout set-up takes one to two days.

Theoretical Background

McKenna (1995) clearly describes the two basic requirements for any piezometer to perform its function. The measured pore-water pressure must be fairly representative of the actual pore-water pressure at the measurement location (i.e., small accuracy error), and the hydrodynamic time lag must be short. At first glance, it does not appear that the fully-grouted method will satisfy these requirements. It would seem that the cement-bentonite grout surrounding the tip might prevent the piezometer from responding quickly to changes in pore-water pressures in the ground due to its low permeability. On the other hand, if the cement-bentonite grout is too permeable to enhance short hydrodynamic time lags, there would be significant vertical fluid flow within the cement-bentonite grout column.

However, the fully-grouted method does satisfy both of McKenna's requirements. A diaphragm piezometer, such as a vibrating wire piezometer, generally requires only a very small volume equalization to respond to water pressure changes (10^{-2} to 10^{-3} cm^3), and the cement-bentonite grout is able to transmit this small volume over the short distance that separates the piezometer tip and the ground in a typical borehole. A practical way to reduce this distance is to set up the tip close to the wall of the borehole by reducing the thickness of grout between the tip and ground using pre-manufactured, expandable piezometer assemblies.

Grout Permeability Requirements

Vaughan (1969) introduced the fully-grouted method and developed closed-form solutions which showed that the error in the measured pressure is significant only when the permeability of the borehole backfill is two orders of magnitude greater than the permeability of the surrounding ground. If the permeability of the cement-bentonite grout is lower than the permeability of the surrounding ground, measured pressures will be without error. As a result, for the fully-grouted method to work, the grout mix used to backfill the borehole must meet certain permeability requirements. A seepage model was developed by the authors to better understand those requirements.

Computer Modeling

A finite-element computer model simulating seepage conditions around a fully-grouted piezometer installation was used to evaluate the impact of grout permeability on the accuracy of the piezometer reading. The seepage model was conducted using SEEP/W, a computer-modeling program developed by GEO-Slope International.

Figure 2 shows the conceptual model developed to simulate the seepage around a piezometer installed using the fully-grouted method. The axisymmetric flow model includes a 7-cm radius, cement-bentonite-grout column surrounded by soil of constant permeability. The simulated cement-bentonite grout column extends 27.5 m and the soil layer extends 33 m below the ground surface with a radius of 50 m. Underlying the soil, a sand layer was incorporated to simulate the lower boundary conditions.

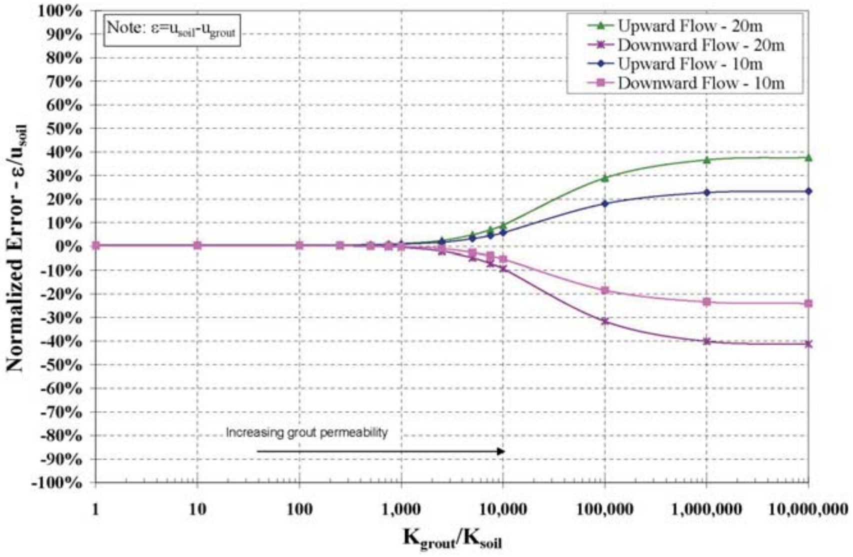

Figure 3. Normalized error versus permeability ratio.

The seepage analyses were performed simulating upward and downward flow using two sets of imposed total head conditions (i.e., 10 and 20 m) that induce flow under steady-state conditions. This set of boundary conditions corresponds to the one-dimensional flow condition in the vertical direction. In all cases, fully saturated conditions were used for all the materials in the model. The error, ε, defined as the difference in computed pore-water pressure between the soil and the grout, was determined during each model run at points in the soil and grout 20 m below the ground surface, as shown on Figure 2.

Results of Computer Modeling

Several model runs were made in which the permeability ratio, k_{grout}/k_{soil}, was varied from 1 to 10^7. Figure 3 shows the results of the seepage simulations in terms of the normalized error, i.e., ε divided by the pore-water pressure in soil, u_{soil}, against the permeability ratio. Figure 3 also shows that the normalized error is zero for all practical purposes up to permeability ratios of 1,000 for downward and upward flow and the two sets of imposed total heads. As the permeability ratio increases beyond 1,000, the normalized error increases up to about ±10 percent at permeability ratios of 10,000. As the permeability ratio continues to increase to 10^7, the normalized error also increases up to about 23 and 40 percent, respectively, for the 10-m and 20-m imposed total heads.

In summary, the finite-element computer model revealed that the permeability of the grout mix can be up to three orders of magnitude greater than the permeability of the surrounding ground without introducing significant error. This finding differs from previous assessments, which indicated that the permeability of the grout mix should only be one or two orders of magnitude greater than the permeability of the surrounding ground. The minimum permeability that is likely to be encountered in natural soils is on the order of 10^{-9} cm/s. As a result, the cement-bentonite grout mix used in the fully-grouted method needs to have a permeability of, at most, 10^{-6} cm/s.

Part 2 of this article will discuss laboratory test results of six cement-bentonite grout mixes and field examples of applications of the fully-grouted method.

The Use of the Fully-grouted Method for Piezometer Installation
Part 2

Laboratory Testing Program

A laboratory testing program was developed to evaluate the range in permeability and strength of cement-bentonite grout for piezometer installations using the fully-grouted method. The test program was designed so that small batches of grout could be mixed in a controlled environment without large grout-batch mixing equipment. Six mix designs were chosen to represent a wide range of values that would reasonably be used on projects.

Sample Preparation

Mixing the grout used for laboratory testing began with calculating the desired quantities of material and then weighing individual portions of cement, water, and bentonite. Additional bentonite was prepared in anticipation

Table 1. Properties of grout constituents			
Mix Component	**Brand**	**Specific Gravity**	**Moisture Content (%)**
Portland Cement Type I	LaFarge	3.15	—
Bentonite Quickgel (Mixes 1-4)	Baroid	2.41 to 2.45	11
Aquagel Gold Seal Bentonite (Mixes 5 and 6)	Baroid	2.4	10

of adjusting the mix viscosity. The properties of the individual mix components used in the laboratory testing are listed in Table 1.

To begin, the cement was added to the water slowly while mixing. The benefit of adding the cement first in the mixing process is that it ensures the correct water:cement ratio before adding the bentonite.

After the cement and water were mixed and the water-cement paste appeared uniform, which generally took five minutes, bentonite was slowly added to the bucket. The cement-bentonite grout was then mixed for approximately five additional minutes until it appeared uniform and did not contain lumps. Viscosity was measured at various times during mixing to evaluate the condition of the mix. Samples of the final mix were taken using plastic molds and the density was measured.

After a short cure period, the samples were carefully extruded out of the plastic molds and stored until the test date. For the Unconfined Compressive Strength testing (UCS), a set of two specimens were tested at 7, 14, and 28 days. Permeability testing was completed on specimens from each mix at 7 and 28 days under three different confining stresses. In addition to strength tests, basic index properties, such as moisture content and dry density of the samples, were also measured.

Laboratory Test Results

Table 2 summarizes the final cement-bentonite grout proportions used in this study. The results of the laboratory testing are presented in a series of figures.

Figure 4 summarizes test results as the average UCS at 28 days versus the water:cement ratio by weight. It shows that the UCS decreases with increasing water:cement ratios. In fact, the UCS at 28 days is approximately 1700 kPa at a water:cement ratio of 2:1; it then decreases to approximately 90 kPa with increasing water:cement ratio. Also included on Figure 4 are data presented by Mikkelsen (2002), which show a relatively strong correlation with the data of this study.

The void ratios of the samples were computed based on the measured water content of the specimens and the specific gravity of the grout-mix constituents. The computed void ratios of the mixes are relatively high, in fact, these are higher than soils with similar strength and permeability. However, the data show that the amount of cement controls the strength characteristics of the grout mix. Bentonite appears to in-

Table 2. Summary of cement-bentonite grout mixes used in the study			
Mix	**Water : Cement : Bentonite by Weight**	**Marsh Funnel Viscosity (sec)**	**Bentonite Type**
1	2.5 : 1: 0.35	50	Quickgel
2	6.55 : 1: 0.40	54	Quickgel
3	3.99 : 1: 0.67	60	Quickgel
4	2.0 : 1: 0.36	360	Quickgel
5	2.49 : 1: 0.41	56	Aquagel Gold Seal
6	6.64 : 1: 1.19	60	Aquagel Gold Seal

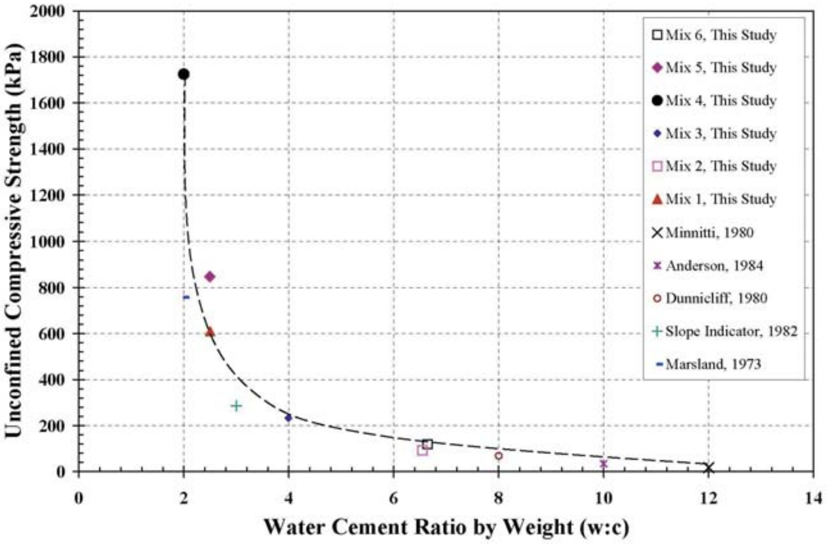

Figure 4. Variation of unconfined compressive strength versus water:cement ratio.

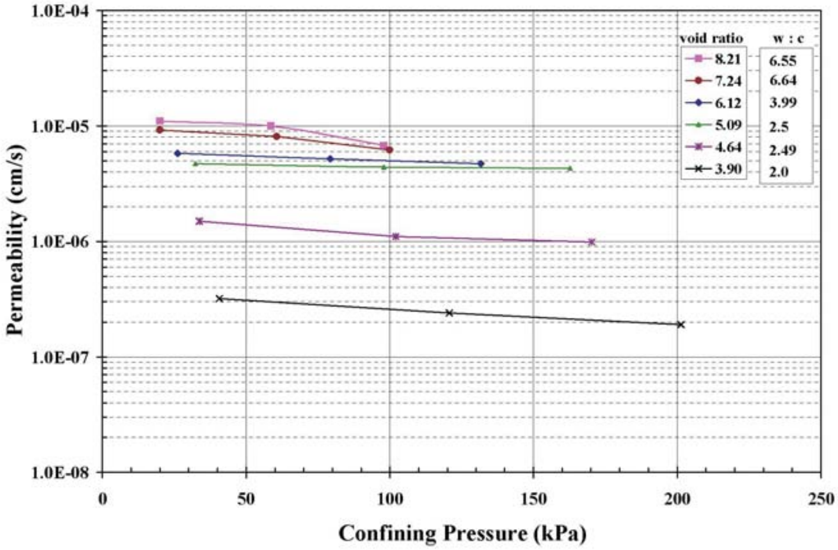

Figure 5. Variation of permeability versus confining pressure at 7 days.

fluence the amount of bleed water and volume change of the specimen during curing. Additional information on the strength and deformation properties of cement-bentonite mixes can be found in Contreras, et al. (2007).

Figure 5 summarizes the test results in terms of the permeability of the specimens at seven days for various confining pressures. The data show that samples with a higher water:cement ratio or void ratio have higher permeability than those with lower water:cement ratios.

Figure 6 shows the permeability in the same format for specimens at 28 days. Data are very similar, showing that the permeability is relatively constant or decreases slightly with confining pressure. One important result is that, from seven to 28 days, the permeability continues to decrease. For example, mixes with 2.49 water:cement ratio indicate a permeability greater than 1.0x10^{-6} cm/sec at 7 days and less than 1.0x10^{-6} cm/sec at 28 days. The data indicate that, as hydration of the cement occurs, the permeability of the mix decreases. The high void ratio and low permeability are two reasons the fully-grouted method works; it allows transmission of a low volume of water over a short distance yet maintains overall low permeability in the vertical direction.

Figure 7 shows the variation in permeability data with respect to void ratio. The data indicate that specimens with lower void ratios typically exhibit lower permeability, while those with higher void ratios exhibit higher permeability. With grout mixes, the cement has a greater influence on the void ratio than the bentonite and is considered the controlling factor in the permeability of the grout. The difference between the seven and 28-day permeability is relatively small, as shown on Figure 7.

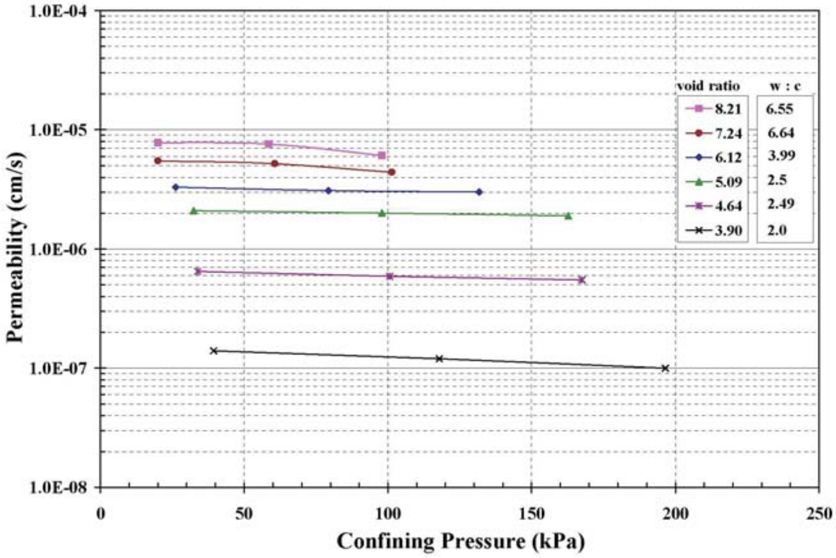

Figure 6. Variation of permeability versus confining pressure at 28 days.

Field Examples

This section describes three field examples in which the fully-grouted method was successfully applied. The first example compares pressure readings between one installation using the fully-grouted method in a nested configuration and the traditional approach with individual piezometer installations in separate boreholes. The second example describes use of the fully-grouted method with the installation of nested piezometers in an upward-flow condition. The third example is for a nested, fully-grouted method installation in a downward-flow condition.

Example 1. Comparison Between Nested and Individual Installations

This field example compares two methods of installation:

- Three vibrating-wire piezometers in a single borehole using the fully-grouted method.
- Four individual pneumatic piezometers in separate boreholes using the traditional sand pack around the piezometer tips.

The two installations were within 7.5 m of each other. As a result, some differences in the pressure readings were expected. Figure 8 shows a comparison of the pore-water pressure profile with elevation for both installations. The figure illustrates a fairly similar response considering the distance between the two sets. Similar data have been presented

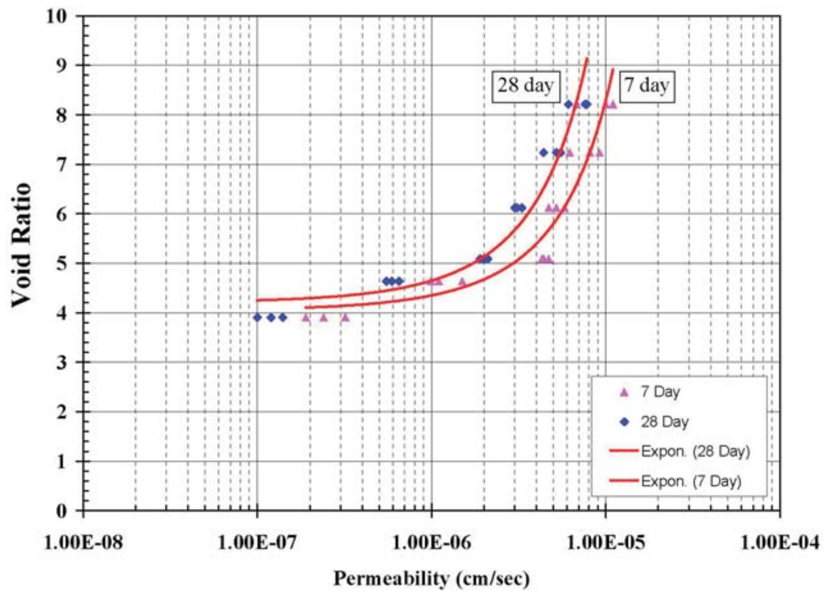

Figure 7. Void ratio versus permeability.

by McKenna (1995), further confirming the validity of the fully-grouted method.

Example 2. Upward-Flow Conditions

This field example illustrates the use of nested piezometers using the fully-grouted method in upward-flow conditions. The site is in an area where three distinct stratigraphy units are found (alluvial deposits, Huot Clay Formation, and Red Lake Falls Formation). The upward-flow conditions play a major role in the slope instability of the area (Contreras and Solseng, 2006).

Figure 9 shows the pore-water pressure and total-head profiles at the site, illustrating the upward-flow conditions. Two vibrating-wire piezometer tips were installed in the Huot Formation and one in the Red Lake Falls Formation. The Huot Formation is fairly uniform and has a permeability in the range of $1.2x10^{-8}$ to $1.9x10^{-8}$ cm/s. The cement-bentonite grout mix used in the nested installation had a 2.66:1:0.27 water:cement:bentonite ratio with a permeability of approximately $2.0x10^{-6}$ cm/s. This example presents the results of the fully-grouted method in a low-permeability unit.

Example 3. Downward-Flow Conditions

Finally, this field example demonstrates the use of nested piezometers with the fully-grouted method in downward-flow conditions. A total of four piezometer tips were installed in three units, with permeability ranging from $1.0x10^{-3}$ cm/s to $9.49x10^{-7}$ cm/s. Where there is a wide range of permeability, the least permeable unit controls the cement-bentonite grout permeability. As a general rule, the less permeable the cement-bentonite grout, the better, and as shown by the computer model, for most soil, a cement-bentonite grout with a permeability of $1.0x10^{-6}$ cm/s will be adequate. Figure 10 shows the pore-water pressure and total-head profiles at the site, illustrating the downward-flow conditions. This example presents the results of an installation of nested piezometers with up to four piezometer tips in a single borehole.

Summary and Conclusions

This two-part article presents a detailed discussion of the fully-grouted method for piezometer installation, including the procedure and theoretical background. It also discusses the results of a laboratory testing program on six cement-bentonite grout mixes, along with an evaluation of a computer model to determine the impact of the difference in permeabilities between the cement-bentonite grout backfill and the surrounding ground. The following summarizes the article's main issues and findings:

- The practice of installing diaphragm piezometers in a sand pack with an overlying seal of bentonite chips or pellets could be discontinued.
- The fully-grouted method is a fairly simple, economical, and accurate procedure that can be used to measure pore-water pressures in soils and fractured rock. It allows easy installation of a nested piezometer configuration, resulting in drilling cost savings. It can also be used in combination with other instrumentation (e.g., inclinometers) to measure deformation and pore-water pressures, provided the inclinometer joints remain sealed.
- The permeability of the cement-bentonite grout mix can be up to three orders of magnitude greater than the permeability of the surrounding ground without a significant error in the pore-water pressure measurement. This finding differs from previous assessments.
- Laboratory test results show that the permeability of the cement-bentonite grout mixes is a function of the water:cement ratio. As the water:cement ratio (void ratio) decreases, the permeability decreases.
- Bentonite has little influence on the permeability of the mix, but rather appears to stabilize the mix, keeping the cement in suspension and reducing the amount of "bleed water."

Acknowledgments

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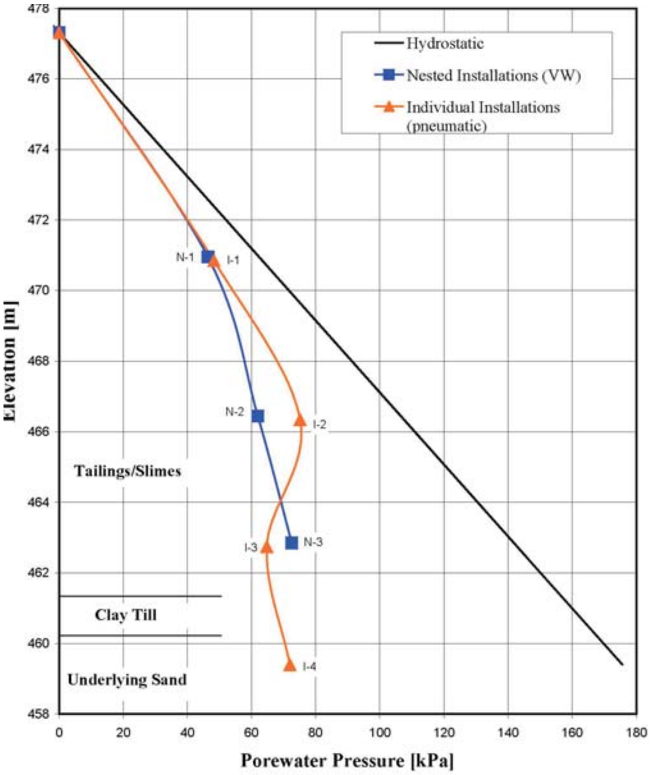

Figure 8. Comparison between a nested fully-grouted installation and individual separate installations.

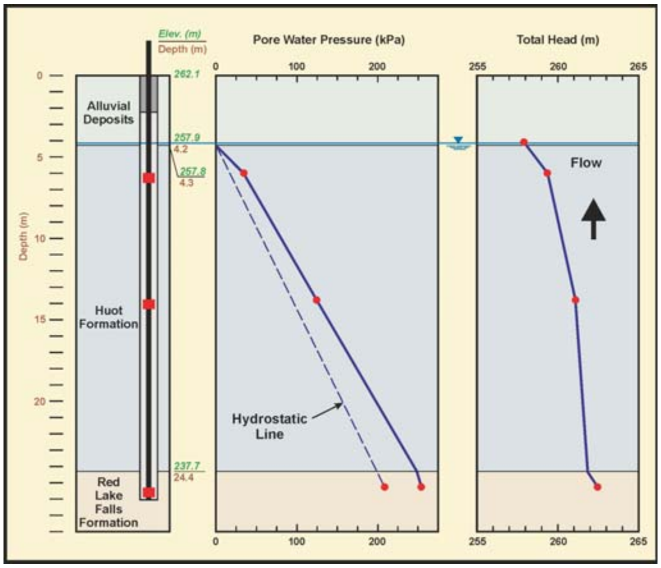

Figure 9. Field example of fully-grouted method in upward flow condition.

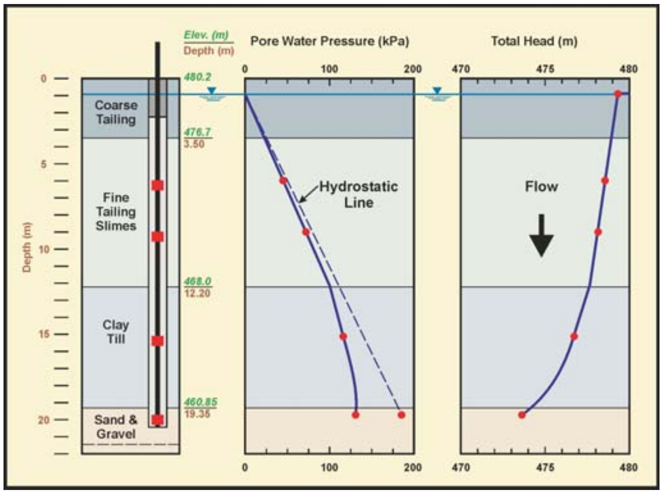

Figure 10. Field example of fully-grouted method in downward flow condition.

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