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-
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.

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.
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 upward-flow conditions play a major role in the slope instability of the area (Contreras and Solseng, 2006).

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 $1.0 \times 10^{-3}$ cm/s to $9.49 \times 10^{-7}$ 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 $1.0 \times 10^{-6}$ 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.”

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References


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