INSTRUMENTATION AND MONITORING

Pierre Choquet, Instrumentation and Monitoring Editor

Pierre Coquet

For I&M column 3, **Iván Contreras***,* **Aaron Grosser** *and* **Richard Ver Strate** *present an overlooked topic — the fact that grouted piezometers remain permanently in the ground. Therefore, these piezometers may be subject to regulations related to the abandonment of boreholes for the protection of groundwater and aquifers, especially where there is a risk of cross-contamination between aquifers.*

I did a quick search and there are regulations for permitting of wells and boreholes in many Canadian provinces and US states, as well as regulations for their abandonment. (Regulations vary, so verify them in your locale.)

In June 2008 and June 2012, these same authors contributed articles on fully-grouted piezometers to Geotechnical Instrumentation News in Geotechnical News. **John Dunnicliff** *considered these two earlier contributions to be among the best GIN articles published between 1994 and 2019.*

One comment on my June 2020 column about fully-grouted piezometers: In that column I wrote, "In mud rotary drilling with casing, smearing with fine cuttings may form along the borehole wall and may create an annulus of low permeability material causing vertical permeability". To expand on this, it is well known that a so-called "mud cake" or "filter cake" is created on borehole walls when using bentonite mud. This is caused by the slight infiltration of mud, due to its higher density, into the surrounding soil with lower water pressure and it can modify the permeability and cause a time lag in piezometer response. To counter this effect, John Dunnicliff's "Red Book" (p 154-155) recommends using a biodegradable mud. The mud cake can also mix with borehole cuttings and create an annulus of lower permeability that can cause some vertical hydraulic conductivity. This topic is not yet fully understood, so any input from readers would be appreciated. Until next time... **Pierre**.

REVISED FULLY-GROUTED MIXES FOR LOWER PERMEABILITY REQUIREMENTS

Iván Contreras, Aaron Grosser, and Richard Ver Strate

Introduction

The fully-grouted method for piezometer installation consists of installing vibrating wire (VW) piezometer tips in boreholes directly surrounded by water-cement-bentonite grout. The method has been extensively used in practice because it is a simple, economical and accurate procedure to monitor pore-water pressures in the field. This method eliminates the need for a sand-pack allowing for easy installation of single or multiple tip configurations and can also be used in combination with other instrumentation. However, appropriate permeability of the water-cement-bentonite grout is crucial for the success of the fully-grouted method.

A detailed discussion of the fully-grouted method including installation procedure, theoretical background, laboratory testing program of grout mixes and field example applications is presented in Contreras et al. (2007 and 2008). Contreras et al. (2011 and 2012) addressed some questions and concerns about the method in regards to response time, installation in soft ground and barometric pressure correction.

Geotechnical practitioners have successfully implemented the fully-grouted method and, over time, increased its use due to the reliability and relative low cost. As presented in Contreras et al. (2007), the most common water-cement-bentonite (w:c:b) grout mix used in practice is 2.50:1:0.35 by weight, which typically yields permeability on the order of 2x10-6 cm/s. However, new legislation has come into effect in many regions that considers geotechnical boreholes as environmental boreholes. This legislation imposes stringent requirements on the permeability of the grout mix to be used in fully-grouted piezometer installations. The main concern from the regulators' standpoint is the need of a very low grout permeability so that communication of groundwater between aquifers does not occur. The requirement of regulators is that the grout used to fill environmental boreholes must have a permeability in the order of 10-7 to 10-8 cm/s or lower. These permeability requirements are lower than the permeability of the most common w:c:b grout mixes used in practice. Therefore, w:c:b grout mixes with lower permeabilities are necessary to comply with these regulations.

The authors engaged in a laboratory testing program to identify/develop w:c:b grout mixes that could comply with the required permeability range established by regulators. This article presents the results of different grout mixes with the goal of achieving the low permeability range required by regulators while maintaining the fully-grouted method as a simple, economical, and accurate procedure to monitor pore-water pressures in the field.

Water-Cement-Bentonite Grout Mixes

Historical (2007) Mix Designs. Table 1 summarizes the six w:c:b grout mix designs presented in Contreras et al. (2007). Table 1 also includes the Marsh Funnel viscosity, unconfined compressive strength (UCS) according to ASTM D-2166 at 28 days, permeability according to ASTM D-5084 at 28 days with confining pressure about 100 kPa and the bentonite type used in each mix.

Mix	Water:Cement:Bentonite by weight	Marsh Funnel Viscosity (sec)	UCS (kPa)	Permeability (cm/s)	Bentonite Type
1	2.50 : 1 : 0.35	50	610	$2.0x10^{-5}$	Baroid Quickge
2	6.55 : 1 : 0.40	54	92	$6.1x10^{-5}$	Baroid Quickge
3	3.99 :1 : 0.67	60	233	$3.0x10^{-4}$	Baroid Quickge
4	2.00 : 1 : 0.36	360	1725	$1.2x10^{-7}$	Baroid Quickge
5	2.49 : 1 : 0.41	56	847	$5.9x10^{-7}$	Baroid Aquage Gold Seal
6	6.64 : 1 : 1.19	60	120	$4.4x10^{-6}$	Baroid Aquage Gold Seal

Table 1 Water-Cement-Bentonite Grout Mix Designs used in the Historical (2007) Study

The results indicate that only Mixes 4 and 5 exhibit a permeability lower than 1x10-6 cm/s and within the upper range of the acceptable values by regulators. In particular, Mix 4 (2:1:0.36) exhibits the lowest permeability, 1.2x10-7 cm/s, within the required order of magnitude. However, the viscosity measured with the Marsh Funnel is 360 seconds and indicates the low pumpability of this grout mix. This suggests that regular drill rig pumps cannot properly handle this material and thus the possible need of a grout pump. It also indicates the grout is too thick and may not create a uniform backfill flowing around the piezometer tips and cables leading to transmission of pore-water pressures between layers or create connectivity between aquifers. In summary, only one of the historical grout mixes provides the low permeability, but it does not provide the viscosity (i.e. pumpability) desired to keep the fully-grouted method as a simple, economical, and accurate procedure to monitor pore-water pressures in the field.

Revised Mix Designs: Table 2 summarizes the revised four w:c:b grout mix designs included in this study. To continue the numbering sequence from the prior work, the new mixes are numbered 7 through 10. Table 2 shows that some of the revised mixes introduce the use of additives, neat-grout cement (as required by regulators) or other commercial products.

Mix	Water:Cement:Bentonite by weight	Additive-Specrete (gm per bag of cement)	Comment
7	2.00 : 1 : 0.36	140	Same as Mix 4 but with additive
8	0.52 : 1 : 0.05	-	Water, cement, and 5% bentonite grout per regulators (neat cement)
9	0.52 : 1 : 0.05	453	Modified neat cement
10	Quik-grout	-	Pre-manufactured grout-Baroid

Table 2 Revised Grout Mix Designs Used in this Study

Mix 7 is essentially identical to Mix 4 in Table 1, which has a permeability within the acceptable range, except that Mix 7 includes a water reducer super-plasticizing additive (Specrete-Flow Aid HR). The idea on the use of an additive in Mix 7 is to achieve a Marsh Funnel viscosity so the grout is easily pumpable with pumps commonly found on geotechnical drill rigs. Mix 8 is the neat cement grout allowed by the regulators to seal environmental boreholes. Neat cement is comprised of water, cement, and only up to 5% bentonite. Note that the amount of bentonite in this mix is extremely low and much less than the historical fully-grouted mixes. Similarly, the water-cement ratio is low and thus the UCS is expected to increase significantly. Mix 9 is the same as Mix 8 except it includes a water-reducer additive (Specrete-Flow Aid HR) with the intention of having a Marsh Funnel viscosity that allows easy pumping. Finally, Mix 10 consists of a commercial product by Baroid, known as Quik-grout, that does not include cement.

Laboratory Testing

The laboratory testing program developed as part of this study included permeability, strength and response time testing. The program was designed so that small batches of grout could be mixed in a controlled environment without the use of large batch mixing equipment.

The program used the same sample preparation procedure utilized in the initial study of the historical mixes. The difference in preparation of the new mixes is the incorporation of additives, which were used following manufacturer recommendations. Sample preparation procedure is explained in Contreras et al. (2007).

The strength tests consisted of unconfined compression tests at 28 days and were performed according to ASTM D-2166. The permeability tests consisted of flexible-wall permeability, also at 28 days, using the falling-head procedure according to ASTM D-5084. The permeability tests conducted as part of this study were performed at a confining pressure of approximately 15 kPa, which is lower than confining for permeability tests reported in Table 1. The response time tests consisted of placing a vibrating wire piezometer in a cylindrical grout specimen and performed at 28 days after formation inside a triaxial cell under pressure. The measurement of response time for the piezometer to changes in cell pressure followed the same procedure as described in Contreras et al. (2011).

Results of Laboratory Tests

Table 3 summarizes the results of the strength and permeability testing conducted. Table 3 includes the UCS at 28 days, the Marsh Funnel viscosity, density of the fresh mix and the permeability at 28 days at a confining pressure of 15 kPa.

Mix	Fresh Density (Kg/m^3)	Marsh Funnel Viscosity (sec)	UCS (kPa)	Permeability (cm/s)
7	1,329	60	1,216	$2.4x10^{-7}$
8	1,778	Did Not Flow	27,722	$5.1x10^{-8}$
9	1,794	130	24,016	$5.2x10^{-8}$
10	1,650	Did not Flow	-	$6.8x10^{-9}$

Table 3 Summary of Laboratory Test Results of Grout Mix Designs used in this Study

Table 3 shows the Marsh Funnel viscosity for Mix 7 is about 60 seconds, which is a significant improvement from the 360 seconds of Mix 4 (no additive). This indicates that the additive is very effective in providing an acceptable Marsh Funnel viscosity so that the grout is easily pumpable. The UCS is 1,216 kPa, which is lower than the same mix without additive. The permeability for Mix 7 is 2.4x10-7 cm/s, which is slightly higher than the value measured for Mix 4 (1.2x10-7 cm/s) but within the acceptable range required by the regulators. It is anticipated that the permeability of Mix 7 is slightly higher than the one measured for Mix 4 because the confining pressure used in the tests in Table 3 was lower (15 kPa) than the confining pressure used for permeability in mixes included in Table 1 (100 kPa). In any event, the Marsh Funnel viscosity and permeability for Mix 7 indicate that this mix achieves the goals of adequate viscosity and permeability.

Mix 8 displays a fairly thick consistency and it was not possible to determine the Marsh Funnel viscosity because the material did not flow out of the funnel. As a result, no Marsh Funnel viscosity value is reported. The UCS is 27,722 kPa, which is much greater than the UCS of any of the mixes previously reported. The permeability for Mix 8 is 5.1x10-8 cm/s, which is lower than the values reported in prior work and within the acceptable range required by the regulators. However, Mix 8 does not achieve the desired Marsh Funnel viscosity although it provides a permeability that is within the acceptable values by regulators. Furthermore, due to the very high strength, this material is brittle and susceptible to cracking where ground movement is anticipated which could lead to connection between aquifers.

Mix 9 displays a Marsh Funnel viscosity of about 130 seconds; while not ideal, it is a very significant improvement from the condition measured for Mix 8, which did not flow. The incorporation of the additive in the mix had the beneficial effect of improving its viscosity so the grout is pumpable with a drill rig pump. The UCS is 24,016 kPa, which is in the same range as Mix 8. The permeability for Mix 9 is 6.2x10-9 cm/s, which is the lowest value measured during this study and within the acceptable range required by the regulators. The Marsh Funnel viscosity and permeability for Mix 9 indicate that this mix achieves the goals of adequate viscosity and permeability.

Mix 10 utilizes a pre-manufactured grout commonly used by drillers to seal boreholes and differs from the other mixes presented in that it does include cement. Upon mixing, following the manufacturer recommendations, the resulting mix did not flow through the Marsh Funnel. As a result, the Marsh Funnel viscosity was not measured. Furthermore, the absence of cement within the mix results in a mix with very little or no strength. Therefore, the UCS was not measured. However, the permeability of Mix 10 was measured and is 6.8x10-9 cm/s.

Testing to evaluate response time similar to Contreras et al. (2011) was performed to assess the behavior of Mixes 7 and 9. Limited testing in a triaxial cell under a variety of pressures showed that Mix 7 performs in an acceptable manner providing a pore-water pressure response within 3 to 15 minutes of cell pressure application, depending on pressure level. Mix 9 did not respond favorably with changes in cell pressure which could be attributed to the high strength of the mix and the low compressibility.

Summary and Conclusions

New regulations classifying geotechnical boreholes as environmental boreholes require lower grout backfill permeabilities if using the fully-grouted method for piezometer installation. A review of the historical grout mixes (Contreras et al., 2007) reveal that Mix 4 provides a permeability within the range required by regulators but its pumpability is questionable with typical drill rig pumps. As a result, four mixes were tested during this study with the goal of achieving the low permeability range required by regulators. A key aspect to this work was to create grout mixes that meet the requirements while maintaining the fully-grouted method as a simple, economical, and accurate procedure to monitor pore-water pressures in the field.

The revised grout mixes described in Table 2, show that Mix 7 and Mix 9 achieve adequate Marsh Funnel viscosity and permeability goals, with Mix 9 having a slower than generally acceptable viscosity but still pumpable based on the authors' field experience. Further review prior to the use of Mix 9 is recommended prior to field use, including additional laboratory testing to evaluate the pore pressure response in greater detail. Until additional data is gathered, Mix 9 is not considered acceptable due to the inadequate response. Mix 8 does not meet the goals due to the pumpability requirements. Mix 10 is also unacceptable for the purposes of the study. Mix 10 used a common geotechnical borehole abandonment material that does not contain cement and as such did not exhibit an acceptable strength in the laboratory setting which may cause settlement/deformation or borehole squeezing over time in most ground conditions. However for very soft ground condition applications, Mix 10 could be considered. It should be noted that grout mixes 7 to 10 exhibit much higher strength than previous mixes and the use of each should consider the implications to the high strength and potentially brittle behavior of the backfill that could lead to cracking and the creation of potential flow routes through the column especially in consolidating or moving ground conditions.

Acknowledgements

Support provided by the Innovation Committee of Barr Engineering Co. is gratefully acknowledged. The laboratory testing by Soil Engineering Testing, Inc. of Bloomington, MN, is greatly appreciated. The authors are also grateful to Mickey Westbrook and Mohammed Suleiman of Specrete for donating the additive for this research and for helping to

identify the dosage for this application.

References

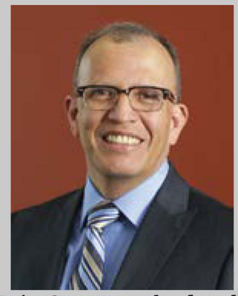
Contreras I. A., Grosser, A. T. and Ver Strate R. H. 2007. The Use of the Fully-grouted Method for Piezometer Installation, in *Proceedings of the Seventh International Symposium on Field Measurements in Geomechanics*." Boston, MA. ASCE Geotechnical Special Publication 175.

2008. The Use of the Fully-grouted Method for Piezometer Installation, *Geotechnical News*, Volume 26, June.

2011. Practical Aspects of the Fully-grouted Method for Piezometer Installation, in *Proceedings of the Eighth International Symposium on Field Measurements in Geomechanics*." Berlin, Germany.

2012. Practical Aspects of the Fully-grouted Method for Piezometer Installation, *Geotechnical News*, Volume 30, June.

Authors ***Iván Contreras*** *(icontreras@barr.com),* ***Aaron Grosser****, and* ***Richard Ver Strate*** *all work with Barr Engineering Co. in Minneapolis, MN. Barr provides engineering and environmental consulting services to clients across North America and around the world. Barr Engineering and Environmental Science Canada Ltd. is based in Calgary, AB.*



Iván Contreras, lead author