Cement-Bentonite Grout Backfill for Borehole Instruments

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The backfill for a borehole instrument is often an item that receives a disproportionate lack of attention. The behavior of the backfill, the material that is in the most intimate contact with both the formation and the instrument, is critical for obtaining correct measurements. In many situations, instrument observations may just reflect unstable backfill, lack of backfill or backfill that is too stiff or too soft. Sand, gravel and various bentonite products have proven to be both too difficult to place and often entirely inappropriate. Experience has shown the author that cement-bentonite grout is the most universally applicable material for successfully backfilling a borehole instrument. Single-component bentonite grouts have been used in related industries a long time, and have been adopted for borehole instrumentation with mixed success. Their uses are more involved and, as explained below, should be avoided. The use of fly ash as a substitute for cement promises to be a good way for reducing grout stiffness when required.

Current Use of Bentonite

Materials and Technology

Although this article advocates the use of cement-bentonite grout it is appropriate to review current bentonite backfill and sealing products to illustrate why their use should be limited. To the uninitiated, there is a confusing array of various pellets, chips, granulated and powder-forms of sodium bentonite commercially available in North America and elsewhere. Calcium type montmorillonite and opalite are also used. The proper use of these products is a mature and complex technology employed by the environmental, water-well and petroleum industries. Basic research has been done and their properties are known. For example, Baroid Industrial Products (1994), a manufacturer of about two-dozen drilling-products gives a five-day workshop in Houston, Texas including a hands-on laboratory day. Here, the user learns about the difference between drilling muds and bentonite used for sealing (single-component grouts) and how to place the materials. However, drillers and geo-professionals who install piezometers and other borehole instruments for the geotechnical industry generally do not have this background and often have limited understanding of bentonite products outside of powder used to make mud and dropping chips down the hole. Going "high-tech" requires more knowledge, better equipment, and a higher level of quality control, which appears to be unrealistic for borehole instrumentation.

Solid Bentonite Seals

Installation of bentonite balls, pellets or chips as seals above a sand pocket have dominated piezometer installation procedures over the last 50 years. It is classic procedure for open standpipe piezometers. Installation is usually very time consuming, particularly on deeper boreholes or when caving occurs. When you manage to get such seals installed without bridging the hole, there is usually no question about their permeability being adequately low. These seals have a very low permeability, often lower than many in-situ clays. Establishment of proper procedures for placement of such materials has been important not only because sealing is important, but also because the installation conditions are often difficult and the procedures cumbersome. Many installations end up less than satisfactory. Over the last decade, experience has shown that bentonite chips (as opposed to balls and pellets) are the easiest to place. These chips look like crushed gravel and hydrate very slowly. However, the fine clay-dust unavoidably mixed in with the chips can make conditions increasingly sticky as filling proceeds, leading to bridging and blockage higher in the borehole. For relatively simple installations where the seal heights and volumes are not too extensive, this material usually does not bridge and is often the seal of choice for environmental observation wells and open standpipe piezometers.

Pellets, chips and polymer-suspended granules can also be tremied to the desired location in the boring. The potential for clogging is always a hazard, but at least a clogged tremie-pipe can be withdrawn and discarded. If clogging or bridging occurs while dropping the materials directly into the borehole, there is no recourse except to start over.

Bentonite Grouts

These products are the least desirable for sealing or backfilling. They are made from water and powdered bentonite mixed into slurry-like drilling mud, but to a higher density with the aid of additives and specialized grout mixing units. The higher the bentonite solids-content is, the lower the permeability is. The water-content of such slurry is extremely high and it never really sets up to anything more than thick paste, not a solid like the chip-seals. A number of bentonite sealing grouts are available, but none appear to set up to a solid form. They are sensitive to over-mixing (leading to a flash set) and can be difficult to pump down the small diameter grout pipes (3/4 inch) often used for piezometers and other geotechnical borehole instruments where space is at a premium. Their working time tends to be too short, and mix dilution to circumvent mixing and pumping problems will lead to a permanently soupy backfill.

Cement-Bentonite Grouts

Basics

A bentonite grout backfill consisting of just bentonite and water may not be volumetrically stable and introduces uncertainty about locally introduced pore water pressures caused by the hydration process. Introducing cement, even a small amount, reduces 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 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 practice among drillers doing test borings.

Strength and Deformation

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 by the author over the years are summarized in Figure 1. 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 to match one quarter that of the surrounding soil.

Water and cement in proportions greater than about 0.7 to1.0 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 1 also suggests 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 contains less cementing agents (calcium and gypsum).

Grout Permeability

Permeability of the grout is mainly an issue that is limited to piezometer installations, and is the subject of a paper to be published in the near future. It is general practice to grout the borehole above a bentonite seal placed above the piezometer "intake zone" (sand that surrounds the piezometer), but the pa-

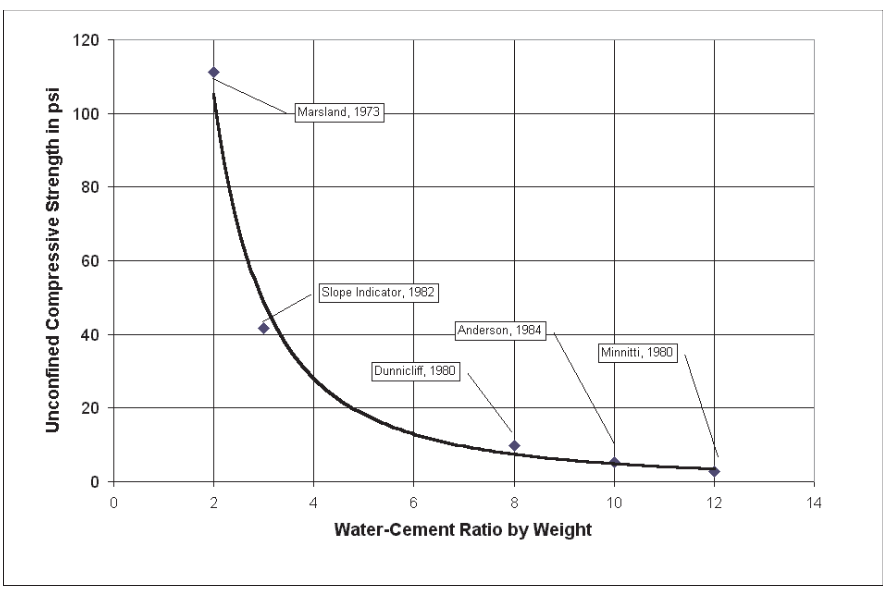

Figure 1. 28-day cement-bentonite grout strength vs. water-cement ratio. Data from author's personal files.

Table 1. 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 x 10^{-8}	Vaughan, 1973

per argues that boreholes may be fully-grouted for diaphragm piezometers, omitting both the sand and the bentonite seal. Two articles by Vaughan (1969 and 1973) make the point clear in theory and practice. This procedure not only simplifies difficult installation situations, but also improves the quality of the installation. It is really not a question of whether or not diaphragm piezometers work when fully surrounded with grout, but rather it is a question of making a grout with a suitable permeability. Cement-bentonite grout is generally well suited to accomplish this task.

The cement-bentonite fabric when set is an irregular honeycomb structure held together with both cured cement and colloidal bonds. It is a highly porous solid with a low permeability that lies somewhere in the cement and bentonite range, from 1x10^{-5} to 1x10^{-9} cm/sec. Typical published values of permeability are listed in Table 1. Vaughan (1973) quotes a coefficient of permeability for a pumpable cement-bentonite grout mix on the order of 5x10^{-8} cm/sec. For low bentonite solid contents the permeability can be expected to be close to 1x10^{-6} cm/sec and for higher bentonite solids content it would be close to 1x10^{-8} cm/sec. This is an area for further testing and research where the water-cement ratio, bentonite solids content and permeability should be established.

Typically used Bentonite

Drilling contractors in the US who do test borings in soil usually carry a high yielding sodium bentonite such as Supergel or Quik-Gel brands on their rigs. This is a finely ground, powered form of bentonite that yields as much drilling mud per sack as possible without additives. Other bentonite powder products have additives to enhance certain mud characteristics such as viscosity, density and filtration. Such additives are probably not detrimental to making a suitable cement-bentonite grout, but are not really relevant or cost effective in such a context. What seems not to be well understood is the feasibility of using coarser grains of bentonite to increase solids content for lowering the permeability in cement-bentonite grout. Would polymer additives be needed for mixing stability, for example?

As a side-note, sodium bentonite absorbs more water than calcium bentonite. According to clay mineralogists (Papp, 1996) the presence of sodium as the dominant exchangeable ion facilitates many interlamellar water layers to be absorbed into the crystalline structure, a phenomenon which does not occur with calcium or magnesium as dominant ions. Sodium bentonite is characterized as capable of absorbing at least five times its weight in water and expands when fully saturated with water to a volume 12 to 15 times its original dry size.

Sodium bentonite powder appears to be the most practicable and efficient to use in this context, but this does not mean that other fillers of different grain sizes and composition could not be used. It is matter of availability and convenience of a good product for this application. For example, in a 50-gallon batch of cement-lime grout, 150 pounds of hydrated lime can be replaced by using about 25 pounds of bentonite powder.

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. This is contrary to procedures used at more sophisticated grout plants for compaction grouting and sealing purposes. 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 done in a barrel or tub with the drill-rig pump, cir-

Table 2. Cement-bentonite grout mixes

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. (1sack)	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.	

culating the batch through the pump in 50 to 200 gallon quantities. The rig pump provides the kind of jet-mixing required for getting the job done quickly. Any kind of bentonite powder used to make drilling mud combined with Type 1 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 2 that varies in 28-day strength from 50 psi to 4 psi for water-cement ratios of 2.5 to 6.6 respectively.

The amount of bentonite that is required for the above mixing procedure would vary due to factors mentioned earlier. The amount of bentonite shown in Table 2 should only be used as a guide, but is also handy for estimating material quantities to be shipped to the site. With this method **more** bentonite is required than if water and bentonite were 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. A lower permeability is generally preferred since cement-bentonite grouts have a higher permeability than high-density bentonite grout or chip seals. Thus, another good reason for mixing water and cement before adding bentonite.

Old habits die hard, so that some users will insist on mixing water and bentonite powder first. 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 thixotropic and rely on industrial type mixing plants and methods. The cement content is difficult to control under ordinary borehole installation circumstances.

Mixing Procedure

A rig pump with one suction hose and a return hose fitted with a jet nozzle and a 50-gallon barrel, shown in Figure 2, 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 the 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 should 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 mixing grout 100 feet or more from the borehole, thinner consistency would be required, but at the risk of some bleeding.

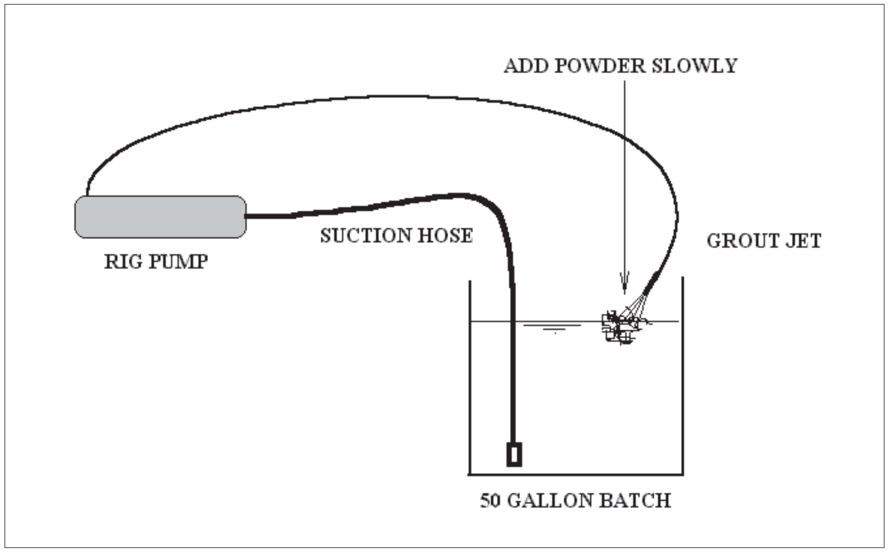

Figure 2. Circulation batch mixing of grout (minimum configuration). After mixing grout is tremied to bottom of the borehole.

Additional Considerations

Strength is often used to characterize a grout for deformation-type instruments, but modulus of deformation should ideally be the basis for judging compatibility with ground conditions. The grout column in a borehole will carry a total axial force smaller or greater than the material it replaced, according to its stiffness. When there is too much stiffness or force, displacements will be diminished and axial measurements can be less than displacements of the surrounding ground. Thus extra grout stiffness for extensometers is much more undesirable than for inclinometers, for example. More care should be taken in making a grout for axial borehole deformation measurements than for lateral deformation measurements.

Instrumentation installations often encounter the combination of both soft and hard ground in the same borehole. Obviously, staged grouting to match the required properties would be the ideal procedure, but this is seldom warranted or practicable. Most of the design and installation challenge lies with deformation measurements in the axial direction of the borehole where large volumes of grout backfill must be placed. So, for extensometers, it is better to err on the softer side of the spectrum.

Lateral displacements of an inclinometer casing are generally unaffected by added grout stiffness. Where the grout column is too stiff the displacements will be distributed over a greater depth interval, but not be diminished in overall magnitude. The same is probably true if the grout is too soft, but there is the additional concern for lack of lateral confinement. Since inclinometer casings generally are under compression, lack of backfill or confinement can produce localized shifts in the borehole, masking smaller actual displacements. So, for inclinometers, it is better to err on the stiffer side of the spectrum.

It may not be possible to achieve a suitable grout with cement for softer clays. Fly ash promises to be a good substitute for reducing the modulus, but more testing is needed in this regard.

Conclusions

Grout backfill should ideally be selected according to the field instrument type being used and the given ground conditions. The reality however is that grouting practices will remain relatively crude and, at best, with only marginal control over the grout properties. Drillers, geologists and engineers alike still have a lot to learn about what is appropriate. We cannot just borrow ideas from drilling mud and grouting technology that have no relevance to what is needed for instrumentation functionality.

1. Avoid using a bentonite alone for a borehole grout. It is not a volumetrically stable material and can influence both piezometer and displacement measurements when it keeps hydrating or desiccating. It is often very difficult to place successfully.
2. A stable grout can be made using cement or fly ash with bentonite. Relatively small amounts of cement or fly ash are used as compared to grouts used for other geotechnical purposes such as compaction grouting and sealing of seepage. Grouting for instrumentation has different property priorities.
3. Grouting for field instrumentation should remain a relatively simple endeavor, using materials commonly available to drillers. However, when working in soils like normally consolidated clay, more attention should be paid to the mix design. Since little information is available on softer grouts, particularly those mixed with fly ash, a few trial batches in the laboratory are appropriate to determine basic characteristics for use on such projects.
4. Grout mixing should start with water and cement (or fly ash) first. Strength and modulus are more predictable that way. Also, and just as important, is that more bentonite solids can be added to the mix to lower permeability where required for sealing.
5. Grout permeability is an issue for piezometers installed in clay. The grout should have permeability no greater than one (possibly two) orders of magnitude above the clay to get representative readings.
6. Grout stability is very important during both the liquid and set conditions. The liquid grout consistency should be as thick as possible, yet liquid enough to be pumpable. This is a property that requires field experience. Field crews tend to err to the more liquid end of the spectrum, resulting in bleeding and possibly cracking when set.
7. Strength is often used to characterize a grout for deformation-type instruments, but modulus of deformation should ideally be the basis for judging compatibility with ground conditions. There is very little in the literature to help us select a grout mix for sealing piezometers in boreholes. Further testing and research is needed (see editor's note below).

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***Editor's Note**:*
John Dunnicliff, Erik Mikkelsen,and Allen Marr have decided to plan and conduct a test program to mix various proportions of cement and bentonite, also fly ash and bentonite, and test for strength, permeability, compressibility and volume stability. The results will be published in GIN as soon as they are available.