A Laboratory Simulation of In-Situ Grouting Using Standard Portland Cement and Polyurethane Materials with Standard Methods

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Introduction

Grouting features below ground is a common construction activity. The main purposes for placing grout have been previously identified (Shannon and Wilson, 1987), and are: 1) lower permeability, 2) reduce hydrostatic pressures under structures, 3) reduce water losses, 4) increase strength and bearing capacity, 5) stabilize rocks and subgrades, 6) backfill annular openings, and 7) fill cavities.

Various requirements on the need for additional research have been identified in the review of the state-of-the-practice in grouting (Shannon and Wilson, 1987). One suggestion was the use of laboratory models as an interim step between theoretical mathematical models and full scale field tests.

The objectives of this research study were to develop procedures and to perform tests to satisfy some of these previously suggested research needs. In-situ conditions were simulated in the laboratory, portland cement grout and polyurethane grout were placed under field-like conditions, and the grouted features were recovered for forensic testing and analysis of performance. Grout properties were measured and grouted modules were examined.

Experiment Set-Up

The major feature of this study was the use of a soil box and a very large test frame to model soil elements with a surcharge load. Modules were constructed to simulate several different conditions, and placed in the soil box. The soil box was a 7-feet by 7-feet square, 4-feet high steel box. The surcharge load, used to simulate overburden, was placed using the 5 million pound universal test machine at the U.S. Bureau of Reclamation laboratory (see figure 1).

Figure 1 – Picture of 5 million pound press and soil box.

Modules conceptually similar to in-situ features were constructed and placed under a surcharge load. Also, additional modules were manufactured and tested outside the soil box. Those modules were manufactured from plexiglass so that grout travel could be observed during actual grouting operations.

The modules were constructed to model several different scenarios, including vertical travel, horizontal travel, void filling, and crack and joint filling in dams and rocks. The modules contained ordinary, full sized material such as gravel. The soil box test features were grouped as summarized below and shown in figure 2. Figure 3 shows a typical floor test module.

Table 1 Module Information

Vertical Travel Modules	Identification
Air Filled Sand column	Module A
Water Filled Sand column	Module B
Air Filled Gravel Column	Module C
Water Filled Gravel Column	Module D
Horizontal Travel Modules	**Identification**
Air Filled Sand Tube	Floor Test*
Air Filled Gravel Tube	Floor Test*
Air Filled Sand Tube	Module E
Water Filled Sand Tube	Module F
Air Filled Gravel Tube	Module G
Water Filled Gravel Tube	Module H
Flat Plate (Rock) Module	**Identification**
1/4" Air Filled	1
1/16" Air Filled	Floor Test*
1/4" Water Filled	2
1/16" Water Filled	Floor Test*
1/4" Air Filled - With Sand	3
1/4" Water Filled - With Sand	4
3' x 3' Flat Plate (Joint) Modules	**Identification**
1/4" Air Filled	Floor Test*
1/4" Water Filled	Floor Test*

* Floor tests were tests outside of the soil box and surcharge, generally in plexiglass for observation.

The columns and tubes placed in the soil box were made of 40 mil HDPE geomembrane and were manufactured with a cap on one end, forming an approximate 8" diameter tube. Each tube module had an entry port for grout injection, and an exit port at the opposite end.

The flat plate modules were constructed of 1/4-inch thick plexiglass with a gap between the faces. The gaps were 1/16-inch and 1/4-inch thick, and were filled with either air, water, or wet or dry sand. The air filled modules were similar to experimental work done previously to simulate field conditions in rock (Houlsby, 1985).

The sand used to fill the modules was a sand with 95% passing a No. 16 sieve and 95% of the sand retained on a No. 30 sieve. The gravel used to fill the modules was graded from 3/8 inch to a #4 sieve size. Modules in the soil box requiring water were filled from the grout plant while the modules were under the surcharge load.

Placement of the gravel in the modules consisted of pouring gravel in the modules. A similar technique was used for the sand. After filling with sand or gravel, the open end was sealed with a cap. Modules tested in the soil box were covered with moist sand.

Several techniques were used to place the sand at 0% relative density in the module. As a practical matter, the modules needed to be moved once filled, and the vibration of moving was sufficient to create a greater than 0% relative density. A near 0% value can be assumed. The void ratio and permeability of the sand and gravel were determined using standard laboratory testing procedures and/or by measuring the values directly during injection. These values and values following the grouting are tabulated with values later in the report in Tables 2-4.

For this test, a surcharge load representing 50 feet of overburden was used. Following contemporary field guidelines, a maximum grouting pressure of 25 psi was used, as measured at the point of injection.

A w/c ratio of 1:1 with a 0.5% high range water reducing admixture (HRWRA) was used in this test. The addition of the HRWRA, making the grout more fluid, is a recent development - different from the Houlsby tests, and was intended to extend existing data.

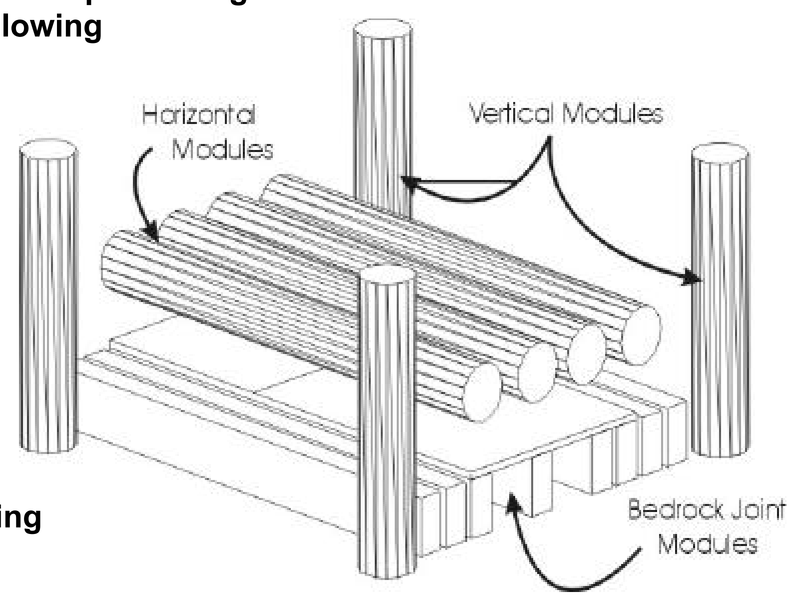

Figure 2 – Location of modules in soil box.

There are no readily available guidelines for the choice of portland cement mixture proportions to grout in soil conditions. To calculate a theoretical gap size for a loosely packed soil, a mass of uniform spheres packed face to face in all directions was chosen for convenience. This derivation is reported in standard texts (Holtz and Kovacs, 1981) as a factor of 15.4 percent of a uniform diameter sphere. That is, a 3/8" sphere packing would permit a 0.06" sphere to pass through. A No. 16 Sieve (particle size 0.047") would permit a particle size of 0.007" to pass through. A No. 200 sieve material such as cement has a diameter of 0.003". These theoretical gap sizes are computed to compare to the Houlsby tests.

For the injection of the portland cement grout a laboratory grout plant was used which was designed to operate in the same manner as a field unit. The grout plant consisted of a high speed colloidal mixer, an agitator holding tank, and a progressive cavity pump (Moyno pump). A flow meter and pressure gage were added to monitor the injection pressure, flow, and total volume injected.

For injection of chemical grouts, a commercially available positive displacement rocker pump was used. A water-activated, low viscosity hydrophilic polyurethane resin was used for grouting. The resin and water were pumped separately through flexible tubing to the injection port. The two materials were mixed together just prior to injection into the modules.

Results of the Grouting Tests

Tests of the Grout

Grouting was conducted so that samples of grout and grouted material could be collected from different sources. Samples were collected from: 1) grout from the mixer, 2) grout from the outlet tube of the modules (see table 2), 3) hand-mixed samples of grout and sand or gravel, and 4) cored samples from the columns and horizontal tubes (see table 4). Cored specimens were taken from the injected modules to give a representation of the permeabilities and strengths along the length of the modules. Obtaining cores from the sand modules grouted with cement was not possible due to very limited penetration.

Modules injected with chemical grout exhibited pressure after gelling. When the modules were cut open, the samples split open and swelled. The samples were still sponge-like after 2 weeks time but the splitting of the injected module inhibited the ability to retrieve samples for testing.

Table 2 Grout Properties from Modules

Module	Cohesive Weight (gms)	Cohesion (mm)	Comp Strength (psi)	Density (pcf)	Flow Cone (sec)	Bleed Water (%)
At Grout Plant	7	0.090	3165	104.5	59.35	22.5
2 (Rock-Open/Water Filled)	5.1	0.066	2887	104.0	59.66	20.0
4 (Rock-Sand/Water Filled)	4.6	0.060	2641	102.5	59.35	21.0
B (Soil-Sand/Water Filled)	3.8	0.051	2788	100.0	57.72	28.5
D (Soil-Gravel/Water Filled)	5.1	0.067	2396	102.0	59.47	23.5
G (Soil-Gravel/Air Filled)	7.3	0.093	3181	106	61	18.0

Table 3 Physical properties of Samples collected from Modules

Module	Weight (Sand/ Gravel) (lbs.)	Vol. of Voids (gal.)	Grout Pumped	Comp Strength (psi)	Density (pcf)	Flow Cone (sec)	Bleed Water (%)
At Grout Plant				3165	104.5	59.35	22.5
2 (Rock-Open/Water Filled)		0.3	0.26	2887	104	59.66	20
4 (Rock-Sand/Water Filled)	8.9	0.51	0.5	2641	102.5	59.35	21.0
B (Soil-Sand/Water Filled)	93	2.5	2.5	2788	100.0	57.72	28.5
D (Soil-Gravel/Water Filled)	98	2.8	2.8	2396	102.0	59.47	23.5
G (Soil-Gravel/Air Filled)	190	6.0	5.37	3181	106	61.0	18.0
Hand-mixed Sand				2176			
Hand-mixed Gravel				3153			

Uniaxial compression tests were also performed on samples cored from the cementitious grouted modules, cementitious grout from the exit of the module, and a hand-mixed sample. These test results of portland cement grout (chemical grout specimens were lost due to swelling and splitting when removed from the modules) indicate that gravel injected under pressure yields strengths about 80% of laboratory mixed samples. The single compressive strength value obtained for grouted sand is insufficient to draw conclusions.

Permeability values were found using flow-pump permeability tests on cored samples recovered from modules in the soil box . The values using these different methods are shown in Table 4.

Table 4 Permeability of injected modules

Module	Type	Initial Lab Perm (Estimated from injection) (Cm/sec)	PCA grout Permeability (Cm/Sec)	Chemical grout Permeability (Cm/sec)
B	Sand - Vertical - Water Filled	$7.5x10^{-3}$	$2.3x10^{-8}$	
F	Sand - Horizontal - Water Filled	$8.6x10^{-4}$		$2.9x10^{-6}$
E	Sand - Horizontal - Air Filled			$1.5x10^{-6}$
H	Gravel - Horizontal - Water Filled	$8.8x10^{-3}$	$5.5x10^{-9}$	

As is expected, the ability of grout to reduce the permeability is significant.

Visual Observations

Visual observations were made of the grouting in two ways: 1) floor tests were conducted in the laboratory using modules similar to the soil box modules, but constructed from plexiglass for observation and filming, 2) the modules as observed in the soil box.

Observations: Floor Tests

Observations from the floor tests showed different flow and penetration resulting from the different test configurations. The observations are summarized below:

- 1. In the air filled 1/16" rock module, grout flowed as a wave with an angle of approximately 30° from vertical, with the leading edge on the bottom of the module. Although the penetration was good, the final permeability was affected by the bleed water. Some voids were present once the grout had hardened.

- 2. In the water filled 1/16" module, grout flowed to the bottom of the module with a mixing zone at the cement-water interface. Final filling of the module occurred from the bottom up.

- 3. In the air filled joint module (figure 4), grout penetrated from the center towards the edges. Once grout reached the exit tube, the remaining three corners were left open.

- 4. In the water filled joint module, grout mixed with the water readily, water was displaced from the module through the outlet tube as filling occurred. The grout front had a doughnut shape with increasing diameter. An apparent penetration was made into all corners but this effect was negated by the grout only partially filling the module below a remaining water level.

- 5. In the gravel filled horizontal tube, grout flowed to the bottom of the tube, and proceeded through the tube with a flat wave front. The final complete filling of the tube was from bottom up. Voids, in general, were filled.

- 6. In the sand filled, horizontal tube, grout flowed to the top of the tube and all flow continued across the top, piping sand from the top of the tube. Thus, the grouting created a void in the penetration and the original sand voids were unfilled. This substantiates the Houlsby conclusions when applied for sand, even through plasticizer was used in this mix.

Observations: Soil Box Modules

Observations were made of the soil box modules following portland cement grout injection and removal from the soil box. The dry sand horizontal modules produced baseball sized grout bulbs within the module immediately adjacent to the injection point due to the failure of the grout to penetrate the sand. Wet sand allowed only slightly larger penetration zones approximately 6" in length. However, in the rock joint module filled with sand, complete penetration was accomplished and a wall board consistency was accomplished. This penetration is believed to have been accomplished by grout flowing along the boundaries of the thin module and then penetrating in the thin direction. The vertical water-filled sand module also showed good penetration throughout the height of the module. We believe that the penetration was assisted by boiling or liquefaction of the sand since the grout was injected from the bottom of the module. One additional test was run at a later time on a water-filled sand module, with injection from the top, and penetration was minimal. For gravel modules, the grout penetrated well in all directions. The total volume injected indicated a complete filling of voids. However, voids were left in the upper portions of the gravel modules probably due to bleed water from the grout.

The grout injected into the 1/4" water filled rock module flowed first to the bottom and then along the bottom to the exit port. As was mentioned previously, a grout sample was obtained from the module during filling and then the grouting was discontinued. Figure 5 shows the gaps left by the grouting due to the travel along the boundary, leaving water trapped in the module.

The ability of the standard grout to penetrate gravels is consistent with the suggestions of penetration through gaps by Houslby. Likewise, the inability of the grout to penetrate a uniform sand is consistent with the thinnest gap that grout can penetrate. Without the aid of boundary effects, such as a boundary for travel or a boiling effect, as suggested above, the guidelines suggested by Houslby appear to provide an initial estimate of the penetration of grouts in soil using a equivalent diameter calculation.

Results of chemical grouting in the soil box modules indicated minimal injection in vertical sand modules. On the other hand, sand modules placed horizontally had 60-inches of penetration in dry sand and 43-inches of penetration in wet sand. Vertically filled gravel modules showed 100% penetration and void filling. Horizontal modules with dry gravel had 64-inches of penetration. Wet gravel had all voids filled.

Additional Testing - Compaction Grouting

An additional test was completed in cooperation with Denver Grouting Services, Inc. The purpose of this test was to simulate compaction grouting in the soil box with a surcharge load and measure pressure changes at different locations in the soil box caused by the compaction grout bulb. A full size grouting system was used and a bulb injected directly into sand in the soil box. A surcharge of approximately 25 psi was applied with the 5-million pound test machine.

The resulting bulb produced is shown in figure 6. This elongated sphere of approximately 1 foot is fairly typical of field shapes. Vibrating wire pressure cells were embedded in the sand at 2 feet and 4 feet from the injection port and at the same elevation to measure the pressure changes in the soil. Pressure readings are shown in figure 7. The cell located 2 feet from the injection port shows each of the three pulses from the grout pump with an elastic relaxation after each pulse. The cell located 4 feet from the injection site shows a slight increase in pressure resulting from the injection.

Results from this test demonstrate that the soil box can effectively be used to study of compaction grouting of different soils at different depths.

DISCLAIMER

The mention of product names, trademarks, or discussion of application by any vendor is for information purposes and does not constitute endorsement or recommendation by the U.S. Government.

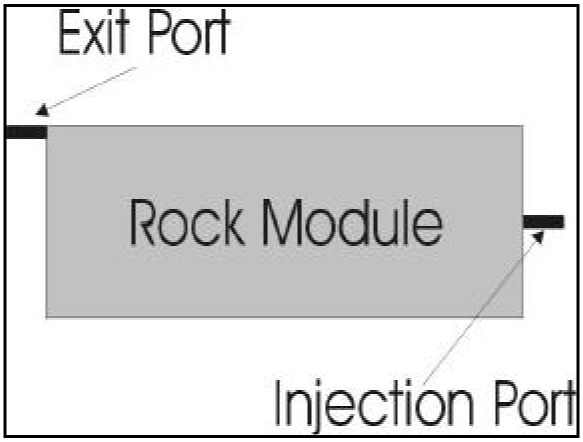

Figure 3 — Typical Floor Test Module

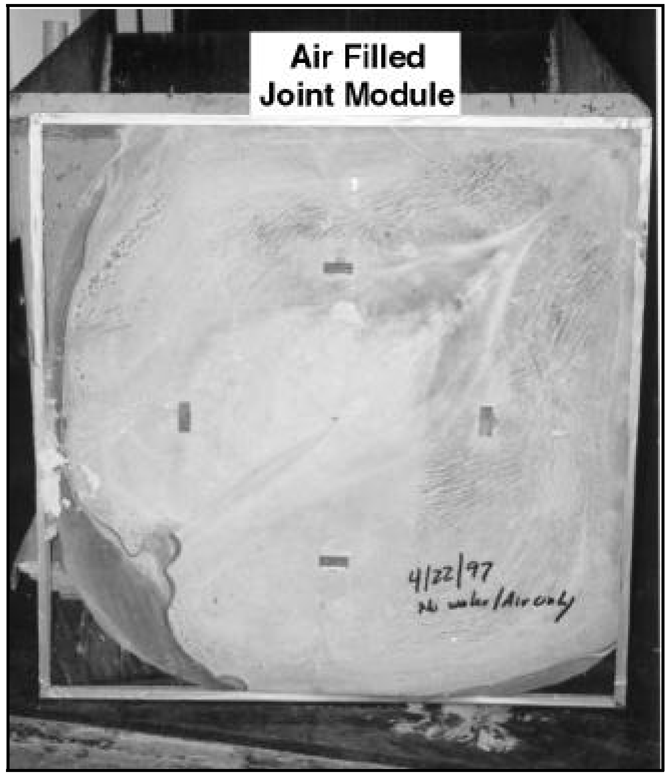

Figure 4 — 3' x 3' Flat Plate Joint Module

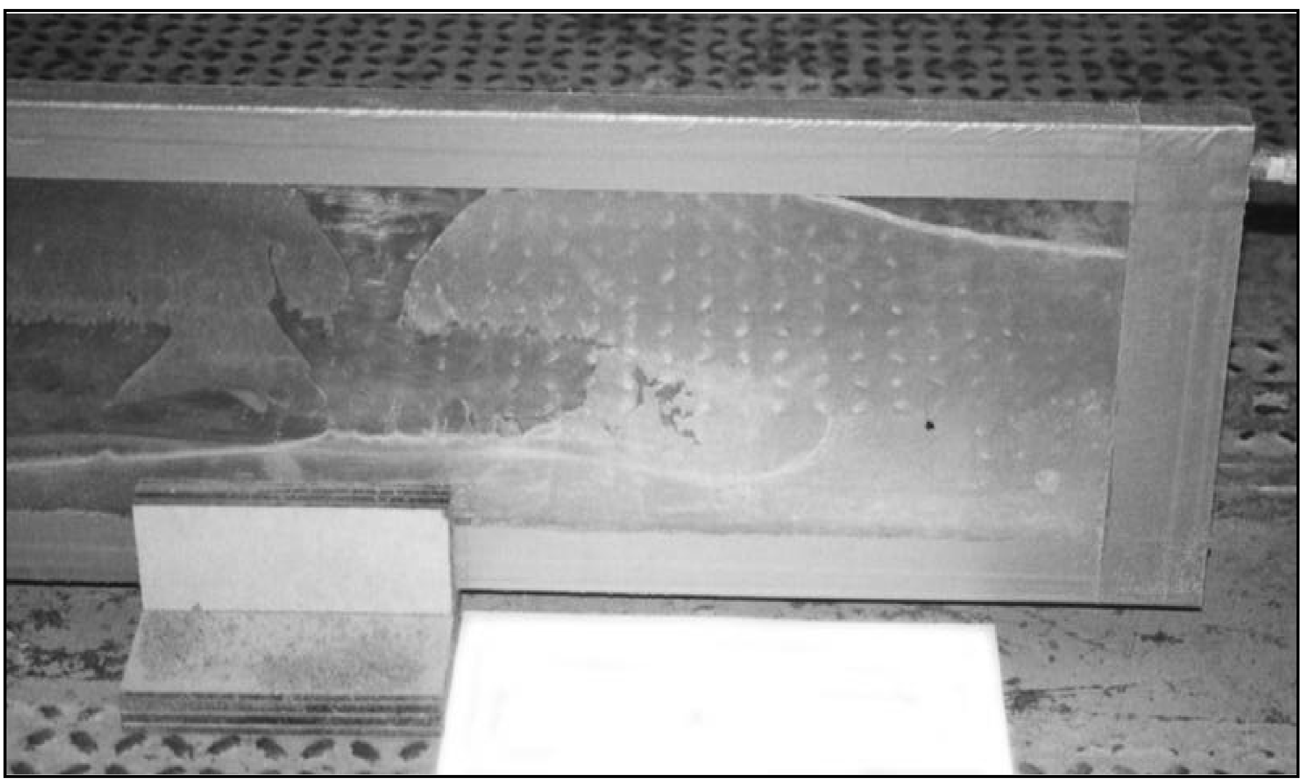

Figure 5 — 1/4" Water Filled Rock Module

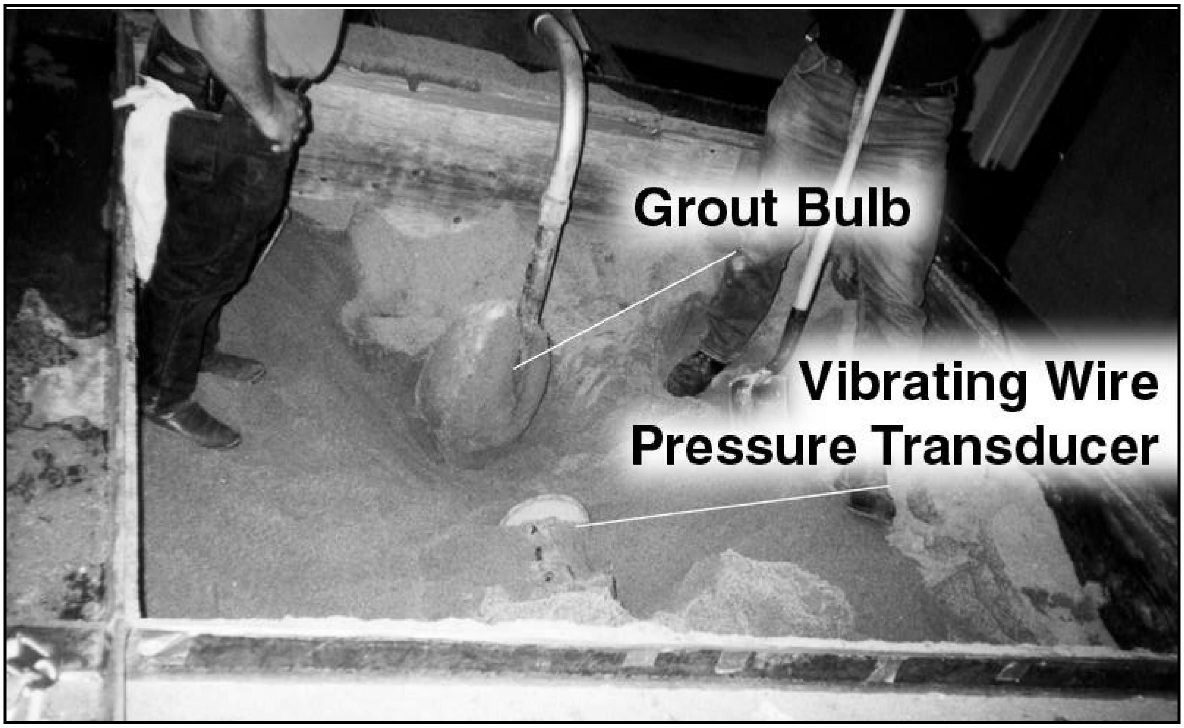

Figure 7 — Compaction bulb produced in the soil box.

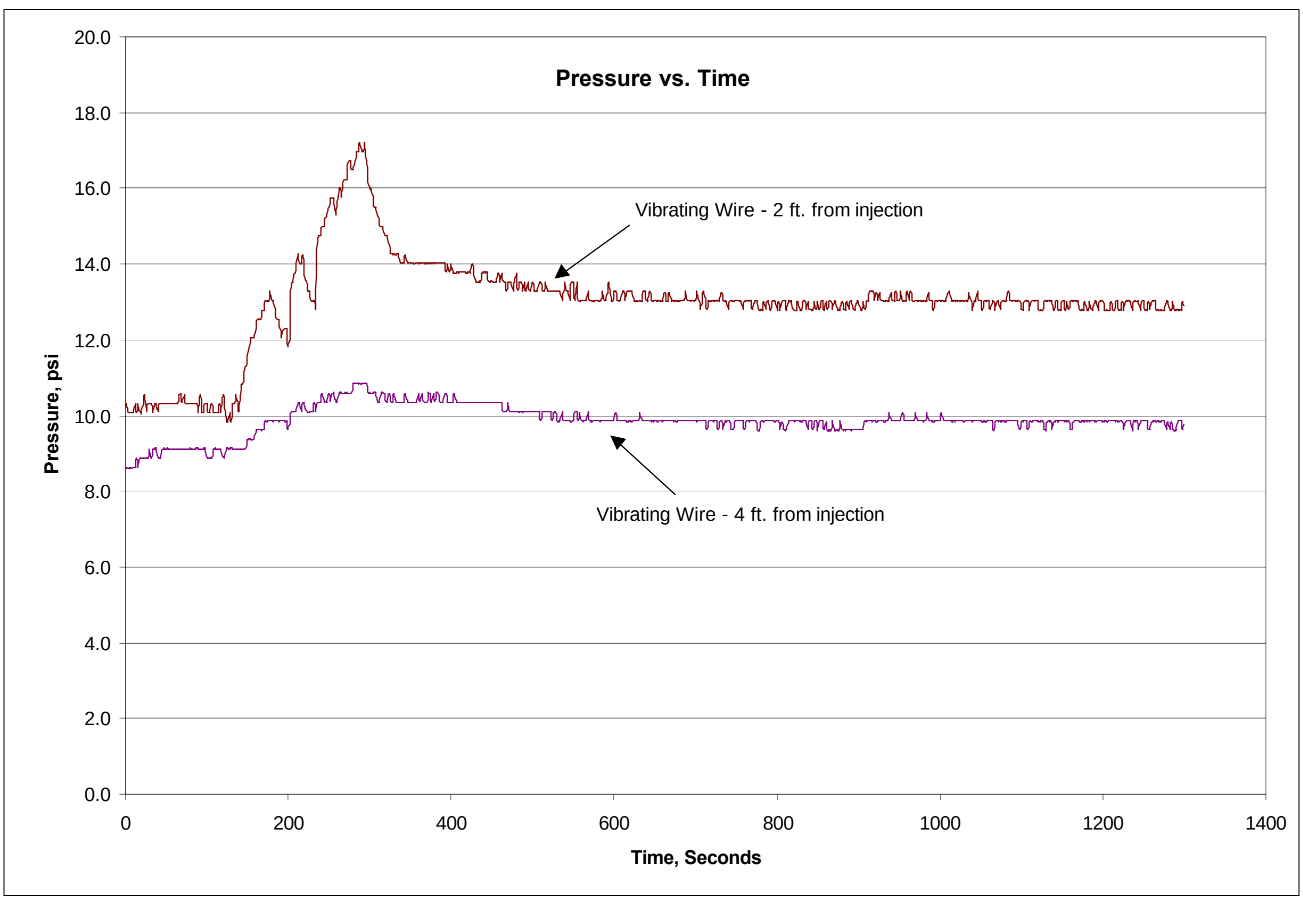

Figure 6 – Pressure pulses resulting from compaction grouting

Conclusions

1. Full scale effects of simplified field conditions were readily simulated in the laboratory for forensic studies of grouting. Grouting of features such as joints, rock openings, and loose soil zones were all demonstrated. Compaction grouting was also successfully completed.
2. Portland cement grout traveled as a wave front in dry open joints and to a lesser extent in open gravels. For in-situ dry situations, voids may be left open after cementitous grouting.
3. Portland cement grout traveled to the boundary and penetrated in from the boundary in wet situations.
4. Penetration from the boundary was observed in thin, rock joint, modules filled with sand.
5. Pumping through dry gravel has very little effect on portland cement grout. There is a thickening effect (lower percentage bleed water and higher density) as the grout travels through the dry gravel.
6. Pumping portland cement grout through water has the greatest effect on strength and cohesion properties, with little effect on density or flow cone results. The bleed water percentages were not consistent, which was probably caused at least in part by nonuniform mixing as the grout traveled along the boundary before exit for sampling. Cement grout mixes with water when passing through wet materials; in these 6 foot modules a 20% reduction in compressive strength was observed in the grout.
7. The compressive strength of grout was reduced by approximately 20% after injection, compared to a laboratory mixed sample of the same material.
8. The ability for grout to penetrate soils generally follows relations suggested by Houlsby for gaps in plates when an equivalent diameter is used for the soil particles.
9. Chemical grout filled gaps when injected from a bottom outlet in a cylindrical tube. Chemical grout was able to penetrate sand and gravel before gelling occurred.
10. Grout penetration was better in an upward direction than in any other orientation. Penetration is believed to be enhanced in wet sands through liquefaction or boiling conditions.
11. Permeability values for samples with fully filled voids change by at least an order of magnitude.

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