FRAC GROUTING – A CASE HISTORY

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ABSTRACT: The United States Postal Service's (USPS) Eastpointe Facility in Clarksburg, West Virginia is located at the site of a former strip mine. Reclamation activities prior to construction were accomplished by backfilling the stripped area with the excavated materials after the coal seam had been removed. Subsurface investigations performed for the design of the facility identified settlement concerns due to loose fill and the existence of nested cobbles and boulders. To address this concern the site was reportedly over excavated and replaced with a controlled engineered fill. Placement and compaction methods utilized during placement of this controlled fill are unknown. Constructed in 1989, the 9,300 m^2 single story steel frame structure is supported by columns founded on spread footings. The floor of the building is a grade supported concrete slab isolated from the primary foundation system. Differential settlement of up to 150 mm has occurred causing structural damage and serviceability problems. This paper details, from a construction perspective, the applied grouting technology utilized to stabilize the structure, along with an analysis of the performance achieved. The work was substantially completed in the fall of 2001.

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FRAC GROUTING BACKROUND AND THEORY

Frac (hydrofracture) grouting is a relatively new grouting technique that originated in Europe. The process is applicable to stabilization and compensation grouting of fine grained soils with low hydraulic conductivity where permeation grouting is not effective or is limited. The original development of Frac grouting was to compensate for soil losses and subsequent settlement during tunneling or excavation activities. The process evolved into a soil stabilization technique for the purpose of preventing future settlement due to an unstable soil mass. This latter application was the purpose intended for the Clarksburg project.

The premise of Frac grouting is to inject a grout under pressure to hydrofracture or open pre-existing fractures within the insitu soil. The grout filled fractures create grout lenses which densify and reinforce the soil mass. Grout is initially injected at pressures required to create soil failure, which in turn fills the fracture. The magnitude of the Frac, with regard to length, width and volume is a function of hydraulic gradient established by the grout injection pressure and insitu soil overburden pressures.

In theory, if a soil is normally consolidated, the first grout lens produced will propagate in the vertical direction (direction of major principal stress), which will cause horizontal pressures to increase and hence cause compression in the soil (Raabe and Esters, 1990). If further injections are undertaken until the principal stresses are reoriented, horizontal fractures will be propagated and eventually (sometimes rapidly) lead to heave. In practice, the direction of the initial fracture is often controlled by pre-existing defects, or weak zones within the soil or weathered rock mass, and not the existing state of stress (Rawlings et.al., 2000).

Initially the grout forms a bulb that continues to grow, until the principal stresses of the soils are overcome. At this point a pressure drop occurs, and flow remains either constant or increases, depending on the fracture that has developed. The dynamics of this process are complicated and often difficult to predict. The process, therefore, requires continuous real-time monitoring of structural movement and the grouting parameters to adequately and safely control the Frac grouting operation.

The grout delivery system typically involves the installation of sleeved pipes called tube-a-manchette's (TAM's) that are drilled, driven or jacked into the soil in some predetermined array designed to provide adequate grout zone coverage of the soil mass. TAM's consist of steel or plastic pipes with one-way sleeved valves spaced at 0.3 to 1.5 meters along the pipe alignment through which grout is injected and if necessary re-injected. A double pneumatic packer assembly is used to seal off the individual sleeved valves, through which grout is injected for the purpose of treating the surrounding soil.

CONTINUOUS ELECTRONIC MONITORING

Soil fracture grouting by nature is a technique that has the potential to cause significant structural damage to adjacent structures and tunnel linings. Once Frac grouting is initiated the insitu soil is subjected to internal pressure, and soil displacement will eventually propagate into surface heave. Controlled fracturing of soil requires real-time electronic monitoring of the pressure and flow rate during grouting operations as well as the real-time electronic monitoring of the ground surface or buildings to detect movement. Based on the monitoring data, informed decisions can be made and the fracturing of the foundation soils can be performed with confidence. The data collected during the project is electronically stored within a relational data base that may be used for quantity reconciliation and execution verification along with post analysis of grouting work.

DESIGN AND CONSTRUCTION EXECUTION

The USPS Eastpointe Facility located in Clarksburg, West Virginia, had experienced differential movement since construction of up to 150 mm. As a result, structural damage to interior floors and walls in the form of cracking was evident; as well as some serviceability issues of doors not closing properly. Several elevation surveys were conducted all indicating continual differential movement.

Soils investigations at the site, prior to the building construction in 1989 found that settlement concerns existed due to the presence of nested cobbles and boulders. To address this concern the site was reportedly over excavated and replaced with a controlled engineered fill. Excavation was apparently performed to a depth of 3 to 4.5 meters, but the placing techniques as well as the origin and quality of the controlled fill are unknown.

Subsurface conditions at the site prior to grouting indicated that the fill material was variable (soils investigations were performed by a soils testing company). Boring logs and laboratory test results indicated that subsurface conditions consisted of silty clay with varying amounts of rock fragments, and sand. Site testing consisted of Standard Penetration Testing, with the resulting N values ranging between 1 and 30, with an average N value of 8.

It was found during shaft excavation that the insitu soil comprised of a gray to brown clayey, gravelly silt. Numerous large sandstone and limestone boulders (±

1m x 1.25m x 1.25 m) with clusters of smaller, densely packed sandstone and limestone boulders were also uncovered. In addition, ground water seepage in the order of 20 liters/minute was encountered during the shaft excavation.

DESIGN

The grouting approach (original design by an engineering company overseeing the project) included the construction of four vertical shafts, with radiating fans of sleeved pipes originating from these four shafts and dividing the building into four separate grouting quadrants (refer to Figure 2). From these four shafts, 4 layers of pipes were installed at locations of 4.56 meters below the building slab (Bottom Layer, Mid Layer, and Intermediate Layer), and 3.05 meters below the building slab (Top Layer)(refer to Figure 3). These were subsequently classified as lower level and upper level holes. This exterior approach, utilizing access shafts, was adopted due to the facility being in use 24 hours a day, 7 days a week. Any work that was to be performed from the inside was considered to be too obtrusive.

The contract specifications indicated the following:

- Installation of pipes to be either drilled or driven.
- Grouting flow and pressure to be continuously monitored in real-time.
- Ground monitoring to be capable of reading and processing movement in real-time during grouting operations with an accuracy of 1.5 mm.

INSTALLATION OF SLEEVE PIPES

Inducing further settlement of the existing fragile soil during sleeve pipe installation was a major concern when determining the sleeve pipe installation method. Conventional drilling methods utilize pressurized air or fluid and have the potential to create further damage to the existing fragile soil beneath the USPS Facility. Jacking of the sleeve pipes would provide the least disruption to the existing soils and eliminate any soil losses during sleeve pipe installation while providing some degree of soil compaction in the process. As a result, custom designed and fabricated steel sleeve pipes were jacked into place utilizing a custom designed hydraulic jacking unit.

This process involved precise initial sleeve pipe alignment with continual monitoring of jacking pressures as well as sleeve pipe alignment profiling during installation. The Jacking unit (refer to figure 1) was custom manufactured to meet contractor requirements and was used to hydraulically jack sleeved pipes under the facility.

Figure 1. Custom manufactured Jacking Unit.

The unanticipated presence of boulders, deflection and early termination of some sleeve pipes presented a constructability issue. Jacking pressures were continually monitored and a refusal criteria of 45.36 metric tons jacking force was established as a maximum termination pressure. In two separate instances, boulders encountered during the jacking operation resulted in abrupt deviations and caused sleeve pipes to penetrate the floor slab of the facility. As a result of these two events, more stringent refusal criteria was established for deviation control based on both jacking pressure and sleeve pipe alignment profile. The sleeve pipes were periodically surveyed using a liquid settlement profiler, and the jacking pressures were continuously monitored. A 1.5 meter buffer zone was established from the tip of the pipe to the top of the building floor slab, and in the event that either this 1.5 meter buffer was breached or jacking pressures exceeding 45.36 metric tons, installation of the pipe was terminated. This revised refusal criteria was successful in completing all remaining sleeve pipe installations without further incident.

Upon the successful installation of a sleeve pipe an optical borehole survey instrument was used to establish the final sleeve pipe location, for verification of grout zone coverage. Additional sleeve pipes were installed when early termination occurred or the sleeve pipe was determined to have excessive deviation that would create a situation of inadequate grout zone coverage.

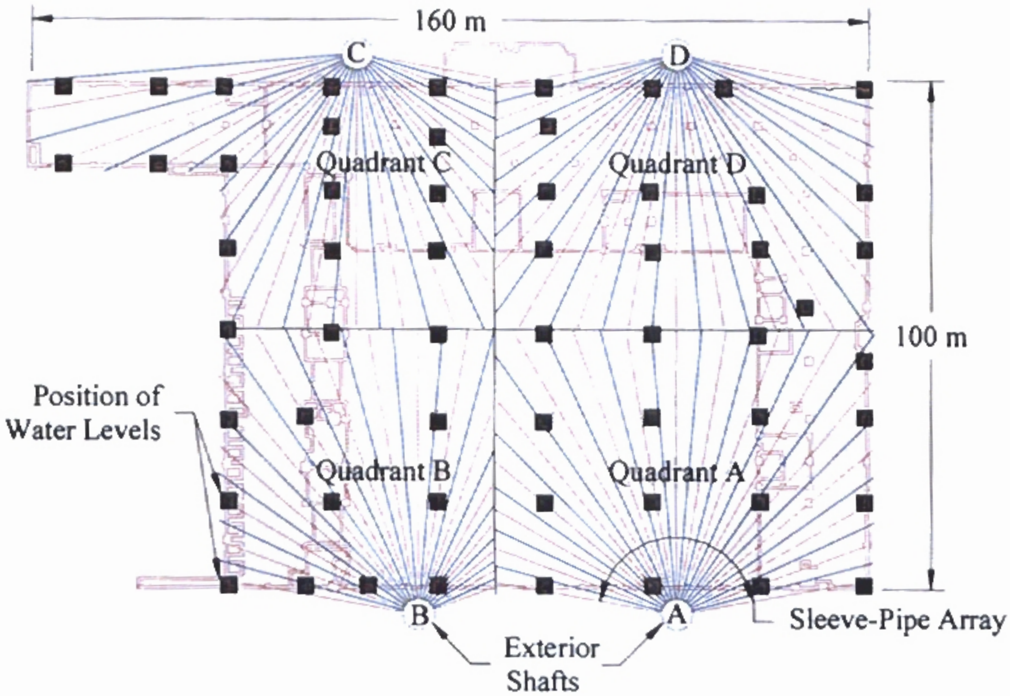

Figure 2. Plan View of Sleeve Pipe Layout.

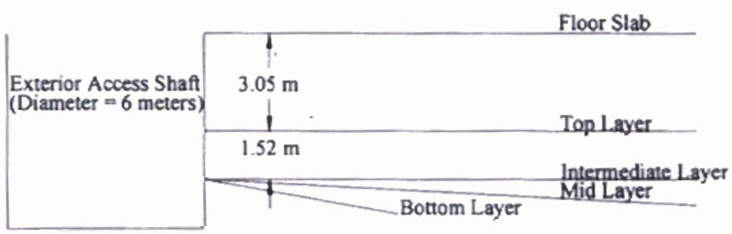

Figure 3. Elevation View of Sleeve Pipe array from one shaft.

GROUTING

The mix design chosen was a slow setting, stable cementitious grout mix with the following formulation and physical properties.

- Mix Design Formulation
  - Water / cement ratio: 2.25:1 (by weight of cement)
  - Pre-hydrated Bentonite: 8% (by weight of cement)
- Physical Properties
  - Compressive Strength: 3.5 MPa
  - Specific Gravity: 1.29 kg/L
  - Marsh Funnel: 80 seconds
  - Bleed: 5%
  - Initial Set: ± 8 hours
  - Final Set: ± 12 hours

This above mix was chosen to provide a reasonably long initial set time to allow time for grout delivery and complete injection and re-injection as required. The strength parameter is based on final shear strength requirements and insitu soil parameters.

Grout was mixed at a central batching plant using high-speed colloidal mixers and was delivered to the point of injection via helical screw type pumps connected to a header and return lines. Grouting within the sleeve pipes was performed via a double packer arrangement used to isolate the individual sleeve ports. All grouting operations were electronically monitored for real-time pressure and flow rate.

The following general guideline specification was adopted for this project:

- Maximum production grouting pressure: 550 KPa
- Maximum target volume per sleeve: 500 Liters
- Maximum movement: 1.5 mm
- Maximum flow rate: 20 Liters/min

ELECTRONIC MONITORING

The grouting operation was continuously monitored for pressure, flow rate and volume parameters. A flow meter and pressure transducer unit was located within the shaft at the point of injection and real-time information was electronically transmitted to a central monitoring control center. The information was visually displayed for the operator and stored electronically for future reference. The grouting technician was in constant radio contact with the header man and batch plant operator, and completely directed and controlled the operation based on the project requirements and real-time monitoring data. The monitoring provided information on the physical injection process and was correlated with building movement to provide meaningful control. Based on the requirements outlined in the specifications, options were given to the selection of electronic ground monitoring devices, with the selection being the electronic liquid level system.

A total of 24 electronic liquid levels were used per grouting quadrant, the locations of which are indicated in Figure 2. These levels were attached to the building columns. However, with the building columns being spaced approximately 23 meters apart additional monitoring points were required at closer intervals. To bridge this gap and to provide monitoring of the lighter floor slab, 2 levels were mounted on moveable carts. The liquid levels mounted on the building columns were referenced to a location outside the potential movement zone and the differential movement between the liquid levels and reference point for all locations was electronically transmitted to the central monitoring control station. The grouting technician could then correlate very discrete building movements with the grout injection process and have full control of the operation. Figure 4 shows a schematic of the grouting operations and the electronic monitoring utilized on this project.

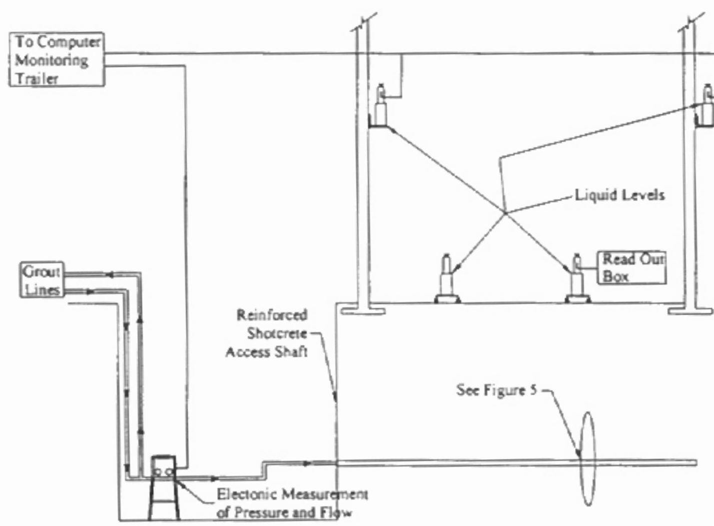

Figure 4. Cross sectional view of grouting operations.

SLEEVE PIPE INSTALLATION ANAYLSIS

The jacking system that was utilized preformed remarkably well from both a production and deviation standpoint. Without the introduction of traditional drilling

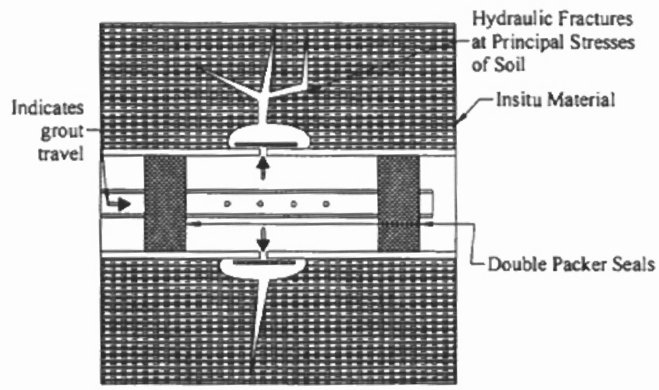

Figure 5. Close-up of sleeve during grouting operations.

fluids for the flushing of the drill cuttings, the in-place soil remained intact and actually received a small degree of compaction from the driving of the sleeve pipes. The presence of numerous cobbles and boulders did provide for a challenging situation that required close monitoring and operator judgment. When a boulder was encountered, early termination and excessive deflection did occur, and additional sleeve pipes were installed in order to attain adequate grout zone coverage. The jacking operation was continually monitored for deviation and jacking pressure as shown in Figures 6 & 7, which represents a typical jacking operation.

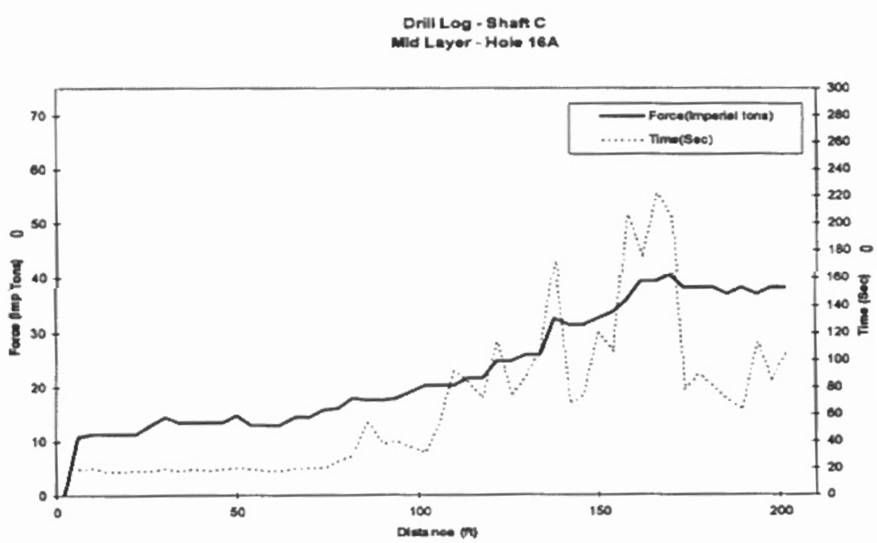

Figure 6. Typical results detailing the jacking pressures and times

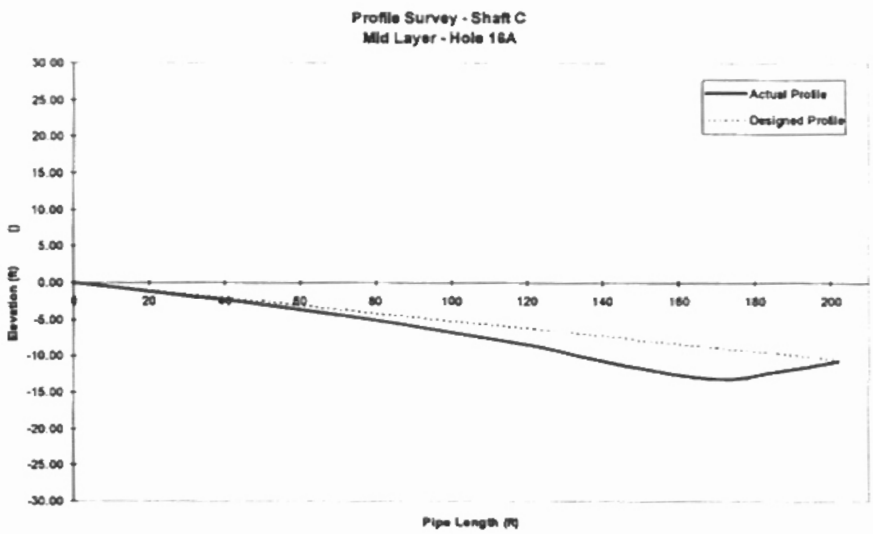

Figure 7. Typical results detailing the profile alignment survey of sleeve pipes.

Deviation of the sleeve pipes exceeded original contractual specifications due to the unexpected frequency of boulders; however grout zone coverage was not compromised due to the installation of additional sleeve pipes to compensate for the early termination, or the excessive deviation of installed sleeve pipes. The following table (Table 1) indicates the average deviation of the sleeve pipes jacked from Shaft A, which is typical of the other three shafts.

PIPES JACKED	AVERAGE DEVIATION (METERS)	DIRECTION
40	1.47	Up
28	1.00	Down
31	1.30	Right
37	1.25	Left

Table 1. Shaft A summary of deviations.

A total of 2,813 meters of pipe was installed at 136 locations from Shaft A with an average deviation of 4%. The magnitude of the deviation is attributed to the presence of the cobbles and boulders within the insitu soil combined with jacking lengths exceeding 60 meters.

GROUTING ANALYSIS

The grouting operation for this project was carefully monitored and was considered to be successful based on post survey data. Analysis of the survey results indicated that subsidence had ceased, thereby indicating that the Frac grouting was a success.

Due to the extensive amount of instrumentation utilized on this project, the primary refusal criteria was based on the electronic liquid level heave monitoring system. This was the only true measure of effectiveness of the grouting operations in terms of real numbers. Detection of very small movements was capable in seconds, which is required in this type of work. The grouting proceeded from the lower level sleeve pipes (Bottom, Mid, and Intermediate Layers, collar elevation at 4.57 meters below the facility floor slab) and proceeded to the upper levels (Top Layer and any subsequent additional pipes, collar elevation at 3.05 meters below the facility floor slab). As expected, the lower zones were able to accept considerably more grout material than the upper due to proximity of the facility. The table (Table 2) below indicates the percentage of the total grout placed per layer on the entire project.

Upper Levels (Top Layer, and any subsequent additional pipes)	28.8 %
Lower Levels (Bottom, Mid, and Intermediate Layers)	71.2 %

Table 2. Project total grout volumes.

Table 2 is an indication that the grouting was being successfully applied. Since the approach was to begin with the lower level holes and to proceed to the upper level, the results indicate that the soil matrix was becoming increasingly compacted, and consolidated.

Figure 8 indicates the responsiveness of the liquid level system to surface heave. As indicated, Sleeve 19 took a considerably greater amount of grout and caused one of the building columns to heave slightly. When grouting resumed on Sleeve 17, the same building column was immediately affected by the influx of a minimal amount of material. Since this heave monitoring system was so responsive, this system was used almost entirely as refusal criteria to ensure that hydrofracturing of the ground was being successful, leading to improvements in the soil characteristics.

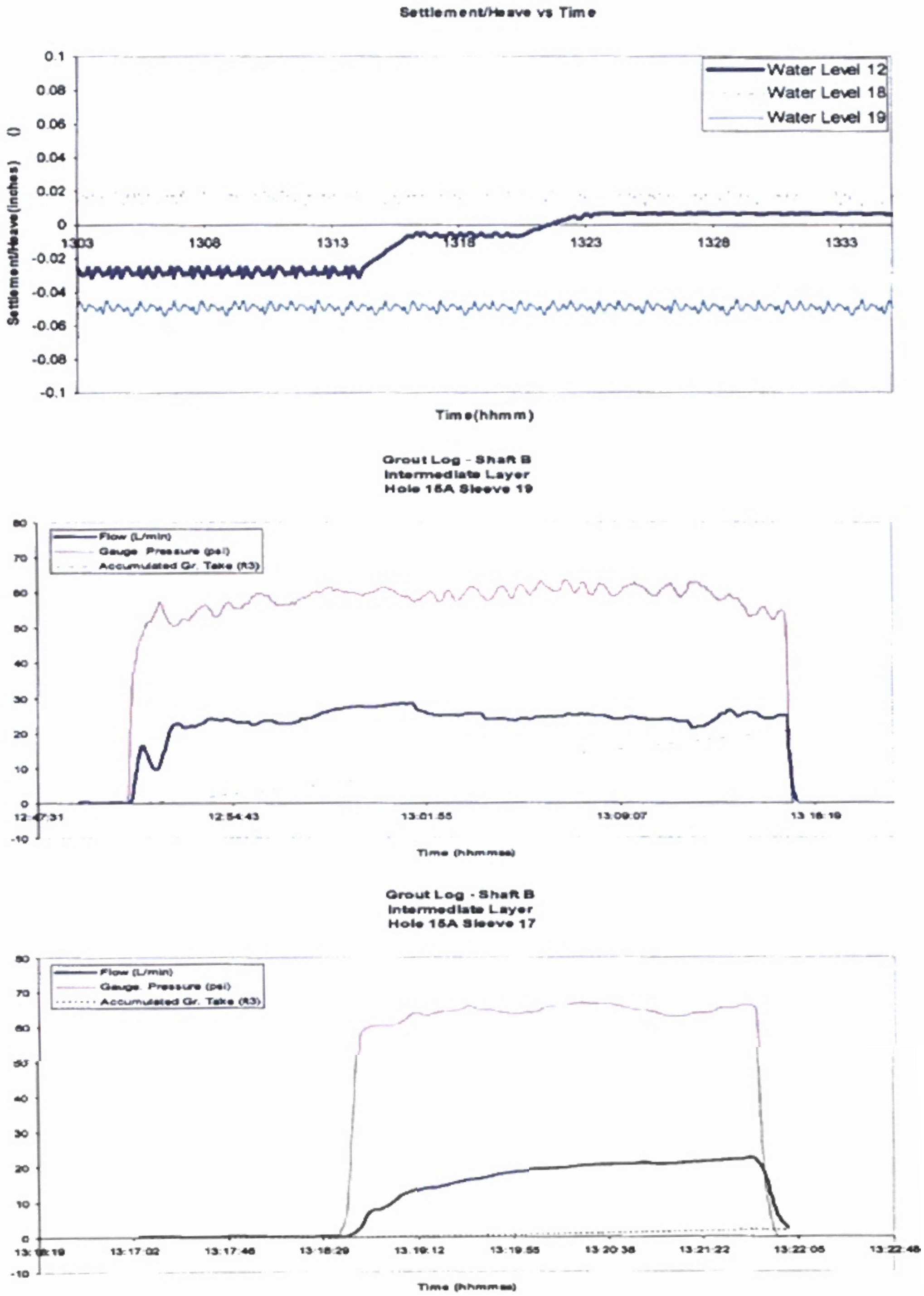

Figure 8. The typical result of grouting a lower level hole (Bottom, Mid, & Intermediate Layers were 1.52 meters lower than the Top).

SUMMARY AND CONCLUSION

Frac grouting on this project was performed to mitigate settlement, and was performed under very stringent operational and performance criteria. A total of 12,800 meters of sleeve pipe was installed and 680 m^3 of grout was injected during the Frac grouting operation over an 18-month period. Early survey results indicate good performance with ongoing surveys being conducted semi-annually.

Frac grouting together with extensive electronic monitoring equipment can alleviate either the anticipated settlement due to tunneling or stop continuing settlement due to poor foundation conditions as was demonstrated on this project.

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