Development of jet grout test sections

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ABSTRACT
The pace of jet grouting developments has been such that there is an urgent need for all those involved in the geotechnical construction industry to have knowledge of the latest technology and developments. From writing of technical specifications to execution in the field, the communication of the ever evolving state of the practice between engineer and contractor is imperative. Inherent to jet grout construction, test sections are often installed to verify assumed construction parameters and performance. It is not uncommon for very large and robust test sections with construction equalling that of the final production work to be specified for projects of limited size. To assist in realizing efficiencies within the jet grout QA program this paper presents the various techniques developed to execute and verify jet grout test sections while remaining both technically sound and economical.

RÉSUMÉ
Le rythme de développement dans le domaine de l'injection à haute pression est tel qu'il existe un besoin urgent d'accès aux plus récentes informations sur cette technologie, pour le bénéfice de toute la communauté géotechnique. Du devis technique jusqu'à l'exécution du travail, la communication à toutes les étapes du processus entre l'ingénieur et l'entrepreneur est impérative dans ce domaine en constante évolution. Des champs d'essais sont régulièrement mis en place afin de vérifier les paramètres de construction ainsi que la performance du produit. Il n'est pas rare de planifier un champ d'essai aussi grand et aussi complexe que le travail à effectuer comme tel. Afin de maintenir une certaine efficacité dans ces situations, ce document présente les différentes techniques et méthodologies utilisées dans les champs d'essai, tout en maintenant un bon rapport qualité/prix.

1 INTRODUCTION

Full-scale field trials or test sections are the current practice in the industry to identify initial performance of jet grout construction and confirm the baseline operational parameters. Jet grout test sections can become very large and be a significant portion of the complete ground improvement program when considering that columns can be constructed up to 5 m in diameter. Historically, project specifications may have stated a given fixed number of columns as a requirement to be installed as a test area. Over the last few years, with the ability to construct these very large columns, the test areas can now potentially equal the size of the final scope of work.

Depending on the application of the work, the three most common jet grout column attributes of interest are geometry/continuity, strength and permeability. This paper highlights the techniques available to efficiently tailor the test programs to suit given site constraints while yielding an optimal data set with respect to the above. Case histories are presented to illustrate these methods of quality assurance.

2 JET GROUT TECHNIQUE

Jet grouting is a Ground Modification technique to create an in-situ mass of cemented soil known as “soilcrete”. Typically a drill rig advances a jet grout monitor to the bottom of the proposed treatment zone whereupon the introduction of high velocity injection media is initialized. The drill tool is withdrawn and rotated at a constant rate to create a column from the bottom elevation upwards.

There are three traditional jet grouting techniques which are achieved by varying the combination or configuration of injection media. The single, double and triple fluid jet grouting techniques are described by Sweeney et al. (2001).

The SuperJet grouting technique is a modified double fluid system that is capable of generating columns up to 5 m in diameter as detailed by Burke et al. (2000). This modified double fluid system utilizes a proprietary multi-chambered drill rod system to convey slurry grout and air to the jetting tool. A high velocity coaxial stream of slurry grout is shrouded in a sheath of high pressure air to mix and erode the in-situ soils. The highly sophisticated SuperJet monitor utilizes opposing nozzles specifically designed to focus the injection media at a given radius in balance with the chosen flow rate, line pressure and specific gravity. Figure 1 depicts the general process of SuperJet grout construction.

With the development of the SuperJet grouting technology and the increasingly large diameter columns the volume of material consumed in a test section, or even a single column, can be considerable. It is this technology that has given rise to the focus of attention to seeking efficiencies in test sections and QA programs.

2.1 Construction Parameters

The main operational parameters that have to be selected upon commencement of the test program are pressure, flow rate, rotational speed, withdrawal rate, step height and mix design of the injection media. Site constraints such as soil type, density and depth of work must be considered in selection of the baseline operational parameters.

Initial estimation of column diameter is highly empirical and relies heavily on the experience of the jet grouting contractor and their observations in similar ground conditions. More often than not, the length of a production jet grout column will penetrate through more than one soil stratum and warrants consideration during design of a test section. Comprehensive analytical studies of construction variables has been undertaken by Ho (2006) and others, which can assist in initial selection of the baseline parameters but will not replace the need for some means of a full-scale field test.

Factors influencing column diameter include pressure, flow rate and density of the injection media along with the focus of the stream. In addition, the pressure and flow rate of the air shroud have a profound effect and play an increasingly more important role with increasing effective stress levels. Typically, two to four rotations of the jetting tool within a given elevation are required to realize the maximum achievable column diameter. Synchronizing the rotation speed with withdrawal rate will ultimately define the amount of time necessary for erosion or construction of a column to occur. Similarly, time of construction with a constant grout flow rate and given specific gravity will dictate the theoretical cement content, thereby having a direct impact on both permeability and strength.

Endless permutations of the mix design and physical construction parameters can be proposed resulting in a very comprehensive and robust test program. Depending on project size and scope these large test programs may be warranted. Bliss et al. (2000) describe a case history of a very large full-scale field test with extensive testing and evaluation on a seismic remediation project which warranted such detail. Conversely, the following sections describe QA methods and case histories where the test sections were optimized to their fullest extent in order to accelerate the project schedules and limit cost.

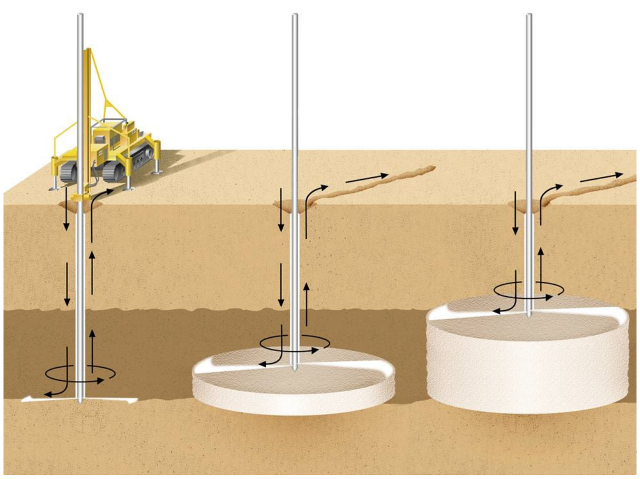

Figure 1. SuperJet Grouting Process

2.2 Field QA Measures

If the near surface soils are representative of the soils to be improved during production grouting, construction of a shallow test section may be undertaken. The use of feeler pipes can then assist with determination of achievable column geometry. Acting as telltales, feeler pipes sense jetting activity during column construction and give indications to the in-situ column diameter.

Starting near the center point of a single test column PVC feeler pipes, or similar, can be installed vertically, located approximately 120-degrees apart (radially) at varying distances from the column center point. Extending from existing grade to the bottom elevation of the test column, the feeler pipes are placed within a drilled hole. The annulus around the pipe is then backfilled with sand. Feeler pipes are left open and clear at the ground surface with a 1.5 m stickup. At the onset of high velocity injection the grouting technician will monitor each of the pipes for vibration or movement. As the column diameter increases with continued jetting it should become apparent when the eroded diameter has meet the first, second and possibly third feeler pipe at the furthest point from injection. Placement of feeler pipes beyond 7 m in depth does not usually give a clear indication of the grouting activity due to the dampening action of the greater depth of overburden. However, jet grouting presence at the feeler pipe can also be visually observed by grout exiting up the center of the pipe once the high velocity jet grout stream has cut through the PVC pipe walls.

The method of using feeler pipes to determine column geometry eliminates the need for excavation/exposure that would be difficult in conditions with high groundwater levels and limited access. In addition to the implementation of feeler pipes, when permissible, excavation to the top of column elevation can further confirm the column geometry obtained. Excavation past the top of the column to view the top 1 to 2 m can further increase confidence of the column geometry with increasing depth below grade, thereby complimenting the information obtained from the feeler pipes.

When constructing shallow test columns with the double fluid or SuperJet system wet (uncured) soilcrete samples can conveniently be retrieved from the constant return of grout. These wet samples can be cast into cubes and/or cylinders for laboratory testing and determination of unit weight, strength, permeability and other desired properties. Although not entirely representative of the material comprising the column, the grout return[TRP1] generated from near surface column construction has a far less likelihood of becoming contaminated by variable overlying soil strata than for columns constructed at greater depths, and has yielded accurate strength data confirmed through coring. Casting of wet samples can also yield early test results such as 7-day strengths, which benefits today's schedule-driven construction projects.

Various down-hole sampling tools have been devised to collect wet in-situ soilcrete immediately after column construction. More time consuming and labour intensive than sampling from the grout return stream, this method returns a truly representative sample for testing and is the only means of retrieving wet samples from columns constructed at greater depths (+10 m).

Continuous cores give information on geometry, continuity and segregation while yielding true in-situ cured samples for laboratory analysis. Soil type and soilcrete strength both have to be considered prior to coring in order to manage expectations of core recovery and RQD.

HQ3 and PQ3 sized coring tools have proven to be the most efficient in obtaining usable cores when working in problematic soil conditions. Typically, coring can not take place until at least 5 to 7-days of curing time has passed, although some success has been observed as early as 3-days.

When core sample recover offers questions about continuity or quality, a borehole video may quickly resolve the understanding of in-situ conditions.

3 TEST SECTION CASE HISTORIES

3.1 Brightwater Conveyance System, Seattle, Washington, USA

Tunnel construction on the East and Central Contracts of King County's Brightwater Conveyance System required ground modifications of the existing site soils, comprised of sandy alluvium to very dense glacial till, to assist with both hand-mined and TBM tunneling operations at vertical access shafts. The required tunnel breakin/breakout depths ranged from about 21 to 26 m below ground surface at shaft locations founded in granular soils with near surface groundwater tables. Consequently, implementation of a ground modification scheme in conjunction with carefully sequenced tunneling stages would be imperative to ensure a safe working environment. It was determined that jet grouting would be the most appropriate ground modification method to satisfy both technical requirements and the project schedule needs. Jet grouting construction on the East and Central Contracts was configured with two discreet test sections. Each test section was either partially or fully incorporated into the final work product by using careful sequencing of both column installation and test data retrieval to enable rapid determination of jetting performance (Hanke and Blanding, 2008).

Jet grouting first started on the East Contract with a test area that was partially incorporated into the production work and consisted of a total of six columns. The first three test columns were sacrificial and were constructed with a conservative set of baseline grouting parameters. Constructed on a triangulated 2.75 m center-to-center spacing with column tops 3 m below grade, these columns were excavated to visually verify the column diameters and geometric overlap. One day after construction, excavation revealed that the designed column diameter of 3.35 m was well surpassed and substantial column overlap was achieved.

Having verified that the design geometry of the columns had been achieved, the test program proceeded to the second stage where the final three test columns were to be integrated into the production work. These three 12.5 m long columns were located within the future tunnel alignment with a bottom of column depth at 24.5 m and a top elevation at 12 m below grade. To later be verified by coring, these columns were constructed using three sets of construction parameters along their length. The variable construction parameters included only the tool rotational speed and withdrawal rate. The bottom third of each column was constructed using the same conservative baseline parameters proven to be successful with the first three test columns. The middle third used slightly less conservative parameters by increasing the rotation speed and withdrawal rate, and the top third the least conservative. By incorporating these test columns into the final product a jumpstart on production was gained while some risk in terms of performance was assumed. By incorporating these test columns into the final work the main risk was not obtaining the required column geometry within the upper third of the test columns, due to the third set of parameters being too aggressive. This situation can easily be remedied by drilling down and jetting at the interstice and surrounding perimeter with the baseline or required jetting parameters. This would not only remedy the geometry concern but would also introduce a well oversized ground improved mass to eliminate any soilcrete strength concern.

Five days after construction, the three column interstice was continuously cored using HQ3 sized tooling. The recovered core sample allowed visual inspection to gauge continuity or segregation with respect to depth in correlation to the three construction parameter sets used (Figure 2). Core samples also provided for laboratory analysis of unconfined compressive strength (UCS), total unit weight and hydraulic conductivity. Analysis determined that all three parameter sets yielded satisfactory results. Although, it must be considered that geotechnical conditions do vary and due to schedule constraints the information on this area is only based on results from a single core hole. Upon consideration of potential unforeseen variables not accommodated for within the current study, and weighing the potential risk during mining, it was decided that the initial baseline parameters offered peace of mind and were the most appropriate for the existing soils and construction constraints.

Figure 2. Soilcrete cores extracted from Brightwater East test section at three column interstice

Approximately 3 km down the tunnel alignment the second test section was carried out for the Central Contract. At this portal the jet grout test program consisted of six test columns, all of which were incorporated into the production work. These 11 m long columns were located within the tunnel alignment with bottom of column at 29 m below grade and were designed to have a nominal 3.5 m diameter. Unlike the soils encountered at the East Contract, the soils present from working grade to depth were not uniform alluvial deposits throughout, but rather a recessional outwash overlying a dense till. This condition did not permit the use of shallow test columns for physical analysis through excavation and exposure. Subsequently, test columns were constructed with parameters similar to those utilized at the East Contract, but with a larger jet nozzle orifice which provided for an increased flow rate thus introducing more mixing energy.

Verification of column geometry and continuity as well as in-situ soilcrete strength was to be determined by coring the overlap of three columns (interstice) and the overlap of two columns at two separate locations each after allowing a minimum of seven days cure. However, as the scheduling demands of this site were not flexible enough to allow adequate time for curing and exploration of the test columns, the project team agreed that it was necessary for production work to continue prior to coring and retrieving laboratory results. This schedule constraint was weighed into the decision as to what initial parameters to use, therefore an aggressive rotation/withdrawal rate was not considered. In order to provide some initial information about the generated soilcrete product, wet samples were taken from the grout return along the drill annulus while jetting the test columns. These samples were molded into 2x4 and 3x6-inch cylinders, which underwent UCS and hydraulic conductivity (permeability) tests. The preliminary tests indicated that both strength and hydraulic conductivity were well within acceptable ranges. Still unknown was if full column geometry was being achieved throughout the full depth.

Following the completion of jet grouting production within the vicinity of the Central Contract test area, HQ coring was conducted and would determine if full grout coverage was achieved. Core samples would also be tested for UCS. Three core holes all indicated that the 11 m tall jet grouted soilcrete block had two lenses of non-grouted clay within the upper half. Furthermore, the presence of gravel and cobble within given till layers hampered obtainment of full core recovery. A soilcrete matrix of grout and sub-rounded to rounded gravels proved to be problematic to core on this project and others. Although very competent and fully grouted, large pieces of gravel (aggregate) can dislodge from the soilcrete while coring and be ground into the advancing front with tooling advancement and cause severe wear and abrasion. The weaker grout portion of the soilcrete matrix is then ground up and washed away leaving only the gravel component within the core barrel. With this occurring, core recovery rates ranged from 50 to 75-percent and did not meet the specified 85-percent minimum.

Recovered through coring, fully intact undisturbed non-grouted clay was laboratory tested to obtain material properties. Analysis revealed this material to be very stiff dark lean clay (CL) with a plasticity index of 13-percent and a coefficient of permeability equaling 1.3×10^{-7} cm/sec. Consideration of the above material properties and the fact that this material remained intact within a core barrel designed to extract soilcrete, concrete or rock, indicated that this non-grouted interbed inclusion of clay is sound and competent. It was agreed that this very stiff cohesive material of low permeability that was bound and encapsulated by soilcrete with an average UCS greater than 7 MPa (1000-psi) was sound and did not require remedial grouting.

3.2 Tacoma Wastewater Treatment Plant, Tacoma, Washington, USA

Construction on the expansion of Tacoma's wastewater treatment plant required ground improvement of the existing site soils, comprised primarily of various fill layers underlain by alluvial and lacustrine sediment, to mitigate the liquefaction potential thus meeting structural settlement and bearing capacity requirements. The scope of work included stone columns to support three of the five new structures. Beneath the remaining structures 3.7 m diameter jet grout columns were placed with the SuperJet system where ground conditions were the poorest and would not be capable of accepting stone column work. A sheetpiled excavation required 3.7 m diameter jet grout columns to act as exposed lagging to a 5 m excavation depth, and to encompass existing utilities that crossed the excavation line while assisting in groundwater control. Similarly, two existing sedimentation tanks required underpinning and excavation support with 1.2 m diameter triple fluid jet grout columns as new construction was undertaken immediately adjacent to the tanks.

With jet grout column construction occurring within three distinct areas of the site, and with two separate tooling configurations, the amount of effort devoted to execution of test sections could become daunting. Analysis determined that excavation/exposure would yield the quickest feedback on geometry and would compliment strength testing data retrieved from wet samples.

A single 3 m long sacrificial SuperJet grout column of 3.7 m diameter was constructed between 4.5 and 1.5 m below grade. Excavation to reveal the column top was limited to 2 m in depth due to a high groundwater level. Wet soilcrete samples obtained from the grout return were collected and cast into 2x4 inch cylinders for UCS testing. The top of the exposed column was measured to be approximately 4 m in diameter. Considering that the work terminated at 11 m for both areas of SuperJet construction, and that the areas were within relative proximity of each other, this single test column was deemed representative. With relatively low design 28-day UCS requirements (517-kPa) the column size was the more critical attribute to determine prior to construction. Assuming some risk, jet grouting commenced prior to obtaining laboratory strength testing data. However, early test results at 7-days revealed that the soilcrete strengths would not be an issue.

Excavation and exposure of triple fluid jet grout columns for underpinning of the primary sedimentation tanks revealed that the design column diameters were surpassed (Figure 3). [TRP2]Sampling of wet soilcrete was accomplished with a downhole in-situ sampler to retrieve samples from 3 and 5 m below grade. As shown in Figure 4, the true test of the work was realized upon excavation which revealed a continuous monolithic wall of soilcrete that both underpinned the sedimentation tanks and acted as the sole means of excavation support, thereby allowing construction of the new infrastructure directly adjacent to and in contact with the original sets of tanks.

Figure 3. Exposed triple fluid jet grout column tops exceeding the design 1.2 m diameter

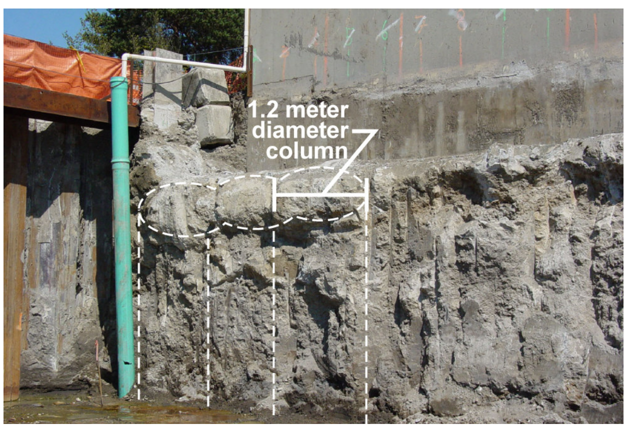

Figure 4. Exposed sedimentation tank underpinning with overlapping 1.2 m diameter triple fluid jet grout columns

4 SUMMARY AND CONCLUSIONS

The constant variables inherent to geotechnical construction do not allow analytical determinations alone when considering jet grouting. Full scale field tests in some form are a requirement for jet grouting works. This paper describes the techniques used to structure and analyze a test program while highlighting some areas of concern and importance. Shown through case histories, augmenting and enhancing these test areas to yield the required data with the fewest number of columns will ensure that jet grouting remains a viable and economically feasible means of ground modification where appropriate.

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