

MISUNDERSTOOD MECHANICS OF A COMPUTER AIDED GROUTING PROGRAM

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ABSTRACT

Computer aided grouting is an evolution that started nearly 4 decades ago but has only been accepted, embraced and instituted industry-wide since the turn of the last century. Admittedly, this has been a remarkable timeline for the acceptance of a “Great Leap” technology, as it has been referred to in the world’s geotechnical community. For better or worse, the rapid ascendancy of this technology has spawned significant misunderstandings of its fundamental requirements to execute a top tier, quantitative, data-driven grouting program.

Market acceptance has pressured all practitioners in the grouting industry to adopt the technology largely without an understanding of its fundamental technical ideology and mechanical requirements for execution. Strikingly, most of the fundamentals are equally pertinent to a simple application of the technology level as to an advanced state of the art program.

THE VISION

In the infancy of the technology there were two visions of what it was to become. One was the pure scientific vision of accurate acquisition of data in real-time to aid in engineering analysis, the other was a practitioner’s vision of efficiency and continuity through the entire grouting construction process. As one could imagine, the two visions from opposite perspectives met with some lively debate even to the point of aggressive interaction between the visionaries. The five-year gestation period where the two visions actively intersected with one another in real-time and real-world practice led to the realization that the differing perspectives were in fact linked on all levels, just prioritized in opposite scales of importance. The final merger of the two visions occurred by the independent analyses on the same project (Penn Forest Dam, PA) carried out by opposed parties each with their own ideology using the same technology demonstrated the many underlying false assumptions held by all participants and their common link to underperforming results. It was the recognition of these false assumptions that provided the basis for the fundamental approach that was developed and has led to the modern Tier 3 systems being employed on the largest projects throughout the world today (Bruce, 2015).

THE FUNDAMENTAL PRINCIPLE

The common procedure and the reality in earlier days was when all aspects of the grouting program were designed, executed, analyzed and directed by traditionalists who were in their turn, utilizing past experience based on observational techniques, smudged oily core logs, and hand tabulated columnar sheets. Once the visionaries figured out that most anomalies, disappointing performance characteristics, and outright failures could be ascribed to the traditionalist side of the equation, weighed down by the lack of consistent measurements, real data, and analytical tools employed systematically throughout the project’s currency.

It is fair to say that the tools of the time employed were dipstick, measuring tape (in various lengths), simple scope level, an assortment of pressure gauges, weigh scales, measuring buckets, Baroid flow

funnel, paper, pen and pencil, and many different data collectors and scribes from the Designer and Project Manager, geologists, drillers, grouters to the laborer counting the cement bags. Quality assurance involved bundling the bags together in ten packs for re-counting. Every single operation was subject to human interaction and judgement interpretation.

In our four-decade experience we can say we never met an individual involved in the project that did not think they were doing the best for "their" project. This is the problem as it is not "their" project but "THE PROJECT" and hidden agendas, prejudices and feelings (conscious and /or unconscious) need to be managed (stabilized) over considerable periods of time. Grouting projects were therefore hand-built using trial and error, by dedicated tradesmen and professionals, the type of people to whom the authors apprenticed.

Embracing the idea that the biggest variable in a grouting project is often the "Fundamental of Human Error", readiness to utilize a computer aided grouting system and to employ all the associated mechanics to secure an efficiently executed, engineered scientific analytical basis seem to be a desirable solution.

PRE-GROUTING CONSTRUCTION ACTIVITIES FOR A COMPUTER AIDED GROUTING PROGRAM

The assembly into a single repository of project geotechnical and construction history whether digital, analog, or paper based is fundamental to developing a knowledge base of known and unknown facts for the project. This is a required step for even a simple Level 1 program (where it might reside in a file cabinet at the onsite trailer) as well as a Level 3 program, where the information digitized, catalogued, residing in the data base and using hot links or similar approaches is available to the operators/analysts for rapid identification and use in real-time operations.

The historical data mining task for a remedial grouting project should encompass at a minimum:

- Original construction plans, as-builts, and subsequent modifications to the facility.
- Original construction photographs.
- Past, present construction/exploration baseline geotechnical reports.
- Commissioning events.
- Subsequent maintenance or repair program reports after commissioning.
- Historic weather and hydrographic information tables.
- Pre-program site conditions (geological and hydrogeological), physical structures, adjacent neighboring conditions.

A summary report should be prepared by the Owner, identifying known characteristics of interest and identification of unknowns to be further investigated either prior to or during grouting construction. When things have turned upside down it is generally a little late to look back, except to establish what should have been done going forward.

DEVELOPMENT OF A 3-DIMENSIONAL CONTROL PLAN

This step is critical to any Computer Aided Grouting Program at any level and begins with a thorough site survey phase to establish the common dimensional baseline from which to execute the project. This includes, but is not limited to, assimilating all contract drawings, elevations, and survey monuments to a contractually agreed baseline from which all parties will work, so avoiding potentially significant errors. There have been more survey busts between design documents and the actual site conditions than a successful simple fluent survey confirmation based on our experience.

With the survey verified, the Grouting Project Model can be refined and developed and must include the following elements:

- Work platform elevation control and X-Y coordinates (the scope for human error in the actual elevation/location of any operation being constructed knows no bounds).
- As designed hole layout and X-Y-Z coordinates along the full designed length of each hole.
- Identification of known physical obstructions for example an intake tunnel or conduit.
- Identification of specific geological features of note from the historic data mining task.
- Geologic fracture sets and bedding planes across the treatment zone(s).
- Interfaces /transitions actual or estimated.
- Designed grout holes and their assigned stages including sequencing.

During the development of the model, conflicts will be discovered as the construction elements temporary and permanent are imposed on the model design. These are to be expected if the project designers utilized different tools and techniques: better to have been discovered in the early planning stage than during high intensity (costly) construction operations.

Not all projects afford the favored option of a constant, fixed work platform elevation across the entire curtain alignment. However, we cannot stress strongly enough that every elevation variable that is constructed into a work enlarges the scope for error. Every effort should be made in the work platform design to minimize the variations and build in failsafe procedures and physical aids to mitigate any errors.

3D modeling is the preferred approach for multiple levels of effectiveness. However, 2D models are adequate for small non-complex projects employing low level Computer Aided Systems (flow and pressure only) and may not contain a 3D CAD linked to graphical relational data base architecture.

The model is the base upon which the entire project is built, and analyses are undertaken. Its accuracy is paramount to achieving the project's measures of success.

INITIAL ESTABLISHMENT OF PROJECT CONTROLS AND PARAMETERS

This is essentially the roadmap of means, methods, tools, and instruments intended to bring consistency to our operation and data streams. Note that the word "accuracy" has been omitted. This is intentional, as it relates to the human factor we are trying to manage. As we develop our controls/parameters it is pointless to apply absolutes to all aspects of the program as this will certainly lead to failure. Not all things/parameters are equal, when expressing a particular truth of a computer aided grouting program. We have the ability to read a deformation or a flow/pressure characteristic to three decimal places with commonly used instruments in physically small units of a couple of centimeters linear or cubic, and pressure to 0.10 of a bar. Yet we tend to ignore or misunderstand the realities that are the simple daily common struggle (a) to maintain drill hole alignment within 2%, (b) set at top of stage the actual packer's seal that is accurate to the same degree as our instruments say within +/- 2 cm (more likely within +/- 30 cm over a 3-meter stage i.e., 20% stage length variance), (c) repeat the procedure twice between water test and grouting and expect the humans did it in the same hole/elevation without question. Then we are puzzled why permeabilities do not reconcile between the two when we actually start grouting!

Even yet, with these realities we can muster the audacity to record our data sets on a closure plot to 3 decimal places and assume "mission accomplished" on that stage, then go on to repeat it say 2000 times on a small project and never look back. The reality with just these variables is that the permeability we assign to that stage pre- and post-grouting is only as accurate as the largest variable i.e., 20%.

Consequently, we tend to accept the lowest measurable denominator (as it must be the most accurate) and assume all is perfect across the entire data spectrum we measure and record.

Once we accept and understand these limitations, we can effectively develop project controls, procedures, and analyses to attain consistency. It then makes sense to embark on the narrowing of accuracy variables to tighter bracketing within the operation/process controls.

SPECIFIC PHYSICAL CONTROLS AND PROCEDURES REQUIRED OF A COMPUTER AIDED PROGRAM

- Individual hole collar Identification means, which must be repeatable and verifiable (graphic, electronic signature, and/or QA procedure).
- Monitoring While Drilling, in particular linear control recording.
- Drill hole alignment survey including the plotting of actual drilled alignment over design coordinates uploaded to model as seamlessly as possible.
- Optical borehole survey including fracture analysis uploaded to model.
- Core logs where available, linked to the corresponding treatment stages.
- All in-hole tooling linear measuring devices to have common accuracy parameters which include common repeatability characteristics (deviation table plotted and known for all tools) including alignment, optical, water testing systems, grouting systems, washing systems, and drilling if not undertaken, each one of these operations may have a large variable elevation skewing the data sets.
- Water testing must mirror the grout placing procedure and equipment to have reasonable correlation between the two mechanically if the data are to be reasonably correlated and the uploaded permeability value assigned in the model to the appropriate stage.
- Fluid delivery to the hole must be a constant designed loop (commonly referred to a return line, to plant). This provides continuous supply controlled from the batch plant, allowing for the detection of variations in density throughout batch life, along with safely controlling pressure variations (spikes) common in a one-way closed delivery system.
- Fluid delivery equipment and associated Instruments must have matched apertures for consistent data capture/velocities/laminar flows just to point out the major considerations (very common execution flaw) including ability to maintain 100% complete volume capacity of the entire system with open conditions at discharge. (Jim, this paragraph needs rewriting)

PRODUCTION CONTROLS

The production controls represent the evolution of applying project specific real-world data that are collected from the full-scale site testing program, including mix design verification, drilling demonstration, in-hole instrumentation surveys, water testing, and grout placing protocols. The test is the first time all instruments and measuring devices can be calibrated in real site conditions and verified as being fit for service.

It can be costly, frustrating, and a somewhat embarrassing process, as Murphy and his laws are in full force. What could one expect when you are essentially bringing online multiple systems simultaneously, where multiple participants are new and unseasoned, and there is integration of an automated, semi-automated, manual, digital, analogue, hydraulic, and electric machinery all at the same time.

Much can go wrong, but that is exactly why this operation needs to be executed, trouble shot, quality assessed, and verified. Participants who think this is a “couple-of-days” operation have no practical sense of the program, complexity, and the necessity to move it to being fully vetted. Failure to treat this pre-production testing phase with the importance and effort it deserves will most certainly lead to underperforming project success and balance sheets.

With the testing lessons learned, products and processes verified, and the assumptions confirmed in the work plan, procedures can be updated with real-world data such as:

- Working times of the various suite of grout mixes (running through the loop).
- Physical working restrictions spatially and time sensitive in accordance with field trial performance.
- Frequency of QA/QC cross checks, manual and automated.
- Productivity manpower and equipment resource loading decisions.

As the project advances through the Exploratory/Primary/Secondary grout hole sequences, these controls should be reviewed and updated accordingly.

INSTRUMENT CONFORMITY

To consolidate and manage the problems that conforming the instruments and tools necessitate, the following should be considered:

- What units of measurement should the project instruments operate under? In North America most of the projects were built using the imperial system and units. Converting as-built data for the modeling purposes to metric is cumbersome. With that drawback, accommodation can be made to maintain the model in its original imperial, but to integrate the grout curtain design as metric, and operate the program in metric units. The benefits to the overall ability to conform instruments and the corresponding analytical tools are profound and should be strongly considered. Instruments/measurement units using pounds, inches, feet, and gallons do not correlate smoothly in the computer aided grouting program and tend to complicate conforming processes.
- Common groups of instruments project wide should all be of same manufacturer and model, for example, flowmeters and pressure transducers.
- Not all instruments and tools will integrate with the computer aided system in real-time, nor communicate seamlessly. However, it is imperative that the instruments and tools being utilized that do not have this feature, do have operator protocols in place to ensure the transfer of data in a timely manner for manual uploading to the system data base and modeling features.
- All instruments should have operator access lock outs with security authority properly assigned. Humans get bored during a long shift, so what better fun than pushing buttons on a slave readout that seem harmless?
- Wireless data protocols should be appropriately partitioned across the instrument groupings to avoid data corruption and commercial industrial systems utilized, not residential WIFI routers.

EQUIPMENT CONFORMITY

With the introduction of advanced instruments and measuring tools across the entire spectrum of operations, and all the individual tasks, some being singular while others being multiples of the same, a computer aided system does not tolerate variations well.

Consistency once again comes into play as neither an operator at the control station nor the instrument measuring flow can differentiate between different pumps, hose runs, and tortuous flow paths created by poor manifold design and identify what's wrong, let alone the special individual or thing standing on a delivery hose. They simply read the velocity of the material passing by its sensor potentially affected by turbulence, air entrapment, pressure variations, and inconsistent densities. The list continues with the result that there are always the same corrupted data. This example is applicable to all processes throughout the project and may result in corrupted data rendering the grouting/drilling results questionable and unreliable.

To mitigate this, it is important that all equipment is matched with identical designs, components, performance, and controls. That matching should be maintained through all the maintenance cycles with original specification components. This includes hoses, couplings, valves, pumps, packers, rods, bits, riser pipes, casings, MPSP's carriers, collection systems, batch plants, and drill rigs.

Particular attention needs to be paid to the fluid delivery systems since the selected gauge diameter must be common through the entire loop. This may sound simple, but it has its challenges. Starting from the packer bore, it is all too common that the male connecting thread is 1-inch NPT and the assumption is the internal bore is 1-inch. However, more than likely it will be 3/4" – 5/8", creating a restrictive condition at the all-important points of discharge. As you track back through the system you might find diverter /control valves that are not diaphragm, but wedge or ball type which may not only be out of gauge but disrupt the all-important laminar flow conditions, especially required across instrument sensing faces. These variations could also be found in hose connections if swage tape is not used. Undoubtedly, when tracking back to the supply point, all the above-mentioned consumables have numerous fittings, manifolds, and hose management reels that all must meet gauge requirements. Each variation will affect the grout flow characteristics compounding the distortion that the instruments will read and record to the data base. Further, there will be areas to which the grout can adhere, so creating a constant build up and playing havoc with consistency in fluid delivery behavior.

Why is it so important to maintain equipment conformity? The simple answer is that the most important and sensitive time is the refusal period of the stage when the grout flow velocity is at its slowest, so taxing the limits of instrument accuracy and the point where we need the best data to ensure that our refusal goals are being met. Not meeting these goals because of false flow data will undoubtedly lead to unnecessary higher order holes being instructed to meet the project's residual permeability criterion.

RHEOLOGY: THE END PRODUCT

The grouting material we place in the project is the only physical deliverable that the Owner will receive. It also is probably the least expensive line item in the overall project. In contrast, it is also probably the least specifically engineered component of the project. In fact, it is likely the least standardized construction product sold in the world. It is the only component that will be required to maintain its integrity and perform for decades after the project completion. All those characteristics make it the last great mystery of grouting for seepage reduction. This is a broad and misunderstood area that we cannot properly address herein. However, we can identify the properties of the grout materials that their mix designs must have for the proper operation of the computer aided program:

- All grout mixes must be balanced and stable exhibiting less than 1% bleed. It is this characteristic of yielding 99% of in place set volume the system relies upon.
- The designs must provide progressive steps in viscosity across the full range, from starter through to closure mixes.
- Working times defined as no change in viscosity from time of mix to placement (minimum 3 hours). This is often confused with initial set which is incorrect and much later in the hydration process of the setting evolution.
- Ensure the repeatability of the batch characteristics (within 5%) over the course of 24 hours, and in all climatic conditions.
- Demonstrate a common appropriate cohesive property (anti wash out).
- Tolerate mechanically induced heating with no change in viscosity/working time.
- Exhibit the properties of a surfactant during the working cycle.
- Pressure filtration coefficient essential? (Jim)

HUMAN CONUNDRUMS AND THE WORKING ENVIRONMENT

Even with the Level 3 computer aided grouting systems, human resources within the operation are still required. Although we have consolidated the decision process to a minimum number of participants with the trained single point of control, the computer aided system brings and empowers those professionally accredited operators with advanced instrumentation and metrics for analysis and field direction. These operations rely on other humans out on site carrying out the many diverse activities required in the execution. Nowadays we have a much better control structure to minimize the variations in decision making on multiple levels that used to be carried out in old school grouting programs.

However, other human issues have emerged, the prime being the propensity for the operator technicians to isolate themselves from the field and not observe the boots on the ground operations. Another is the magic of the single shift or last shift before a weekend/holiday attaining closure on all working holes within a couple of hours before shut-down. Surely not.... These issues can be resolved through enlightened management of the work environment by exercising some of these concepts:

- Grouting programs should always operate on a continuous round-the-clock basis minimizing placing interruptions.
- Technical operators should not follow the same shift change regime as the crews but should stagger by at least an hour.
- All shift changes should have at least a half hour overlap.
- Technical operators should be required to rotate through the field at least an hour every shift to assist or observe logging/measuring or placing operations to stay grounded with reality.
- Everyone in the computer aided grouting program should have an understanding of everyone else's job/task, best accomplished by switching out positions for a half shift and rotating through all the positions. It is amazing the synergy developed when we understand and appreciate the other humans' jobs in the chain.
- Commonly most projects are out of town affairs for a lot of the staff. If you want to retain vigilante team members, regular quality family time is requisite. Consider 10am to 2pm day weeks (Jim?) with extended 4-5 days off which easily handles the travel providing full 3 days at home. This will streamline the personnel roster.

ALSO OF NOTE

From the onset, a good program strongly feature these elements (not in order of priority):

- A) Clearly defined closure criteria for acceptance.
- B) Clearly defined allocation of responsibility and liabilities.
- C) Articulated chain of command and reporting.
- D) Technical dispute resolution process.
- E) Integrated project cost/schedule controls updatable daily or at least weekly to the Owner and their authorized agents.
- F) Complete safety program with Activity Hazard Analyses tied to the operational procedure manual.
- G) Site communications system.
- H) Robust effective Q&A program tied into operating system protocols. Avoid multiple level Q&A. It should be a single transparent team shared reporting/reconciling process.

THOUGHTS FOR THE FUTURE

As our ability to apply new measuring technologies to the processes, the knowledge gained is growing exponentially and is in danger of creating a bottle neck to analysis and application in real-time. This not resolved, will have a negative effect on productivity and efficiency of our projects or will result in quality

data not being fully exploited or worse, even wasted. The utilization of AI in our systems may be the solution and we hope it is the next step in the evolution of Computer Aided Grouting Programs.

REFERENCE

Bruce, D.A. (2015). "The Evolution of Specialty Geotechnical Construction Techniques: The 'Great Leap' Theory," The Terzaghi Lecture, International Foundations Congress and Equipment Expo (IFCEE), March 17- 21, San Antonio, TX, 89 slides.