Computer Monitoring in the Grouting Industry

Dr. Donald A. Bruce[1]

[1] President, Geosystems, L.P., P.O. Box 237, Venetia, PA 15367, U.S.A., Phone: 724-942-0570, Fax: 724-942-1911, dabruce@geosystemsbruce.com

ABSTRACT: Computer monitoring and specialized equipment in the grouting industry has undergone multiple levels of technological advancement over the past two decades. The implementation of these technologies over recent years has greatly enhanced the industry's ability to more efficiently collect and evaluate pertinent data. This has subsequently resulted in more reliable and sound decision making, an increase in efficiency, and ultimately, cost savings to the owner. Dreese et al. (2003) discussed advances in the grouting industry and defined Levels 1 to 3 Technology for real time monitoring and data collection. Level 3 Technology (Advanced Integrated Analytical Systems) represents the current level of advancement in real-time monitoring of grouting in the industry today.

The multitude of technical challenges faced during any grouting project, includes assessing the geologic formation and identifying characteristics most likely to impact the grouting program. This paper documents the progression of the industry in using state of the art technologies to not only collect data and make real-time assessments of the formations response to grout injection, but also the use of high resolution images to evaluate discontinuities with the formation prior to injection, the implementation of digital photogrammetry for assessing outcrops and/or structures in three-dimension, assessment of Monitoring While Drilling (MWD) information and its integration, and real-time monitoring of instrumentation data for evaluating the formations immediate response to grout injection.

INTRODUCTION

The application of new and existing technologies within the grouting industry has increased substantially over the past 15 years (Bruce, 2012). These technologies have led to balanced stable grouts, improved equipment for efficient grout mixing and quality control, and specialized drilling equipment to produce accurate grout holes at greater depths (Weaver and Bruce, 2007). The incorporation of new technology by the grouting industry has helped to solve various technical challenges involving grout curtain depth and location, grout mix characteristics and quality, and project schedule constraints. Interpreting the subsurface geologic conditions and response during production, however, often presents the biggest challenge for any grouting project. Fortunately, there are also technologies available to the industry that allow the engineer/contractor and owner (the project team) to make informed decisions to better effectively treat the formation and accomplish project goals in accordance with contract documents. Some of the more important technologies are discussed in this paper, and are summarized in Table 1.

Table 1. Summary of State of the Art Technologies

Method	Description
Real-Time Computer Monitoring	Real-time data collection and display of grouting and water testing operations. Enables operators to make sound engineering decisions, effectively measure project performance, and generate project records
Monitoring While Drilling (MWD)	Automated real-time collection, storage, and display of drilling parameters. Frequently recorded parameters include instantaneous advance speed, tool pressure, torque, injection pressure of the drilling fluid, rotation speed, penetration rate, and thrust (bit load). Specific energy is commonly determined based on recorded parameters.
High Resolution Borehole Imaging	High resolution images of the borehole sidewalls and discontinuities. Capable of measuring borehole deviation and producing stereonets and joint poles based on fracture picking
Digital Photogrammetry	Allows geologic mapping of areas with difficult accessibility. Capable of producing 3-dimensional models including digital terrain models (DTM) that can be directly incorporated into the project and subsequent geotechnical evaluations.
Automated Instrumentation	Real-time collection of piezometric and other data for monitoring of the subsurface geologic formation or piezometric surface response to grouting operations.

In the author's experiences, the use of MWD, high resolution borehole images, and automated instrumentation, integrated with computer monitoring, greatly enhance the project team's ability to interpret the geologic conditions. Each of these technologies is of limited value when used alone. The integration of these systems allows the user and owner to quickly visualize and understand large quantities of data and information in real-time to effectively manage a grouting program.

REAL-TIME COMPUTER MONITORING

The integration of automated computer monitoring of grouting operations has greatly enhanced the industry's ability to make better immediate decisions related to the formation's response to grout injection. Wilson and Dreese (2002) and Dreese et al. (2003), discussed the three levels of technology for the monitoring of grouting operations that were available in the industry as of 2003:

- *Level 1: Dipstick and Gage Technology*
- *Level 2: Real-Time Data collection & Display Systems*
- *Level 3: Advanced Integrated Analytical Systems (AIA Systems)*

This definition applied to rock grouting projects for dams, although the basic framework is equally applicable to other types of grouting, in soils as well as rock.

Level 1 Technology represents the general state of practice prior to around 1997 and does not utilize electronic pressure gauges and flow meters that are widely available in the market. Nor does Level 1 Technology incorporate the speed and power of the computer that makes most of the calculations required for monitoring fast and accurate. For this reason, only Level 2 and 3 Technologies are recommended as only they are truly able to produce real-time displays of grouting operations. Level 3 is considered the superior level of technology in the grouting industry today. Unlike the other levels of technology, the engineer or geologist operating the system has the tools and capabilities to provide onsite technical support and real-time assessment of the grouting results in addition to monitoring the operations. As discussed in detail in the referenced papers, Level 3 Technology is comprised of 4 major components that when combined, produce a unique and powerful monitoring system: (1) a real-time data display of information retrieved from field operations; (2) a central database to store all collected and calculated information; (3) linked customized CADD functions to automatically display up to the minute information stored in the database on demand; and (4) customized queries to quickly and accurately mine data from the database for daily report generation and up-to-date analytical capabilities. The CADD display allows the project team to visually observe the results as they are obtained, and assess the project status in relation to adjacent hole series and lines. The real-time monitoring and analytical capabilities allows the operator to make sound engineering decisions efficiently. Figure 1 shows a 3-dimensional closure plot of a single grout line through fourth order hole series at varying depth intervals. Analytical capabilities such as this allow the operator to assess grouting performance, resulting in better informed decision making.

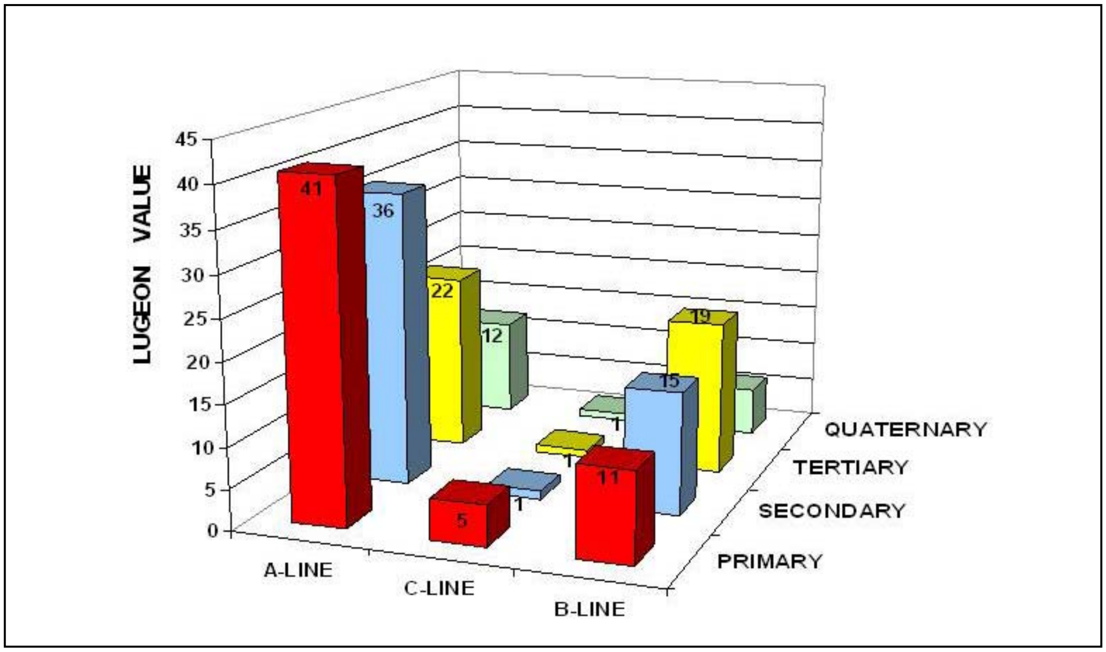


Figure 1. 3-Dimensional Closure Plot

The linked functionality of the grouting database to both CADD and customized queries is what makes true Level 3 Technology a powerful tool for fast and accurate analysis of grouting results. CADD plots and query analyses can be performed on demand and contain up-to-the-minute information. The rapid nature to which current grouting information can be presented and displayed for analysis by the project team is of substantial benefit over technologies that require a longer turn-around time of information in the form of drawings and queries, time on the orders of weeks, days or even hours. True Level 3 Technology gives the user the ability to present information on-demand in a matter of minutes. This is especially important for projects of a critical nature that require special attention to grouting progress and risk reduction. True Level 3 Technology is also important for projects with widely varied and unpredictable subsurface conditions, such as karst formations, that require careful, but relatively quick analysis and grouting method selection. The same level of care is warranted when conducting any grouting activity of high short-term risk potential, e.g., jet grouting under or adjacent to delicate, existing structures.

Technical challenges are faced frequently on any given grouting project, specifically due to the unknown nature of the subsurface. Technology in the grouting industry has fortunately advanced to new levels of sophistication to include additional methods of assessing the subsurface conditions to customize the program in order to effectively accommodate the geologic formations encountered. Two technologies that have proven to be valuable in analyzing subsurface conditions are Monitoring While Drilling (MWD) and High Resolution Borehole Imaging. While these technologies are not new, recent advances in the technology and their use in conjunction with the real-time monitoring and analytical tools has greatly enhanced and improved the ability to understand the subsurface conditions, resulting in a more efficient and productive program.

MONITORING WHILE DRILLING (MWD)

Interpreting the subsurface conditions and how it will impact the grouting program can often provide many challenges on a grouting project. Exploratory production holes only provide a small, unrefined picture of the subsurface conditions due to the limited amount of rock coring typically authorized, based on budget and schedule constraints. The limited number of exploratory core holes results in a relatively small number of intact subsurface specimens that can physically be evaluated. Although the majority of the holes drilled in a grouting program are considered production holes, the frequency and abundance of these production holes provides an opportunity to better define the subsurface conditions with the use of technologies that record drilling characteristics. Monitoring While Drilling (MWD) data allow each and every production hole to be treated as an 'exploration' hole (Bruce, 2003). That, combined with other advanced technologies such as borehole imaging, can provide the necessary subsurface information to optimize the grouting program. Each MWD production hole provides valuable information regarding the subsurface conditions. To compliment the subsurface investigation, Monitoring While Drilling (MWD) is recommended to collect and display real-time drilling parameters measured during advancement.

The subsurface investigation on a typical grouting project without MWD primarily consists of evaluating small cuttings and or water return produced from destructive drilling methods. In addition, some contracts specify that only one inspector (geologist or engineer) is required to inspect multiple drilling operations. Consequently, valuable information can be overlooked or missed. MWD provides continuous real-time information of the subsurface conditions for each and every drilling operation.

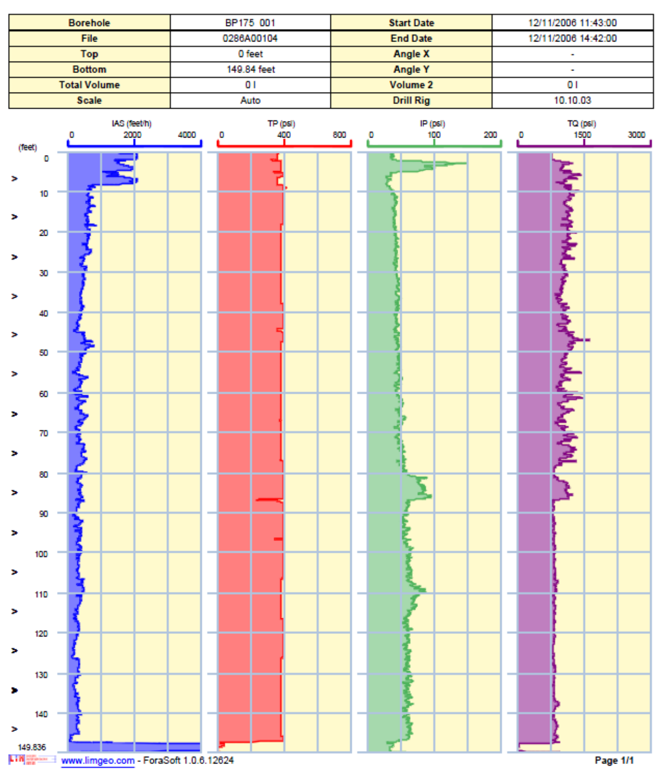


Figure 2. Typical MWD Log

Typical drilling parameters collected through MWD include instantaneous advance speed, tool pressure, torque, injection pressure of the drilling fluid, rotation speed, penetration rate, and thrust (hold back pressure). Figure 2 presents a typical MWD output log obtained from the field. There are other drilling parameters that exist and typically can be displayed. Specific energy is commonly determined based on recorded parameters. Plotted with depth, this parameter defines the energy required to advance through each lithological unit. The equation (Eq. 1) as defined by Weaver and Bruce (2007) is as follows:

$$e = \frac{F}{A} + \frac{2 \pi N T}{A R} \qquad \text{Eq. 1}$$

where:
e = specific energy (kJ/m^3)
F = thrust (kN)
A = cross sectional area of hole (m^2)
N = rotational speed (revolutions/second)
T = torque (kN-m)
R = penetration rate (m/sec)

As discussed by Weaver and Bruce (2007), MWD information can benefit both the owner and the contractor. The data allow the owner to monitor the effectiveness of the program, and provides a basis upon which he can make a responsive change to the grouting program based on the results. The data also allow the contractor to optimize construction parameters and schedule work items.

As discussed by Bruce and Dreese (2010), meaningful electronic MWD data may be unobtainable for some drilling technologies. Drilling through critical zones should be observed by a geologist or engineer in these cases.

HIGH RESOLUTION BOREHOLE IMAGING

Borehole imaging has become a valuable tool for investigating subsurface conditions and identifying geologic attributes relevant to any grouting or foundation remediation project. High resolution borehole images provide many levels of detail and information that can be utilized for improving or optimizing any grouting program. In addition, composite cut-offs (the combination of concrete cut-offs and grout curtains) (Bruce et al., 2010) is being recognized as a superior approach to constructing seepage barriers through and below earthen embankments. The borehole images can be used to identify potential slurry loss zones that require additional attention through grouting to avoid major cut-off wall construction problems or dam safety issues. Imaging equipment exists in the industry that can perform the following:

- High resolution borehole imaging that provides a continuous oriented 360° image

- Fracture picking analysis: Software designed for feature analysis that determines strike, dip, and aperture thickness of identified fractures
- Produce tadpole plots and stereoplots
- Perform borehole deviation

Identifying the strike and dip of geologic discontinuities within the actual bedrock being treated will result in optimized grout hole orientation, the significance of which can lead to increased frequency of fracture and joint intersection during grout injection. Additionally, the aperture thickness identified during the fracture picking sequence provides a better understanding of injected grout travel distances as well as substantiating injected grout volumes.

As noted above, obtaining specimens via core drilling is generally limited to a few holes on production grouting projects due to budget and scheduling. Consequently, identifying the geologic attributes most likely to impact the grouting program is left to literature reviews, mapping of nearby outcrops, assessing the rock cuttings flushed during destructive rock drilling operations, and if used, MWD. The challenges inherent with interpreting the subsurface conditions are obviously intensified when limited samples can physically be observed. In addition, images of the in-situ condition provide a different interpretation than the core samples, for example solutioned zones with pipes often look like a "broken rock" zone in a core box.

Borehole images provide an accurate visual representation of the subsurface conditions that can be used to modify and improve the technical approach to the grouting program. For instance, a program that specifies high mobility grout (HMG) for rock treatment may require a sanded grout (medium mobility grout or MMG) or low mobility grout (LMG) based on the opening sizes observed in the images. If larger size cavities are observed in the images prior to treatment, such as the cavity shown in Figure 3, MMG or LMG may be identified as the appropriate initial grout type for a particular stage, prior to injecting HMG for final permeability reduction. Identifying these zones in advance can increase the contractor's efficiency with

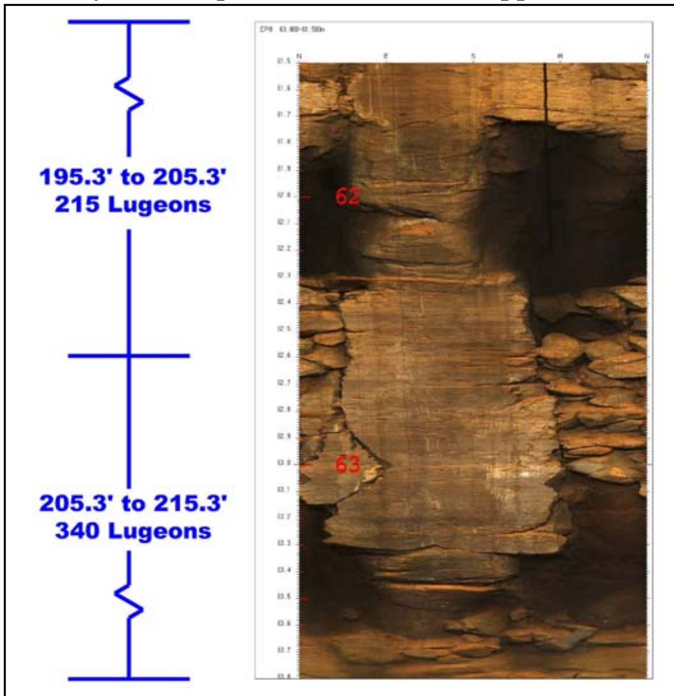


Figure 3. Unwrapped Borehole Image (depth measured in meters)

regard to scheduling daily production work, and can reduce the amount of unnecessary grouting time and material by allowing a more appropriate grout mix to be used from the start. As discussed by Bruce and Dreese (2010), switching between HMG to MMG to LMG on a given hole is often specified in the contract, but is not easily achievable in the field as different equipment and delivery systems are required to inject MMG and LMG, as compared to HMG.

Borehole images can diagnose issues encountered during the production rock drilling program such as caving, 'rapid advancement' zones, rod drops, or water loss zones. While borehole imaging should not replace the need for core drilling, high resolution images can provide information that core specimens cannot. For instance, low recovery zones during core drilling can be attributed to a cavity, soil infilling or clay seam that washed out in the return water, or mechanical breaks due to the coring. The exact cause of the low recovery and location where the loss occurred can be difficult to ascertain. The borehole image allows the user to view these zones in situ.

Zones of high permeability are often difficult to explain without visual interpretation. High resolution images provide an understanding and meaning of pressure tests and magnitude of results as shown below in Figure 4.

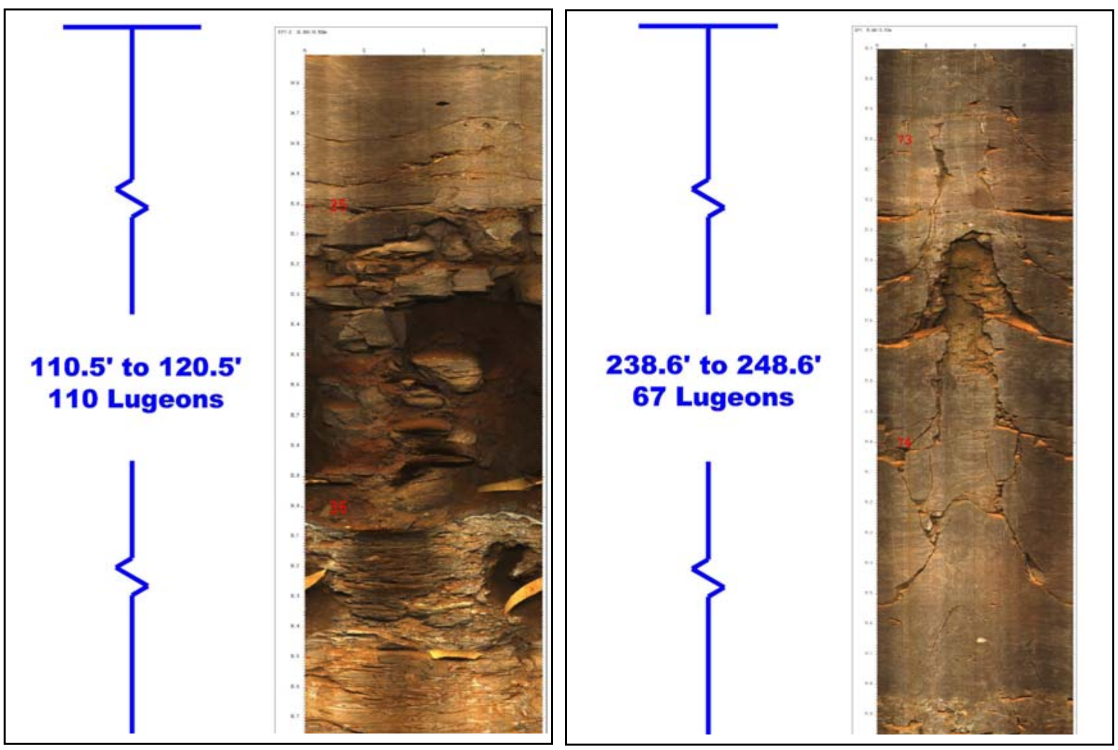
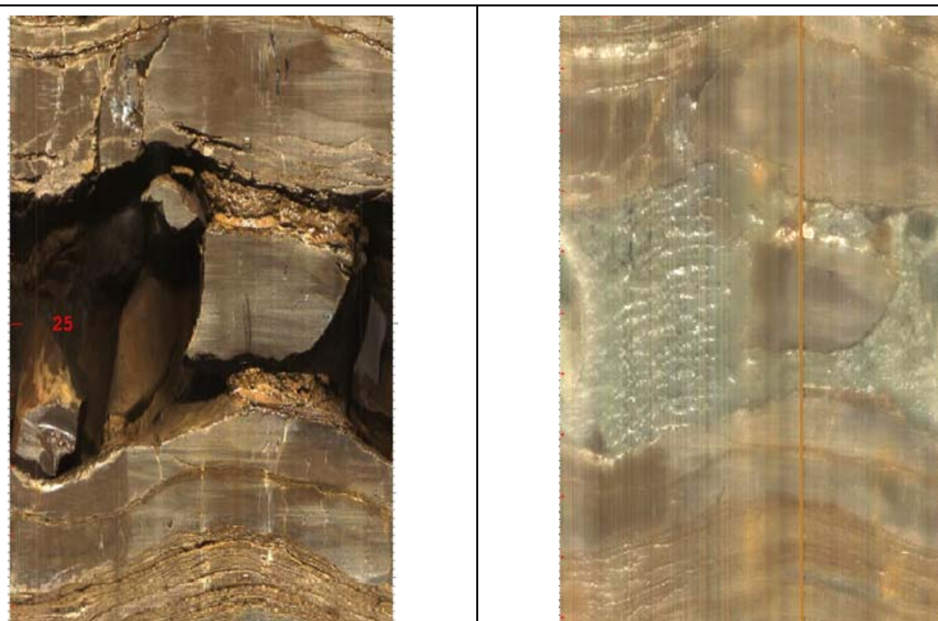


Figure 4. Correlation Between Digital Borehole Image and Lugeon Value

Borehole images can also be used to determine the effectiveness of the grouting program between each successive hole series (Primary to Secondary to Tertiary, etc) as well as between each grout stage along a hole during a downstage grouting program. Borehole images can identify grouted features and zones and can also identify un-grouted or incomplete grouted zones. Such information is valuable for evaluating closure plots and determining if or where additional treatment is required. Figure 5 below provides an example of a feature before and after treatment.



Pre-Treatment	**Post-Treatment**

Figure 5. Before and After Treatment

Grouting projects often include a verification program to measure post-treatment permeability, and to determine if project goals were achieved. Typically, the verification holes are core drilled to visually assess the conditions of the rock specimens, but with the advancement in high resolution imaging technology, a large percentage of verification boreholes may be destructively drilled and imaged.

Images of the pre-treated boreholes should also be utilized as part of the daily computer monitoring operations throughout the grouting program. Inflatable packers are commonly lost or damaged due to inflation in cavities or highly fractured and broken zones that are often overlooked during production rock drilling. When available, borehole images should be reviewed for such issues. Over the duration of a large project, the potential cost savings could be quite high. Imaging systems are frequently overlooked due to the turbidity of the water generally encountered during the high production type grouting programs. High resolution acoustic televiewers are recommended as a viable alternative to optical televiewers, and generally can provide similar useful information produced by the optical televiewer.

In addition, such televiewers are often used to investigate the actual in-situ conditions of jet grouted or deep mixed columns or panels when core recoveries have been poor, but there is a likelihood that the coring process itself has caused the poor coring result.

DIGITAL PHOTOGRAMMETRY

Geologic mapping to determine orientation of bedding planes, structural features, and discontinuities in general is prudent to fully understand the bedrock characteristics and permeability relationships. This information serves to guide, plan and implement successful grouting programs. Such data provide the necessary information for determining hole orientation and spacing, and even the number of lines required to adequately treat the formation. Historically, such data have been obtained through classical geologic mapping using line surveys and a Brunton compass. Recently, very precise and accurate digital photogrammetric methods have become available to supplement historical methods. Digital photogrammetry allows for safe data collection of digital images taken of rock exposures with exceptional optical location and planimetric/depth accuracy. These methods offer improved data collection for relatively inaccessible rock outcrops such as steep dam abutments and highway rock exposures which are unsafe to access.

Digital photogrammetry allows geologic mapping of areas with difficult accessibility, and is capable of producing 3-dimensional models including digital terrain models (DTM) that can be directly incorporated into the project and subsequent geotechnical evaluations. Additionally, the number of discontinuity data sets collected through digital photogrammetry can be orders of magnitude higher than the number collected manually given the ability to collect images efficiently of the entire rock exposure without climbing or rappelling.

AUTOMATED INSTRUMENTATION

Monitoring the response of a structure, its foundation and any adjacent structures concurrent with grouting operations is an essential element of any grouting project. Instrumentation provides a quantitative measure of the formation's condition and the structure's performance. Automating the instrumentation provides real-time monitoring of the 'vital signs', and operating in conjunction with real-time computer monitoring, will provide the critical data necessary to make informed and educated decisions in a timely manner.

The subsurface foundation being treated during a grouting program is typically monitored with vibrating wire piezometers for pressure and weir monitors for seepage. Automated instruments can be installed in existing manual monitoring stations, such as existing casagrande piezometers, monitoring wells, and weir structures, or they can be installed at new defined locations. Important structures and foundations that may be adversely affected by the grouting operations can be monitored with crack gauges, strain gauges, tiltmeters, settlement sensors, inclinometers, load cells and earth pressure cells.

Automation of the various instruments installed provides a real-time response of the subsurface foundation and adjacent structures to the drilling and grouting operations performed throughout the duration of the grouting program (Figure 6). The information provided can be used to determine acceptable operating parameters during grouting operations such as appropriate grouting pressures to use due to existing pore pressures. The information can also be used to identify critical areas requiring special or immediate attention such as localized piezometric highs or lows, or zones of significant seepage, settlement or movement. During production, automated instrumentation data can be used by the project team to schedule work items, to analyze the performance of the grouting program, to minimize adverse effects of the grouting operations to the structure, foundation, and adjacent structures, and to help modify grouting methods and procedures. After the grouting program is complete, the automated instruments can also be used to analyze the post-construction effectiveness of the grouting program by recording any changes in piezometric levels, measured seepage, settlement, or movement of adjacent structures. In order to better determine the effectiveness of grouting program during production and post-construction, it is recommended that the automated instrumentation system be installed prior to the start of drilling and grouting operations to establish baseline conditions.

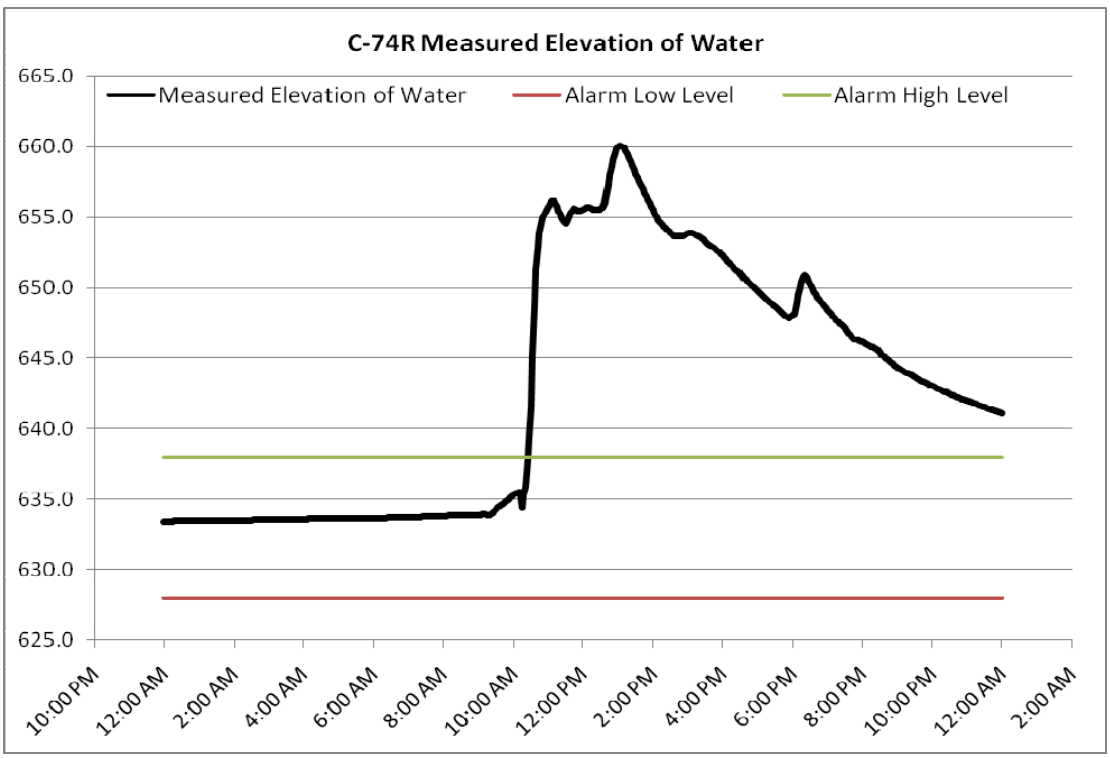


Figure 6. Plot of Piezometer Response to Grouting Operations.

Communication between project team members is essential when viewing and analyzing instrumentation data, and when modifying project procedures based on observed responses of the subsurface foundation and adjacent structures. Open communication is essential to determine and disseminate the acceptable operating ranges and threshold values of each instrument. Standard Operating Procedures should be developed to address the monitoring and maintenance of the instruments as well as to provide an action plan for the proper notification of critical personnel in the event of an instrument exceeding its threshold value. Threshold values may need to be adjusted as grouting operations progress, program modifications are made, and subsurface conditions change.

CASE HISTORIES

Case histories that document the successful use of the state of the art technology discussed in this paper include three U.S. Army Corps of Engineers DSAC-1 Dams. DSAC, or Dam Safety Action Classification is a USACE initiated risk-informed approach and ranges from DSAC-1 which is the highest priority and highest risk to DSAC-5. The three DSAC-1 dams discussed herein are Clearwater Lake Dam, Missouri; Wolf Creek Dam, Kentucky; and Center Hill Dam, Tennessee.

Clearwater Lake Dam, Missouri

Clearwater Lake Dam, located in Piedmont, Missouri is a U.S. Army Corps of Engineers (USACE) owned dam. In 2003, a sinkhole was discovered on the upstream slope of the 4,200-foot-long, 150-foot-high earthen embankment dam. As an interim risk-reduction measure (IRRM), the USACE decided to install a grout curtain approximately 200 feet in length immediately downstream of the sinkhole to investigate and determine the cause and extent of the sinkhole. During this initial exploration, a large solution feature, approximately 25 feet wide by 170 feet tall was discovered in the foundation bedrock. Low mobility grout (LMG) was successfully utilized as the appropriate grout type to fill the feature, but it was determined that additional treatment would be necessary in the vicinity of the sinkhole. To accommodate this additional work, and to explore the foundation bedrock underlying the remaining embankment to identify potential locations of other solution features, two other projects were awarded; Phase 1 and Phase 1b Exploratory Drilling and Grouting. More extensive efforts were performed along the entire length of the embankment during the Phase 1 and 1b contracts. The two projects (essentially combined into one) consisted of a 2-line grout curtain with holes drilled on 10-foot centers from left to right abutment, with the intention of characterizing and pre-treating the foundation material in preparation for a proposed cutoff wall.

Level 3 Technology was utilized for real-time monitoring, display, and collection of all data. To complement this technology, high resolution borehole images were obtained to map bedrock discontinuities and other geologic features, identify opening sizes for determining most appropriate grout type, verifying complete treatment of openings, and for performing borehole deviation. MWD was also utilized at

Clearwater on various drilling rigs for obtaining real-time drilling characteristics of the underlying material for correlation of drilling characteristics with borehole images, pressure testing results, and injected grout volumes. The treatment of the solution feature and pregrouting of the karst bedrock has permitted the construction of the cutoff wall without a major slurry loss incident.

Wolf Creek Dam, Kentucky

Wolf Creek Dam is located near Jamestown, Kentucky within the USACE Nashville District. From 2007-2008, a grouting program was implemented both for interim risk reductions measures, and as an initial phase for the construction of a composite cutoff consisting of a grout curtain and a concrete barrier wall along the length of the embankment section of the dam. Additional grouting at the right abutment, the rock foundation below the concrete section of the dam, and along a downstream section adjacent to the concrete/embankment interface has also been performed, or is currently under construction.

In addition to the use of Level 3 Technology for monitoring grouting operations, other technologies utilized at the site included weekly upload of grouting as-built drawings to a website, and high resolution borehole imaging for the Phase I program. The Level 3 Technology of the grouting operations allowed for the rapid dissemination of grouting results to critical personnel at various levels of project oversight within the USACE and an independent Board of Consultants tasked with making technical decisions concerning grouting methods and determining whether additional holes were required and their appropriate locations. Borehole imaging was utilized to identify the condition of the rock foundation in critical areas, and to identify zones that required additional grouting. In addition to the image data, the camera probe also recorded borehole deviation data that was used as a quality control measure to ensure the consistent alignment of the grout curtain along the entire grout curtain length to a maximum depth of 345 feet from the top of work platform. The incorporation of these technologies resulted in the fast and accurate construction of 3,750 feet of a two-line curtain, which was completed within an accelerated project schedule and allowed for the timely start of the second phase of work, the construction of the barrier wall.

Automated instrumentation was added to key critical areas of the dam after Phase I for analysis of the performance of the subsequent work phases. The automated system was installed by the USACE to supplement the manual instrumentation system of piezometers, survey points, inclinometers, and extensometers that already existed at the site. The automated instruments were designed to record and display the response of the subsurface foundation and embankment to future grouting operations as well as the construction of the barrier wall. However, the real-time monitoring of the grouting operations and the automated instrumentation were not integrated. Consequently, operators were not always aware of issues for hours or days after completion of a stage, and forensic investigation to identify all activities at that specific time were not always possible.

Center Hill Dam, Tennessee

Center Hill Dam is also within the Nashville District and is located near Lancaster, Tennessee. From 2008-2010, Phase I of the remediation at Center Hill Dam was performed as both interim risk reduction measures and as part of an overall grout curtain and composite barrier wall cut-off, built to reduce overall seepage and instability at the site. Phase I work consisted of the grouting of the main dam embankment, left abutment groin, and left rim sections of the dam. Phase II of the project involves the construction of the barrier wall portion of the composite wall cut-off along the embankment section of the dam. Work for Phase II is scheduled to begin in late 2011.

State-of-the-art technologies utilized during Phase I operations included Level 3 computer monitoring, weekly update of grouting as-built drawings to a website for technical review, geophysical analysis of subsurface conditions using electrical resistivity, high resolution borehole imaging, down the hole camera technology for inspection of a large open-air cavity encountered during drilling operations in the left rim, and a real-time automated instrumentation system consisting of vibrating wire piezometers and weir monitors. Real-time monitoring results and on-demand grouting as-builts were used by USACE personnel and an independent Board of Consultants to make rapid, but informed technical decisions and program modifications, including the addition and deletion of holes based on grouting results.

The incorporation of the automated instrumentation system by the contractor that included alarm levels allowed for the real-time display and analysis of the piezometric response of the subsurface foundation to the drilling and grouting operations. The ability of the automated system to both record and display in real-time the changes in foundation pore pressures during operations allowed for the comfortable use of increased grouting pressures in specified zones to more effectively penetrate difficult rock formations with grout, and was integrated with the computer monitoring as a result of experiences at Wolf Creek Dam. Subsequently, automated instrumentation is required in the Center Hill Phase 2 Cut-off Wall contract.

CONCLUSIONS

The technological leaps in grouting in the few years prior to 2003 caused a renaissance in grouting in the United States, a rethinking of the usefulness and viability of grouting. The incorporation of new technologies over the last 10 years has redefined the role of grouting from use as a secondary measure, to that of a reliable and durable solution to a wide variety of projects, including interim risk reduction measures, permanent foundation remediation, and composite barrier construction.

The incorporation of computer monitoring, high resolution borehole imaging, MWD, and automated instrumentation provide many advantages when properly integrated. First is the ability to present relevant up to the minute information.

Second is the ability to "see" the actual subsurface conditions that exist at the site. Third is the ability to quickly and accurately reduce, filter out, and display pertinent information and grouting results. Finally, is the ability to view in real-time the response of the subsurface foundation and critical structures to current drilling and grouting operations. All of these program advantages result in the following project benefits:

- Fast and reliable information
- Rapid response to encountered foundation conditions and grouting results
- Informed decision making by project team
- Reduction in project schedule
- Reduction in project cost
- Increase in confidence of grouting results
- Greater success in meeting or exceeding project goals

The benefits that these integrated technologies provide also depends largely on the personnel responsible for its daily operation. Critical decisions made by the operators that may impact project performance and/or overall condition of the structure, require the assigned personnel to have experience with each of the tools as well as experience in dam safety issues and considerations.

The incorporation of these technologies into the field of grouting has allowed the solution of grouting to be considered as not only a viable alternative, but as a leading recommended, and even superior solution for a vast number of foundation stability and seepage remediation projects for critical infrastructure.

ACKNOWLEDGEMENT

The author is indebted to colleagues at Gannett Fleming, Inc. for permission to reproduce much information from one of their recent publications (in print). Thanks Adam, Daniel, Christopher and Trent.

REFERENCES

Bruce, D.A. (2003). "The Basics of Drilling for Specialty Geotechnical Construction Processes", Grouting and Ground Treatment: *Proceedings of the Third International Conference*. Ed. Lawrence F. Johnson et al. New York: American Society of Civil Engineers.

Bruce, D.A., and T.L. Dreese. (2010). "Specifications for Rock Mass Grouting", *Proceedings of the Association of State Dam Safety Officials Conference on Dam Safety*. September.

Bruce, D.A., T.L. Dreese and D.M. Heenan. (2010). "Design, Construction, and Performance of Seepage Barriers for Dams on Carbonate Foundations," Environmental and Engineering Geoscience, V. 16, No. 3, August, pp. 183-193.

Bruce, D.A. (2012). "Specialty Construction Techniques for Dam and Levee Remediation: The U.S. Technology Review," Spon Press an imprint of Taylor and Francis.

Dreese, T.L., D.B. Wilson, D.M. Heenan and J. Cockburn. (2003). "State of the Art in Computer Monitoring and Analysis of Grouting." In *Grouting and Ground Treatment*, Edited by L. F. Johnsen, D.A. Bruce, and M.J. Byle. ASCE, Reston, VA., Geotechnical Special Publication No. 120, 1440-1453.

Weaver, K.D and D.A. Bruce. (2007). *Dam Foundation Grouting*. Revised and Expanded Edition. American Society of Civil Engineers, Reston, VA.

Wilson, D.B., and T.L. Dreese. (2002). "Advances in Computer Monitoring and Analysis for Grouting of Dams." U.S. Society on Dams Annual Conference Proceedings, San Diego, Calif. USSD, Denver, CO.