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.

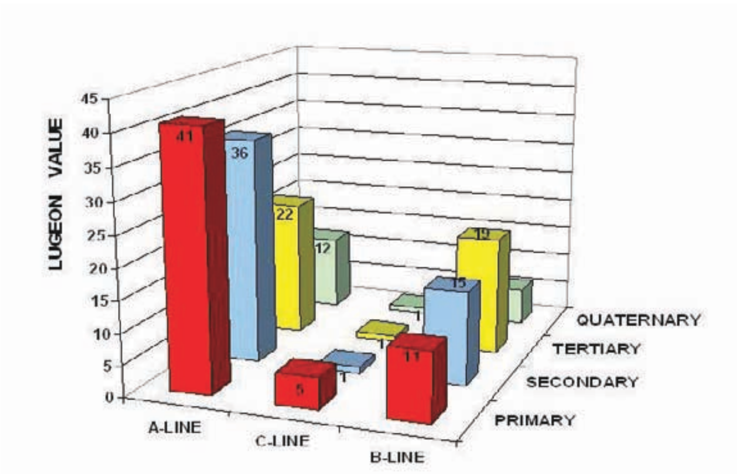


FIG. 1. 3-Dimensional Closure Plot.

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.

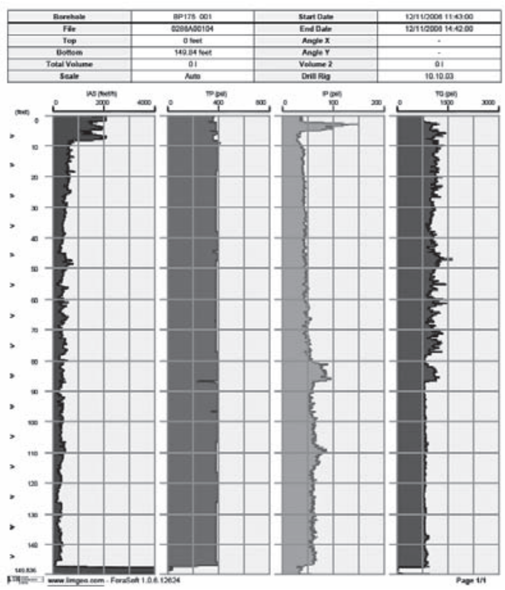


FIG. 2. Typical MWD Log.

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

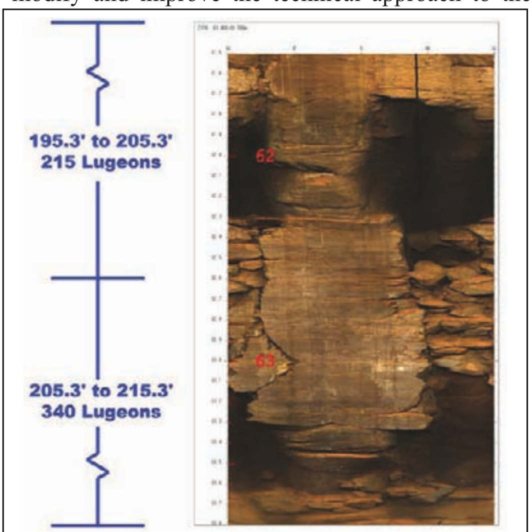


FIG. 3. Unwrapped Borehole Image (depth measured in meters).

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.

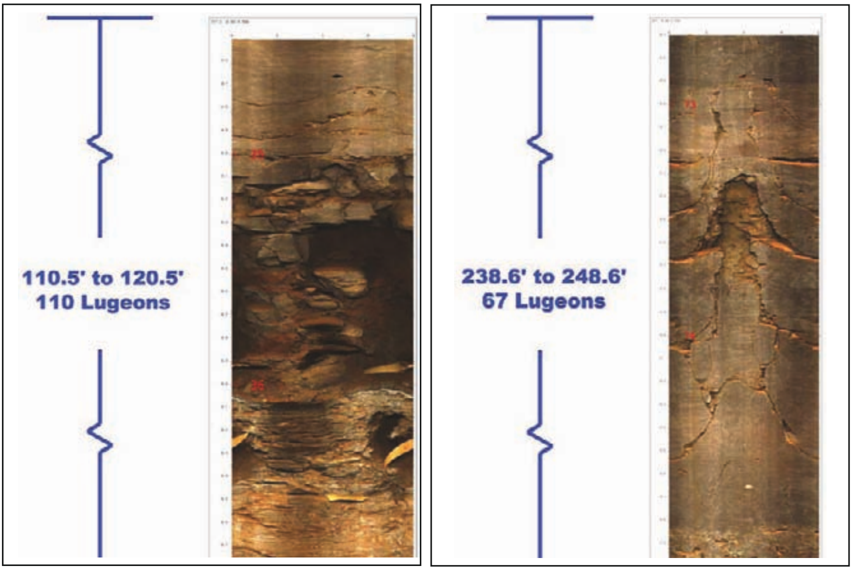
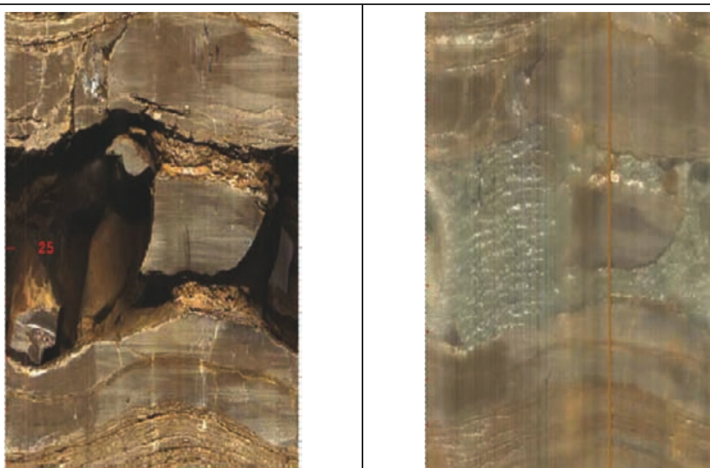


FIG. 4. Correlation Between Digital Borehole Image and Lugeon Value.

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**

FIG. 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.

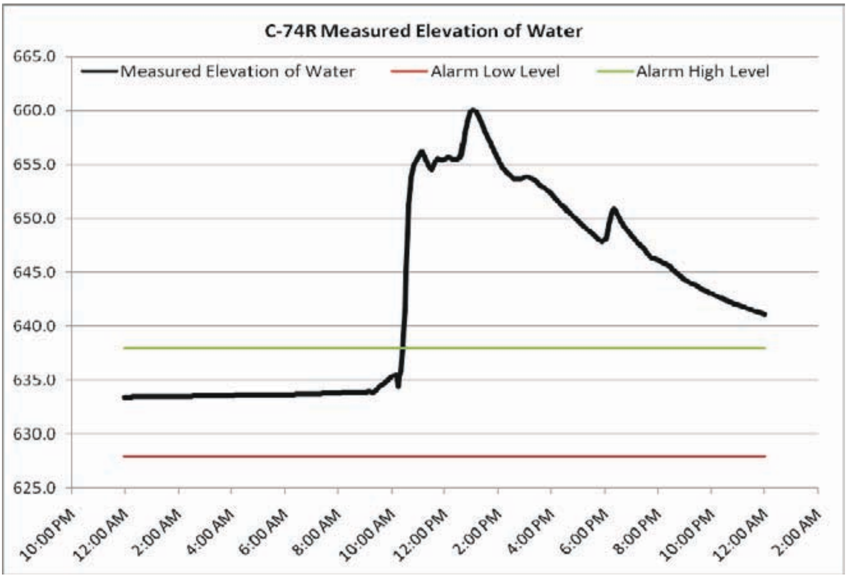


FIG. 6. Plot of Piezometer Response to Grouting Operations.

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