STATE OF THE ART IN COMPUTER MONITORING AND ANALYSIS OF GROUTING

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ABSTRACT

Computer monitoring and analysis of grouting has come of age as a reliable and effective tool for better, faster, and less expensive grouting. This paper traces the development of computer monitoring and control systems, summarizes the benefits that can be realized from use of the systems, and presents the latest developments in specialized technology developed specifically for permeation grouting.

Several case history applications of successful use of computer monitoring and analysis are presented. The Penn Forest Project, a new dam construction project in Pennsylvania, was a landmark project in the utilization of computer monitoring technology and is the only large project where full scale, side by side comparison of conventional monitoring techniques and computer monitoring systems is available This project provided clear, quantitative illustration of the many technical and cost benefits that result from computer monitoring. The Patoka Lake Seepage Remediation Project, located in southwestern Indiana, was another vital project in that it was the first grouting project requiring the use of computer monitoring undertaken by the U.S. Army Corps of Engineers (USACE), and in that it has helped set the standards for contracting methods and field application. The Hunting Run Dam

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Project, recently completed for Spotsylvania County, VA, utilized new, state-of-the-art technology that advances computer monitoring and analysis of grouting to an unprecedented level of automation. This new system completely automates operations and allows real-time, comprehensive onsite display and simultaneous real-time onsite or remote analyses of grouting results.

History of Computer Monitoring

Recognition of the potential benefits and experimentation with "automated" monitoring or data recording systems for grouting started in the 1960's (Weaver 1991). Use of electronic measurement devices mated with computers was recognized as having significant potential almost as soon as desktop computers came into being in the early 1980's (Jeffries et. al. 1982) (Mueller et.al. 1982). The U.S. Bureau of Reclamation (USBR) was the first federal agency in the U.S. to experiment with the use of computers for monitoring of grouting. Utilized at Ridgeway Dam in 1982, the problems with the first system were numerous. However, this first experiment resulted in the USBR developing a comprehensive hardware and software system that would provide, generate, and record all the information that was needed for monitoring, control, and analysis of grouting (Demming et.al. 1985). The USBR implemented its use at Stillwater Dam in 1985. Although relatively little is written about the experience on Stillwater Dam, significant problems were experienced with consistently maintaining signals to the equipment. During the same time period, the USACE began using portable site recorders to obtain real-time grouting data, but severe field reliability problems were experienced (Houlsby 1990).

Beginning in the mid-1990's, there have been dramatic improvements in both the number and type of flow and pressure measuring devices, computer hardware, data acquisition software, and data management and display software. It has been proven that the use of computer monitoring systems clearly allows permeation grouting to be more technically effective, performed at a lower cost, and in less time. The systems are now sufficiently robust and user friendly to make it wise to consider their use on all future projects.

The Science of Grouting

Grouting is an especially unique type of construction. Grouting involves managing and performing dozens of simultaneous operations, each of which requires an extraordinary degree of care and any of which, if not performed properly, will result in ineffective grouting and loss of value in the project. Performing as much as 95% of the work properly can still result in nearly complete failure of a grouting program and almost total loss in program value. Studies of imperfect seepage barriers show that if only 5% of an otherwise impervious barrier is defective, the barrier efficiency in terms of seepage reduction can be as low as 10%.

Grouting is further complicated by the fact that all operations are performed underground. The fact that we cannot see the formation to be grouted or see grout permeating the voids or fractures has led to permeation grouting commonly being described as an "art". However, if proper investigation, design, contracting mechanisms, materials, and field techniques are employed combined with real-time data collection and analyses by a competent grouting engineer or geologist, engineered grout curtains can be constructed with dependable, predictable, performance and with virtually the same confidence in quality as visible "above ground" construction. Further, these measures will assure that grouting will be performed faster, better, and at lower overall cost. Grouting performed at this level is a science and is no longer merely an art.

Advantages of Computer Monitoring

The specific quality, cost, and time benefits that can be attributed to computer monitoring and analysis technology are summarized below:

1. Real time data is obtained at much smaller time intervals (5-15 sec. frequency vs. 5-15 min. frequency).
2. Eliminates missing critical events such as pressure spikes.
3. Data obtained is more accurate than data from "conventional" methods.
4. Higher grouting pressures can be used with confidence.
5. Formation response to procedure changes (mix or pressure) are known instantly.
6. Facilitates multiple hole grouting.
7. Damage or no damage to a formation due to over-pressuring can be easily detected or determined.
8. Significant acceleration of pressure testing and grouting operations.
9. More consistent grouting procedures due to central control location.
10. Reduction in inspection manpower requirements.
11. Provides detailed, permanent graphic records showing the entire time history for each operation on each stage.
12. Permits reallocation of resources to analysis of program results rather than on process management and data collection.

Many of these advantages can only be realized if plots of the apparent lugeon value (Naudts 1995) are automatically displayed in real-time by the monitoring system. The apparent Lugeon value is simply a way of expressing the permeability of the formation using grout as the permeant, and is determined using the standard equation for determining the Lugeon value with water times a correction factor. This correction factor is equal to the ratio of the apparent viscosity (marsh funnel flow time) of grout to the apparent viscosity of water. The real time graphical display of the apparent Lugeon value is extremely useful to the operator. Although the actual apparent lugeon value may not be a true measure of the formation permeability due to the assumption made in determing the correction factor, it is a measure of the relative permeability change during the grout application and does relate the injection pressure to the magnitude of the take. The display of this value allows the operator to instantly interpret the response of the formation to any changes in the grouting program such as changes to the injection pressure or grout mix. A plot of flow rate divided by effective injection pressure can be substituted for the apparent Lugeon value. Constant monitoring of the formation response to increases in pressure allows the practitioner to confidently move away from the conservative rules of thumb for grouting pressures that have been traditionally utilized. The rate of grout take and the radius of grout penetration are directly proportional to the injection pressure, and therefore, one should utilize the highest safe grouting pressure on every stage of every hole.

Dilation of rock fractures is easily ascertained from review of a plot of the apparent lugeon value versus time. As an example, Figure 1 is a grout record from Penn Forest Dam for a grouting stage from 0 to 20 feet. As indicated, a nominal grouting pressure of 20 psi was being used for this surface stage, which exceeds the U.S. rule of thumb of 1 psi per foot. The record also indicates a significant pressure spike at a time of 25 minutes. As expected the flow rate spiked at this same time and without a plot of the apparent lugeon value the impacts would have been unknown. The plot of apparent lugeon value shows a very slight increase in the formation permeability at this time (fracture dilation), but upon reduction of the pressure to previous levels the formation permeability returned to previous levels, indicating no permanent damage to the foundation. Continuous review during each grouting stage permits confirmation that the pressures being used are in fact safe.

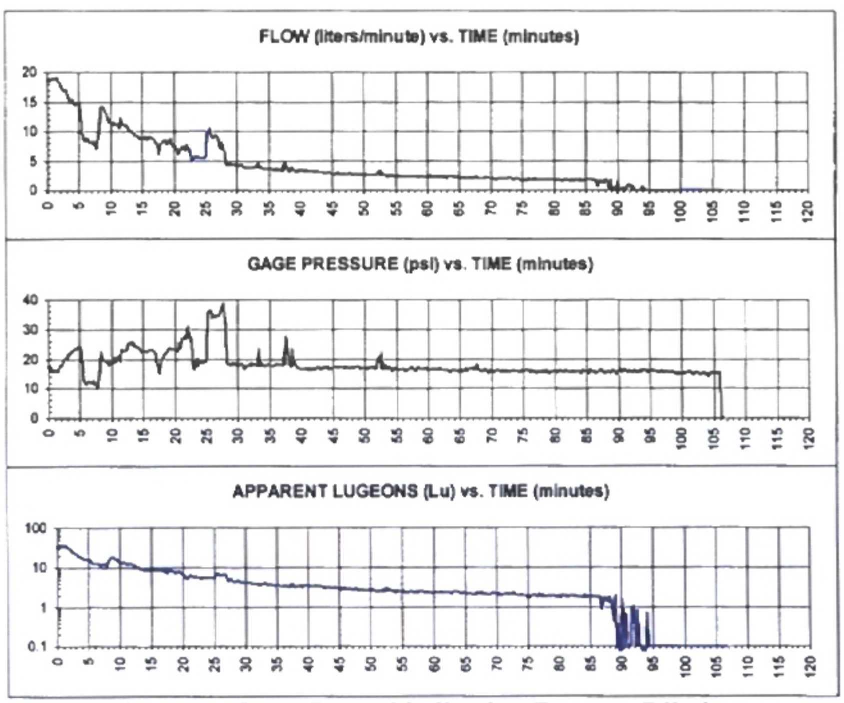

Figure 1: Grout Record indicating Fracture Dilation

Available Levels of Monitoring Technologies

Three levels of permeation grouting monitoring technologies are currently in use (Wilson and Dreese, 2002). A brief description of each level of technology and commentary on that levels applicability and considerations for use is provided below.

<u>Level 1 Technology: Dipstick & Gage</u> – Utilization of this technology represents the general state of practice prior to 1997. Most agency guide specifications that are publicly available are still based on this technology and many U.S. Contractors are still set up to operate exclusively with this type of monitoring. This method of monitoring is based on using a dipstick for measuring grout take, a pressure gage for observing water or grout injection pressures, and a nutating disk water meter for measuring water take. Wilson and Dreese (1998) provided a summary of the accuracy of various measuring devices for measuring flow rates and pressures. Due to the inherent inaccuracies of the measuring devices used with this technology, readings are commonly taken on 5 to 15 minute intervals to allow sufficient time for a reading change to be observed. If best practice is being followed, the engineer in charge of grouting of the stage will do limited manual calculations as the data is being obtained and make a plot of average grout take per time interval for the stage as it is being grouted. After completion of a stage, the data is later manually entered onto a large master wall chart that usually shows the hole location, and the grout take in bags of cement. Water pressure test results might or might not be shown on the chart.

This method of monitoring and control is rapidly disappearing and it is the authors' opinion that this level of technology should no longer be considered for grouting projects of any significant size or in a critical application. The minimum level of technology that is recommended for consideration based on the current state of technology and practice is the use of Level 2 Technology as described below.

<u>Level 2 Technology: Real-Time Data Collection, Display, and Storage</u> – Any system that uses electronic devices for measurement of flow and pressure and sends those signals to one or more other devices where the measurements are automatically displayed and recorded falls within this level of technology. At the low end of this technology, current readings of flow and pressure are displayed without any corrections for elevation, head loss, mix properties, or other factors. An XY-Recorder records the data or a data file is created by a software program for storing the data throughout the operation. This type of software functions as an automated electronic record book. At the high end of the technology, the collected data and correction factors are used in automatic calculations to produce and display corrected or calculated parameters of interest for the stage being grouted in real-time. A widely recognized software system in use at the high end of this level of technology is CAGES, which stands for Computer Aided Grout Evaluation System. CAGES

software is a proprietary product developed and owned by ECO Grouting Specialists, Ltd. Two other systems that clearly operate at Level 2 Technology are a system by PARTNERmb of the Czech Republic and one from Soletanche of France. Information on these systems can be found on the internet at each companies web site. The authors are not familiar with these systems and the operation level may approach Level 3 Technology.

Level 2 Technology is a huge improvement, but it falls well short of the full potential envisioned for an automated grouting system. Data is more readily available for analysis than at Level 1, and onsite PC's enable the grouting engineer or geologist to perform better, but still very limited, analyses of the overall program as it progresses. However, onsite personnel are still faced with a mountain of numbers in which they are looking for patterns and anomolies that might or might not exist. The single paper wall chart used to plot the water testing and grouting results contains so much information that it is nearly impossible to comprehend in a timely manner, if at all. Level 2 Technology is considered applicable for any grouting project and should be the minimum level of technology considered for projects with a construction value exceeding $250,000 (in consideration of system acquisition and setup costs) or any grouting project in a critical application.

Level 3 Technology: Advanced Integrated Analytical (AIA) Systems – AIA systems are fundamentally different in nature and represent an enormous leap forward in comparison to Level 2 Technology. An AIA system provides integration of data collection, real-time data display, database functions, real time analytical and query capabilities, and CAD. The first AIA System for grouting, the IntelliGrout™ System (U.S. Patent Pending), was introduced in 2001. IntelliGrout was jointly developed and is owned by a Contractor & Engineer Team, Advanced Construction Techniques Ltd. and Gannett Fleming, Inc. Development of IntelliGrout was completed in 2000, and the system was used successfully on the Hunting Run Dam project in 2001.

IntelliGrout is a totally integrated system for data collection, monitoring, record keeping, and, most importantly, real-time onsite and offsite analyses. It not only contains all of the features of Level 2 Technology, but also includes real time graphical display of geologic features and stratigraphy, hole geometry, water test data, and grouting data, which is provided through customized programming developed within AutoCAD. AutoCAD, like the real time monitoring software, reads data from and writes data to a relational database. This relational database is the power of the system. The database allows for the generation of standard and custom reports and also allows queries to the database to search for relevant information. In addition, the proprietary AutoCAD programming is also directly linked to this real-time database, which permits real-time graphical display of grouting results on a profile. Utilizing the relational database, the system is able to perform practically unlimited, complex real-time grouting program analyses and can display the grouting results on a simple to understand and interpret, visual color display on a profile. Patterns, anomalies, compliance or non-compliance, and areas of special interest are immediately evident. The system is equipped with two monitoring stations, each with three monitoring screens (see Figure 2) to allow the operator to observe or perform multiple operations.

Figure 2: IntelliGrout Monitoring Station

A partial listing of some of its input and output capabilities and the end products produced by the system are:

- Project parameters include choices of data units and permits identification of project specific refusal parameters. Refusal alarms indicate meeting of refusal parameters.
- Topographic surveys are input and converted into a 3-D digital terrain model.
- Geologic structure surfaces, consisting of units and orientations, is input in a manner similar to topographic data.
- The curtain lines are defined through CADD and a profile of each curtain line is generated indicating the ground surface and geologic structure.
- Holes can be defined using CADD functions and can be automatically distributed according to any criteria for depth, length, "x" feet into a geologic unit, spacing, and inclination or holes can be entered via a Hole Definition Screen within the monitoring program. The hole identification, station, elevation, and inclination are automatically determined and recorded within the database.
- Identification and definition of stages can be done either automatically or manually.
- Intersections of stages with geologic units are automatically calculated and the predominant geologic unit within a stage is recorded by the system.
- Real-time data displays versus time include gage pressure, effective pressure, flow rate, current mix, and Apparent Lugeon Value. These displays are automatically printed as permanent hole records as shown on Figure 3.
- Proposed holes appear on the CADD profile as a dashed line and color coded by hole series. After drilling, the hole is time stamped and the hole is displayed as a solid line providing real-time visual display of progress.

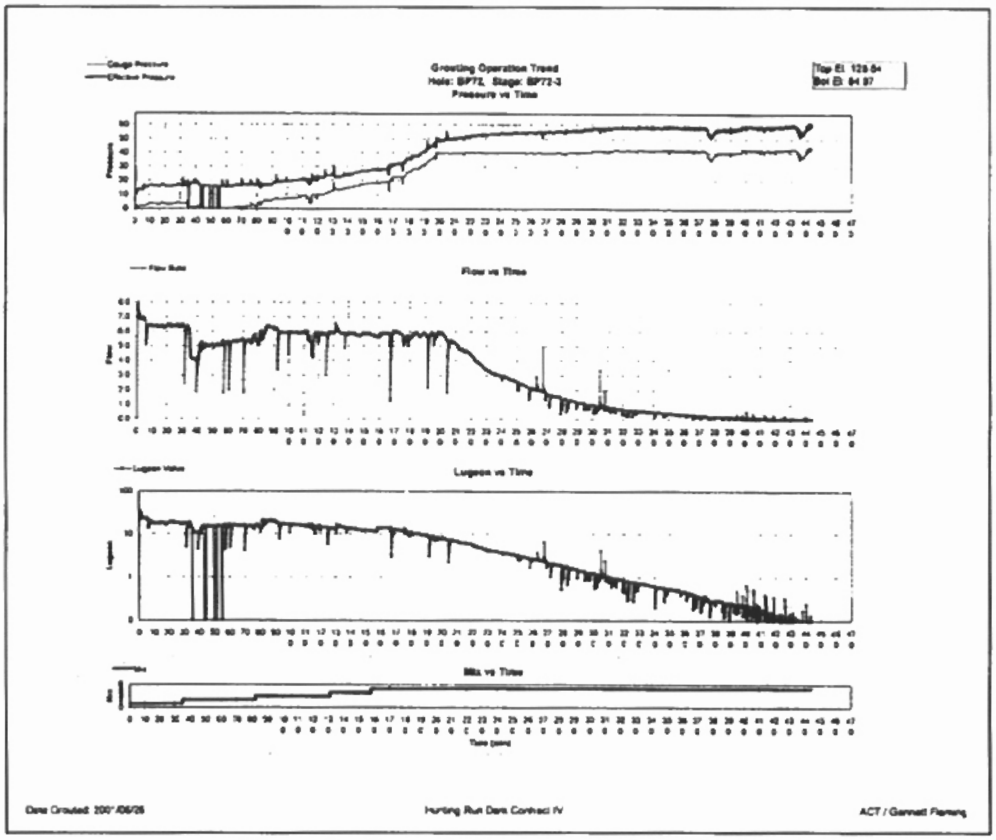

Figure 3: Example Permanent Hole Record

- o Immediately upon completion, water test and grouting results appear on the CADD drawing.
- o Display options includes the numerical Lugeon value for the stage, color coding of stages by Lugeon value, and diameter scaling of the stage by Lugeon value or radius of grout take (Figure 4).
- o CADD layering permits instant generation and viewing of any combination of information desired. Grout holes of different series (i.e. Primary, Secondary, etc.) and the drilling, grouting, and water test results for that hole series are on discrete levels within AutoCad. Therefore, the profile view of water testing and/or grouting results can be viewed on the profile for one or multiple series of holes.
- o Both water test results and grouting results can be displayed in 3-D CADD displays as cylinders scaled to magnitude of values (Figure 5).
- o The system is equipped with color plotter to produce working drawings for review or analysis or record drawings. It is also equipped with a computer projector to display grouting profiles at a scale suitable for easy viewing by multiple persons.

- o All database tables and AutoCad drawings can be electronically exported to a remote location for detailed review and analysis by peers.

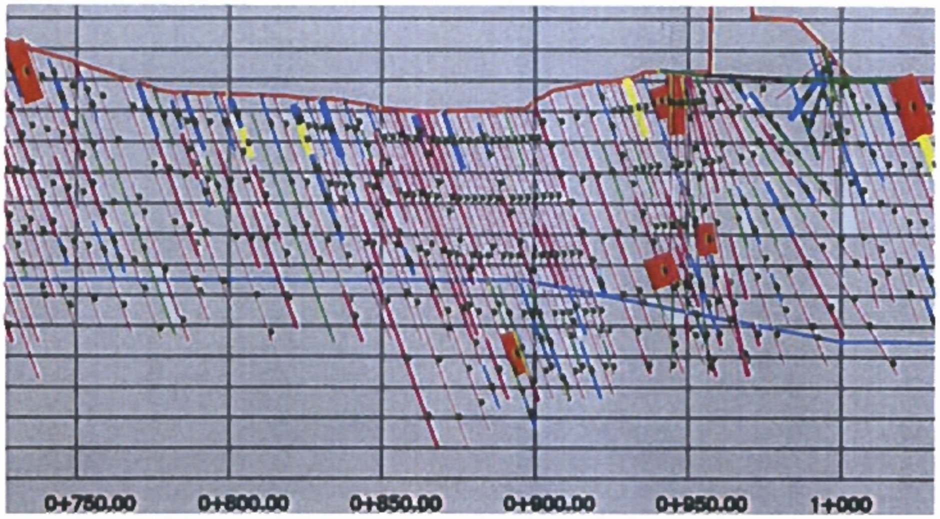

Figure 4: Water Test Results displayed in 2-D

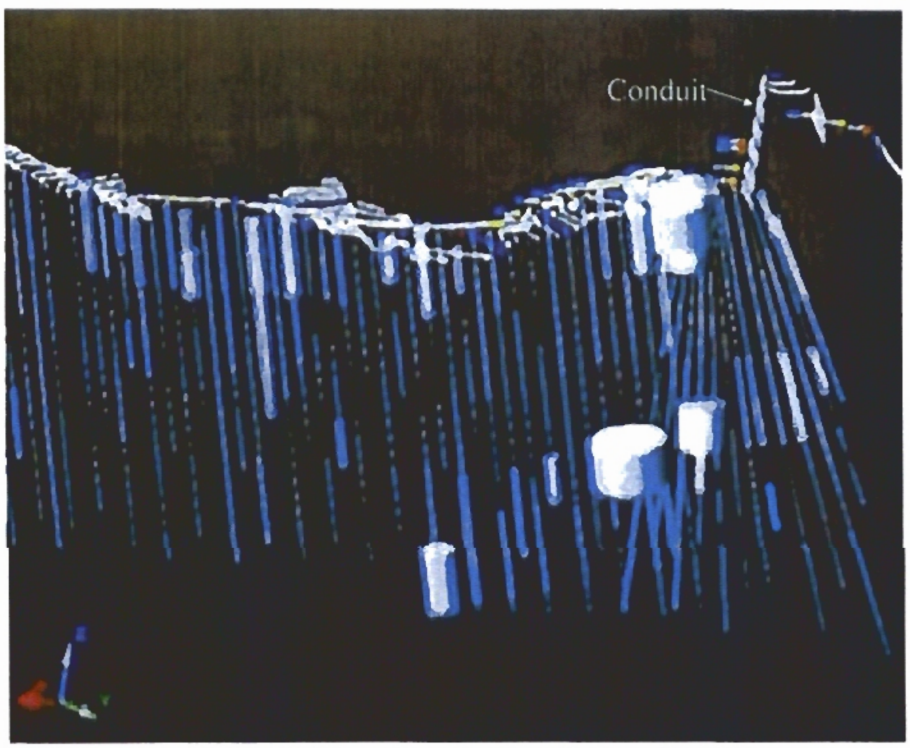

Figure 5: Water Test Results displayed in 3-D

The relational database permits the user to write queries to quickly obtain the desired information. Custom queries can be written at any time. Standard queries within the system include the following:

1. Available work listings including holes available for drilling, water testing, washing, or grouting.
2. Completed hole records (flow, gage pressure and effective pressure, Apparent Lugeon, and grout mix all displayed graphically as a function of time)
3. Searches of holes or stages for particular characteristics of interest. A useful query under this category is determination of all stages for the final hole series that have a lugeon value greater than the project performance requirement (Figure 6).

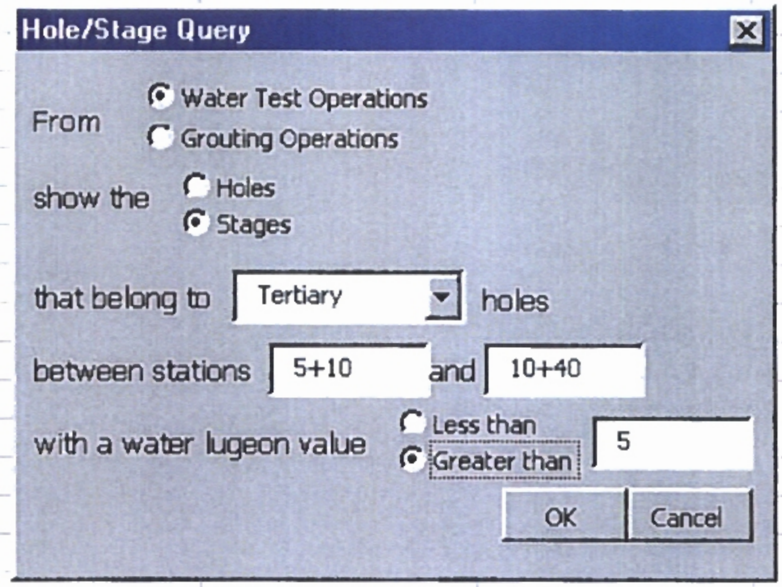

Figure 6: Example Stage Query

4. Closure Plots can be generated for both water pressure tests and grouting according to the criteria defined by the operator for inclusion in the analysis. For example, data to be included in a particular analysis can be selected based on stage depth, elevation, or geologic unit of interest and can be limited to a length of the profile using stations or primary grout hole identifications to define the area of interest (Figure 7).

AIA Technology is an enormous step forward in comparison to Level 2 Technology and is a major development in Computer Monitoring and Analysis of Grouting. AIA systems further reduce the onsite inspection staff time and optimize and increase the quality of reviews and interpretations of the results by decision makers through the data display options and the remote access capabilities. The systems are appropriate for consideration on Projects equal to or exceeding $750,000

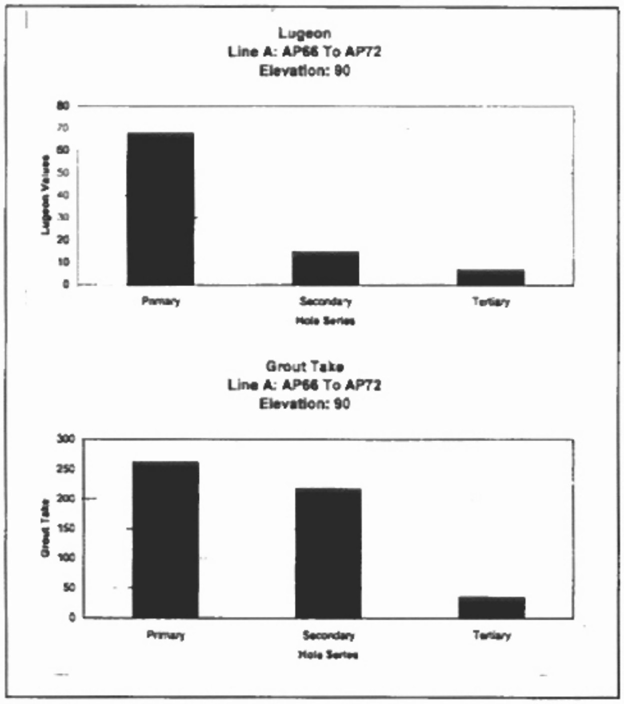

Figure 7: Example Closure Plot

in construction cost (in consideration of system acquisition and setup costs) or any project with high consequences of poor performance such as an environmental containment project. Projects of this value are of a size where the economic and technical advantages of these systems can be fully realized. Level 2 Technology can be used for these projects, but as the value and complexity of a project increases, the ability to adequately consider and interpret all of the data being collected becomes increasingly more difficult.

Case Histories

The Penn Forest Dam is critical to the water supply for the City of Bethlehem. The replacement project was constructed on a fast track schedule to avoid potential water shortages during construction. The new dam is approximately 180 feet high and 2,000 feet long and has a 3-Line grout curtain to an average depth of 140 feet. An accelerated schedule resulted in the foundation grouting being split into two separate contracts. The A-Line (first line) grouting contract specified Dipstick & Gage Technology. However, sufficient time existed before the issuance of the second grouting contract for the authors to adequately evaluate the applicability of Data Collector & Display Technology. Therefore, the B and C Line (second and third lines) grouting was specified and performed using Level 2 Technology. (Wilson and Dreese 1998). Penn Forest is the only project known to exist where a large scale, side-by-side comparison of the two technologies has been performed and where the project cost savings and time savings attributable to technology improvements are well-documented.

A detailed comparison was made of project costs for the first line, which was performed using Dipstick & Gage Technology, and the second line, which utilized Data Collector & Display Technology. The interior line was not used in the comparison, because this line was used as the closure line and was impacted by the grouting of the outside lines. For a 1,000-foot length of work in the valley, the estimated construction cost savings attributed to using the system was approximately 10%, and the savings in inspection costs were on the order of approximately 25%. The combined cost savings for this comparative length was about 20%. The estimated savings in construction time was on the order of 25%.

The Patoka Lake Seepage Remediation Project, completed by the Louisville District USACE in 2001, involved grouting a limestone ridge between the left abutment of the dam and the emergency spillway. This project was a milestone project for the USACE and reestablished the USACE as one of the industry leaders in grouting technology. Selection of the Contractor was based on Best Value Selection instead of traditional low bid contracting and the project represented the first time the USACE successfully used balanced, stable grouts and computer monitoring. The work was accomplished by a Contractor & Engineer team who performed the work, furnished and operated the computer monitoring system, and performed onsite analyses of the results. A full-time USACE geologist provided oversight of the program.

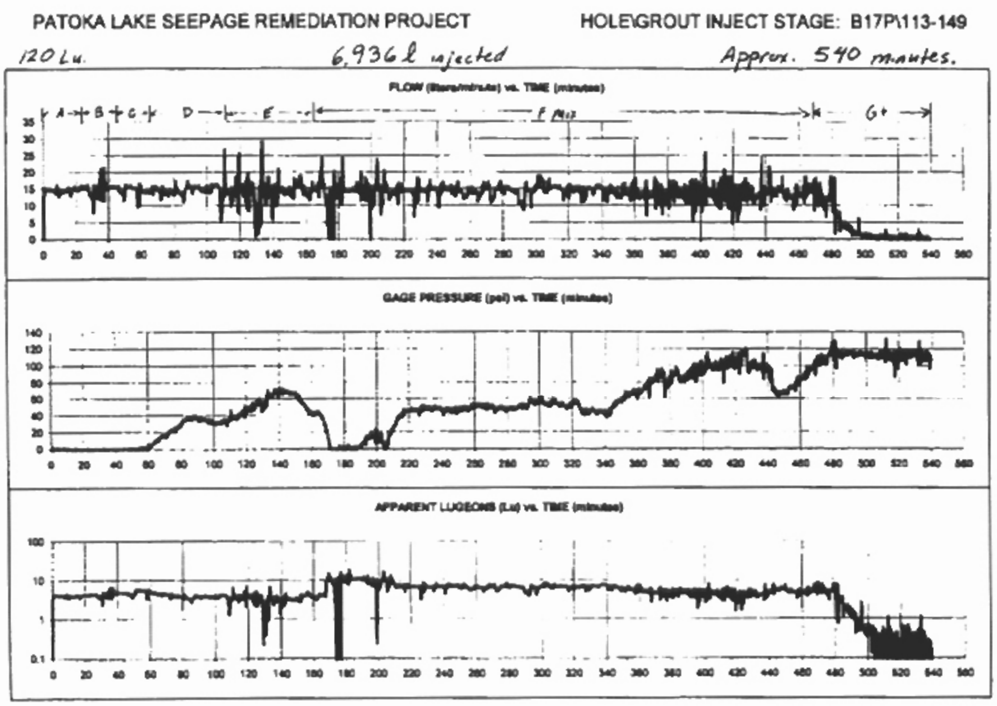

Figure 8: Example Grout Stage Record from Patoka Lake Project

In addition to the clear operational time savings and reduced inspection costs resulting from Level 2 Technology, quality benefits attributed to the system were the ability to confidently use higher pressures and the generation of superior contract records and documentation. The example grout record from the Patoka Lake Project (Figure 8) is typical of a grouting project in karst geology. Early in a grouting stage it is difficult to build pressure and the apparent viscosity of the grout mixture is increased quickly. Once pressure starts to build it is not uncommon to break through a clay seam resulting in loss of pressure. Having this information on a real-time basis and available for review is important in understanding the formation being grouted. Upon completion of the project, permeabilities in the grouted area were reduced by three orders of magnitude. Based on the results of the Patoka Lake Project, the USACE concluded that use of balanced stable grouts and computer monitoring provides a high degree of confidence that grouting can be technically effective and that grouting can be a cost effective alternative to concrete cut-off wall methods that have often been used in limestone (Flaherty 2001).

Grouting at Hunting Run Dam in Spotsylvania County, Virginia was completed in 2001. Hunting Run Dam is a water supply dam that creates an off stream storage reservoir. The grout curtain was a quantitatively designed curtain with a defined performance criterion of less than 5 Lugeons. Achieving the seepage reduction provided by a 5 Lugeon curtain was required due to the high cost of water in a pump-storage reservoir. The basic grout curtain was a single-line curtain 1,100-feet in length constructed to depths of up to 125 feet. The design included provisions to add additional curtain lines of variable depth in reaches wherever geologic conditions were found to require additional grouting to achieve the defined performance. The construction value of the grout curtain was approximately $1.1 million.

The work was accomplished using the IntelliGrout System, which was its first full-scale field trial. The ability to visually display the water testing results by hole series combined with the ability to query the database for all Tertiary hole stages with a water Lugeon value greater than 5 before grouting permitted a rapid assessment of the performance as the grouting proceeded. Locations requiring additional quaternary holes for confirmation or additional grout lines to achieve the required performance were easily identified. The analytical capabilities and analysis display features of IntelliGrout were found to be of tremendous value in locating and isolating specific geologic features requiring additional treatment and allowed highly effective program modifications to target these features to be developed in a time frame compatible with the rapid construction pace. Figures 4 and 5 show the water testing results from Hunting Run Dam in both 2-D and 3-D. The high permeability zone starting to the right of the conduit and dipping to the left and the high permeability weathered zone near the center of the valley are easily identified from either view. The weathered zone near the center of the valley was known to exist from the design subsurface investigation. However, the high permeability feature under the conduit, which followed a weathered intrusive dike, was unknown during design and the design curtain depth was short of the depth required to cut off this permeable zone. The systems operators were able to rapidly identify this zone and deepen planned holes or add additional holes to ensure that the project performance requirements were achieved. On a conventional wall chart, it is highly likely that this feature would have gone unnoticed and an area of concentrated residual leakage after construction could have easily been the result.

The IntelliGrout System also provided substantial value to the Owner. This included the economic advantages of the reduced inspection force and reduced time for peer reviews of the grouting results, as well as the owner being able to visualize and clearly understand the geologic conditions and grouting results that were the basis for program changes being made to accommodate those conditions. Output from the system provided understandable information on assurance of effective, quality construction.

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