MOSUL DAM – DATA MANAGEMENT

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ABSTRACT

The emergency grouting to stabilize the karstic foundation of Mosul Dam was conducted from a 3-meter-wide grouting gallery, at the base of the dam to establish a double line grout curtain (over 4,500 grout holes). Agile data management practices and processes were critical to providing the information needed to plan, execute, revise, and adapt drilling and grouting operations continuously on a 24-hours per day, 6-days per week basis. These data management practices and processes were structured so field personnel knew what information to collect and report and agile enough to quickly allow new information to be collected and incorporated for refined interpretation.

The data logging system developed by AECOM to support the USACE Task Force enhanced efficiency, reduced errors, and improved the type and quality of data captured in the field. This information combined with daily observations of issues experienced in the field allowed the engineers to better understand the foundation conditions, revise drilling and grouting plans, and develop technical solutions to the problems encountered.

The data management practices and processes evolved to address the better understanding of the foundation conditions, requests for new data, and to facilitate the drilling and grouting operations transition to the Iraqi Owner.

1. INTRODUCTION

Mosul Dam is located approximately 40 km northwest of Mosul, on the Tigris River (Fig. 1). The 3.4-kilometer dam is constructed in 1984. The dam is a multi-purpose dam providing flood control, irrigation, power generation, water supply, and gets majority of its flow from the snow melt from Turkey.

The 113 meter tall dam serves as a flood control structure protecting more than one million people residing in the flood plain from imminent threat. The dam is founded on a layered sequence of rocks including marls, chalky limestone, gypsum, anhydrite, and limestone. A feature of the geology is the occurrence of karstic limestone and the development of solution cavities within the limestone, gypsum and anhydrite layers. The dissolution and erosion of gypsum by water seeping under the dam has created a significant void system. The crest is at elevation 343 meters with 13 meters of freeboard at the normal pool elevation (330 meters).

To address the issue associated with dissolution of gypsum, a dedicated grouting gallery was constructed at the base of the dam along the dam centerline (Figure 2). This 3.7-meter-tall and 3-meter-wide grouting gallery also provides access for continuous maintenance grouting of the deep grout curtain. To organize and track grouting activities the grouting gallery was divided into 36-meter-long sections.

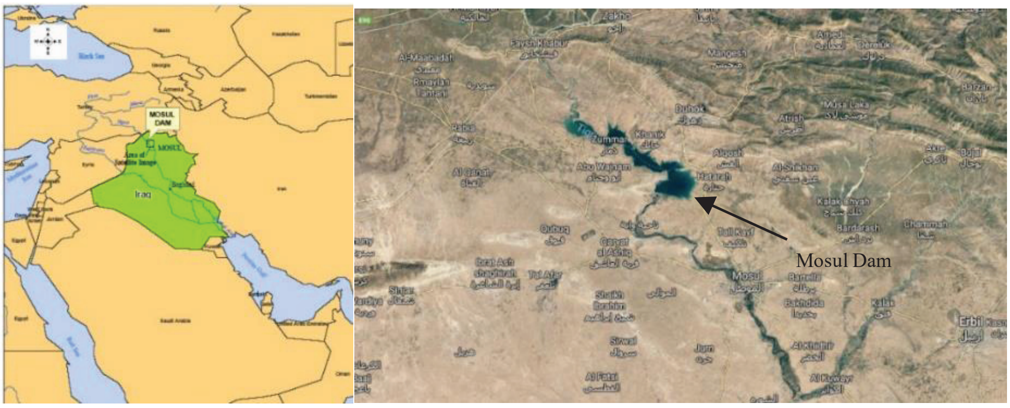


Figure 1 : Project location map.

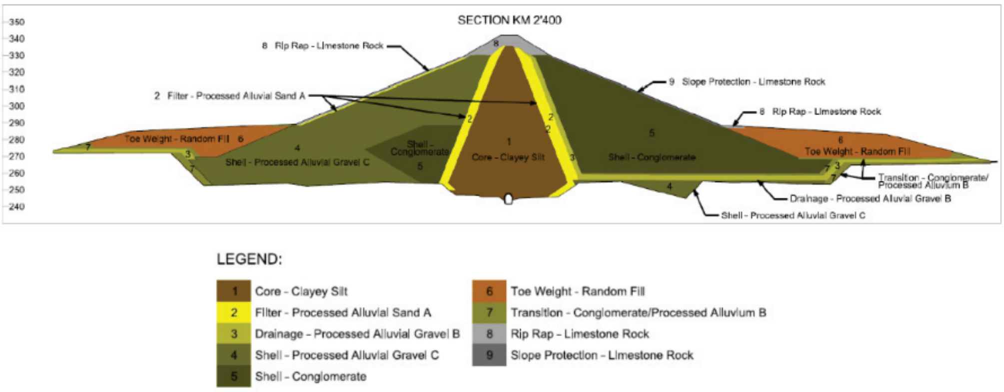


Figure 2 : Typical section of main embankment.

2. EMERGENCY GROUTING PROGRAM

The emergency grouting program was initiated to stabilize the dam foundation beginning in 2016. The main objective of the emergency grouting program was to install a double/triple grout line curtain along the full length of the grouting gallery and to connect curtains from the crest of the dam east of the spillway and west abutment. The emergency program was completed in a phased approach. The magnitude of the grouting effort required special infrastructure including:

- Construction of 3 grout mixing plants.
- Installation of grouting and water lines, electrical, and fiber optical cables.
- Procurement of 18 new drill rigs and rehabilitation of 6 MoWR drill rigs.
- Construction of new electrical, ventilation, communication/internet, and water/wastewater systems.
- Procurement and setup of 32 Batching and Grouting Units (BGU) and ancillary equipment.
- Construction of 6 new office buildings and a new repair-maintenance shop
- Construction of a secure base camp facility to provide living and working accommodations for the approximately 1000 people on site.

The engineers required specific information to plan, execute, revise, and adapt drilling and grouting operations continuously on a 24-hours per day 6-days per week basis. This included information about which holes were being drilled and/or grouted; whether those holes were being drilled and/or grouted according to the established plan and requirements for time and distance; what the status of each hole was; what issues, if any, were being encountered; was the contractor addressing those issues as required; was the right grout mix being used; did the grout mix meet the standards set; and whether the right equipment being used correctly. The data management practices and processes were developed and revised to provide the engineers with the required information.

The data management practices and processes AECOM implemented were designed to document and report on the progress and quality of the contractor's work. These quality assurance (QA) efforts directly supported the United States Army Corps of Engineers (USACE), the Mosul Dam engineer of record for the GoI. The data needs were ever evolving as new insights about the dam were observed, data gaps were identified, and technological requirements changed. The data management practices and processes needed to be agile to adapt to the new data needs. The result was an evolution from paper forms reviewed on-site to custom electronic forms on Panasonic ToughPads reviewed on-site and in the U.S. to web-based forms housed and reviewed on-site by trained Iraqi personnel.

3. INITIAL DATA MANAGEMENT

The early days of drilling and grouting were hectic as initial thoughts and plans were evaluated and updated as experience with the new drilling and grouting equipment progressed. The field personnel were necessarily learning on the job how the equipment worked at the dam with its unique geologic characteristics. At the same time, the overall infrastructure of the dam (i.e., network, lighting, power) was being established and updated as was the entire base camp (i.e., roads, buildings) housing the entire Task Force.

The initial data collection was done on paper by both the contractor and the engineer (i.e., USACE supported by AECOM and other contractors). Information included the hole identification, depth of the top and bottom of each stage, what mix type was used for grouting, and what the geology was like for drilling. The data and the procedures the contractor was using to drill and grout were continuously reviewed and analyzed to determine the quality and effectiveness of the contractor's actions. The contractor was also developing software, called T-Grout, to help automate and record data from the grouting process. AECOM was developing automated forms to collect QA data based upon the experience and lessons learned in this initial period.

4. DATA MANAGEMENT EVOLUTION

As the drilling and grouting activities progressed and expanded the data management practices and procedures adapted to support the on-site team. AECOM equipped its field engineers with windows-based tablets with a custom-built Microsoft Windows Forms application (see Figure 3). The application utilized a SQLite backend database. The application was designed to be an internal tool used primarily by the QA Field Engineers to improve the quality and efficiency of the data collected. To access the application the user would enter their username and password. The application home page contained links to each of the seven forms, reports and filings, references link, and user management, for users with administrator rights.

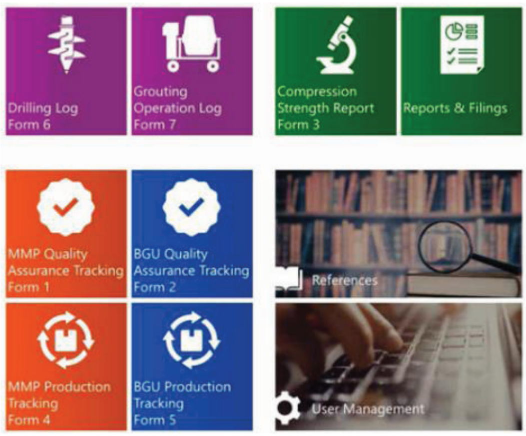


Figure 3 : Mosul Dam QA Application

To access a form, the field engineer would click on the form's link which would take the user to the forms landing page. This page would list all of the forms (e.g., Form 7) that had been created. The field engineer could view previous forms, add a new form, and in some cases edit existing forms. The purpose of each form is listed below.

Form 1: This QA form captures the grout characteristics for base mix produced at each of the main mixing plants (MMP) at various times throughout each shift. The QA shift engineer can review existing Form 1s or create a new form. The new form has fields for the name of the QA shift engineer which is automatically entered by the system. The engineer can then enter the shift (day/night) date, MMP identifier, and hole identifier (optional). This information is associated with each record which has fields for grout type, test time, mix temperature (Celsius), density (g/cm3), marsh viscosity (sec), and a checkbox to indicate if a cylindrical sample of the prepared grout batch was collected to establish the unconfined compressive strength. The form displayed the theoretical density (g/cm3) for the mix type selected. Mix batches that met the specifications for the base mix were pumped into the circulation feeder lines. Batches that did not meet the specifications were corrected to meet the specifications, if possible, or dumped.

Form 2: This QA form is the same as Form 1 except that it captures the grout characteristics for the mixes at the batch grouting unit (BGU) rather than the MMP, that includes a field for the BGU identifier. The base mix pumped from the MMP through the feeder lines is drawn by local BGUs (at the grout headers) to produce various grout mixes by adding grout constituents based on approved formulas. The values for each parameter entered for the mix batch was checked against its standard for temperature, density (g/cm3), and marsh viscosity (sec). Mix batches that met the specifications (i.e., passed) were injected into the foundation. Batches that did not meet its standard were either corrected or disposed of depending on the quantum of deviation from the specifications.

Form 3: This QA form documents the 7-day and 28-day unconfined compressive test results of the cylindrical samples collected at the MMP and/or BGU. Forms 1 and 2 were programmed to auto-populate the samples information making it available for use in Form 3.

Form 4: This QA form captures the base mix produced at the MMP that has been circulated through the feeder lines. A new form automatically fills in the QA Shift Engineer. The shift engineer enters the shift and the date. This information will be associated with each record added. For each record the shift engineer enters the MMP identifier, the mix type and the number of 1 m3 batches observed. The form displays the theoretical and total grout constituents consumed (based on the formula for each mix type) by weight to produce the number of batches entered into the record. The difference between the grout volume produced and the grout injected into the foundation (at BGU's) represented the grout in the circulating feeder lines or grouted wasted.

Form 5: This QA form captures the same information as Form 4 except that the form captures the various grout mixes produced by the BGU near the grout headers, includes a field for BGU identifier and calculates the theoretical and total constituents consumed based upon a batch size of 100 liters.

Form 6: This QA form was developed to document the drilling information (see Figure 4). The form is developed to create multiple stratigraphic layers and capture associated descriptions, drilling parameters and challenges encountered. The format of the form is structured to facilitate easy integration and development of gINT logs. Each depth interval contains a run number, depth (m), depth to top (m), depth to bottom (m), drill start time, drill stop time, lithology, formation, a text field for description, and a text field for comments.

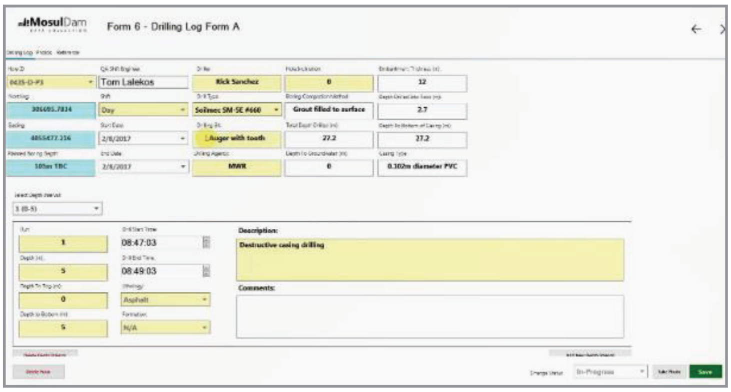


Figure 4 : Drilling Log (Form 6)

Form 7: This QA form was developed to capture grouting information on each grout hole (see Figure 5). The method of grouting on a hole (upstage, downstage, nipple) is dependent on the foundation conditions and available technology. The form is developed to adapt to the grouting methodology chosen and capture information on each grouted stage. Information related to stage interval, different mix types consumed, prevailing pressures at the end of each grouting step, elapsed time, challenges encountered, and any repeat grouting conducted are captured on the form. As with runs in the Form 6, Form 7 was designed to capture information for each stage that was grouted. The data fields available include the stage top and bottom information, grouting method, mix type, average flow rate (L/min/m), grouting date, grouting start time, grouting duration, average pressure p (bar), volume consumption (m3), weight of total solids (tonne), stage refusal (yes/no), and comments. The format of the form is set in a way to create a comprehensive grout log, after completion of grouting on a hole.

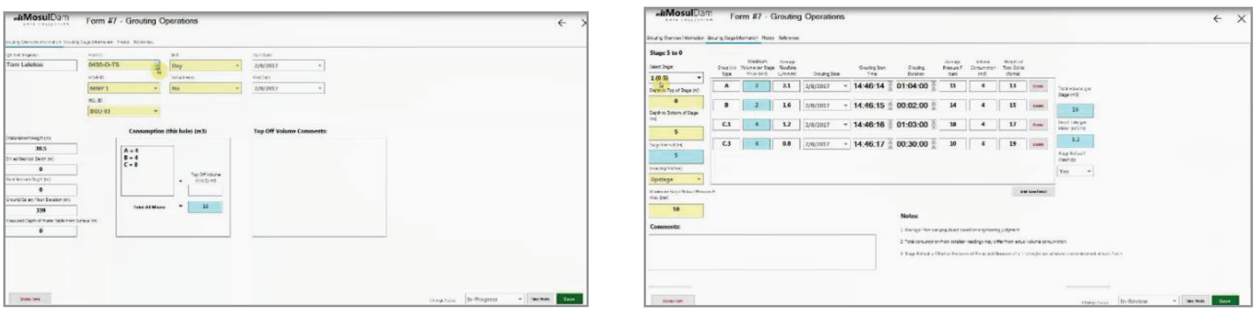


Figure 5 : Grouting Log (Form 7)

In addition to storing the data on the backend database, all data collected in the forms was synchronized to the U.S. AECOM initially developed a system to back up and synchronize data using RaspberryPI servers but this approach had to be abandoned when all data was required to be stored on the contractor's servers. The information from these forms was synchronized to a MySQL database on the contractor's server at the Mosul Dam. The Mosul MySQL database was replicated to a US AWS server hourly using an encrypted rsync transmission. Another synchronization process was also run from the Mosul server to capture image files from the tablets and post to SharePoint. The data from the US MySQL database was then processed and synchronized to an AECOM master SQL server database also located in US twice daily. During the synchronization process from the US MySQL to the master SQL database several other processes run as well. The combined synchronization and processing of data is dubbed as the “black box”. Once data has been synchronized it was available to view on the Web Portal that was developed for review and quality checking of the data collected in the forms.

The synchronization process (Figure 6) in place was a one-way synchronization from Mosul to the U.S. and ownership of the data was controlled based on the workflow status. Data “In Progress” could only be edited in Mosul using the tablets and data that has been set to “Field Complete” could only edited on the web portal. Edits made via the web portal could only be viewed on the web portal and are not synchronized back to Mosul. In addition to the data synchronization process manual checks were run daily by the data management team to confirm the synchronization process yielded expected results. A final process was run daily which exports the master SQL database tables to an Access database which was posted to SharePoint the following business day.

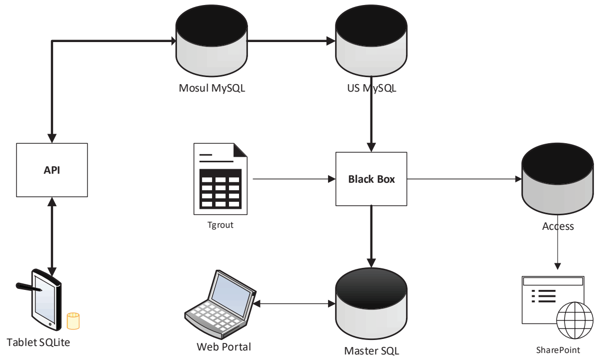


Figure 6 : Data Synchronization Process

Quality checks were performed in the U.S. by AECOM staff on the synchronized data that was Field Completed at the Mosul Dam. Field Complete meant that the form was complete and ready for review. Forms 6 (drilling) and 7 (grouting) would be kept In Progress while work on the hole progressed over the course of time. The quality checks would look to see if values entered were realistic. For example, mix type C02 had an acceptable viscosity specification range of 38-80 seconds and an acceptable density specification range of 1.46-30.00 g/cm3. The team would check to see if these values were entered into the other field making both values incorrect. As errors were found the records were noted and placed in the category of Field Update for the field engineers on-site to correct. This ensured that the correct information was in the database based on the observations of the field engineers.

The contractor deployed and modified its grouting software, T-Grout. From mid-January through May 2017, grouting data was collected using Form 7 and T-Grout. A thorough analysis of the data resulted in the acceptance of T-Grout as the official grouting data source for grouting data. The contractor was able to export some of the key grouting data into an Excel spreadsheet daily. AECOM synchronized the exported T-Grout data with the Form 7 data to create the Access database mentioned above.

The drilling and grouting data was reviewed and analyzed continuously by the on-site team to plan, execute, revise, and adapt drilling and grouting operations. The data was also being incorporated to populate the ESRI geographic information system (GIS) for graphical representation. For this purpose, the Access database export created from master SQL database tables and developed routines to bring the data into GIS. The data was used to further refine the understanding of the dam and the ability to better direct drilling and grouting operations. Figure 7 depicts the drilling and grouting issues encountered. Figure 8 provides the stage-based grout take information

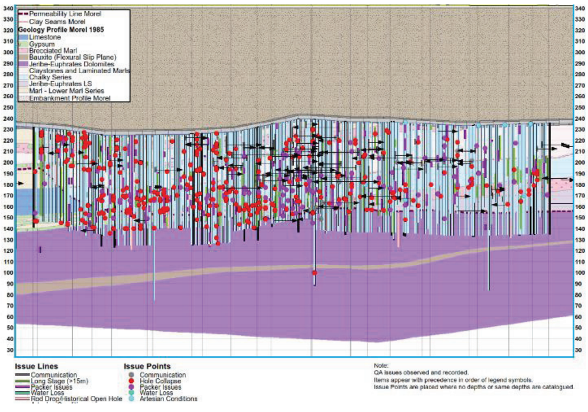


Figure 7 : Graphical Representation of the Field Encountered Issues

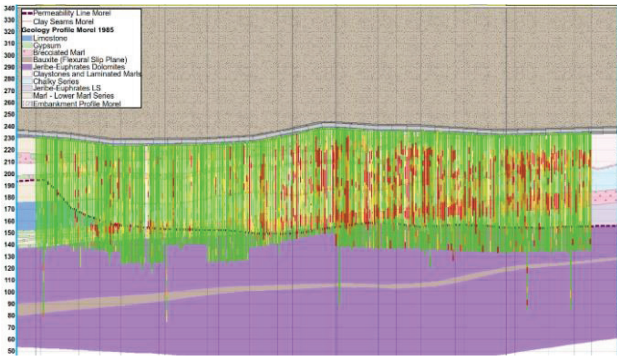


Figure 8 : Graphical Representation of the Grouting Data

The issues encountered varied across the dam and were sometimes unique to a section, but most of the time were representative of a geologic area that covered multiple sections. Consistent logging of the field information was important for interpretation of the encountered issues and associated geology. To this effect a consistent set of definitions were stablished for the drilling and grouting issues as indicated below:

Grout/Drill Water Communication: The issue can be observed during either drilling or grouting. A communication is observed when drilling or grouting fluid from one hole is observed in adjacent holes confirming a connection between the two. Communications suggest that a network of rock fractures and or voids exist in a geological bed.

Hole Collapse: A hole collapse is generally observed subsequent to significant hole washing post drilling. Hole collapses correlate with the geology.

Packer Issues: Packer issues relate to challenges in setting the packer in place, damage to the packer, grout bypass around the packer, or other malfunctions. The issues may be due to the nature of the local geology or equipment.

Water Loss: This issue was typically observed while drilling holes from the crest of the dam. Water loss indicates loss of drilling fluid during drilling which is generally due to a geologic feature such as a fracture or void. This impacts production and progress due to premature wear of the drill bit.

Long Stages: The length of grout stages typically range from 5m to 8m. However, longer grouting stages occurred due to multiple reasons. When stages were longer than 15m, they generally need to be re-drilled and re-grouted in order to ensure grout takes were accurate.

Artesian Conditions: This was the biggest challenge so far on multiple sections along the dam. A combination of high back pressure, high artesian flow rates, or both were observed under portions of the dam. This made both drilling and grouting difficult to perform

Consistency in use of the definitions helped in uniform interpretations of the encountered issues and associated geology, and promoted quick decision making and repeatable state of practice. The revised forms with built-in definitions and easy logging approach, helped in quick and uniform dissemination of field information and assisted in informed decision making.

The daily field report was a good way to hand-off the ongoing work from one shift to the next. The DFR provided information on grouting activities completed during one shift and plan for the next shift. The DFR underwent a number of revisions to support the data management needs. To support reporting on the effectiveness of equipment use, the report was modified to capture information on how many hours each rig and BGU was in use, idle, or unavailable. This data was summarized and presented in bi-weekly reports. Other information included in the DFR included personnel present, key decisions made, drilling and grouting accomplished, infrastructure upgrade work, and summary of the QA data. These reports also document the shortcomings on any of these aspects.

The information from the DFR's provide information necessary to:

- Assess the current positioning of each equipment and plan for their movement based on the drilling and grouting plan.
- Track the productivity of the equipment and consumables. Equipment down time needed to be understood from geological, wear and tear, and maintenance standpoint.
- Personnel utilization.
- Metrics on drilling and grouting completed and challenges encountered.
- QA documentation provided insight into sub-standard grout mixes, their sources and causes and provided continuity to the monitoring process.
- Tracking of infrastructure upgrade progress.

Electronic filing of these reports provided immediate access of the information to the management, and field staff. The combination of the forms data and the DFR provided a full view of the status and progress of operations at the dam.

5. INTEGRATION AND TURNOVER

With Phase 2 of the emergency grouting program underway, the Mosul Dam Task Force began planning to turn the entire program over to the GoI. All aspects of work were evaluated, and plans made to train and integrate Iraqi personnel into the day-to-day operations with members of the Task Force. The data management goal was to link QA data to T-Grout data and incorporate it all in the GIS, and to have all this done on a stand-alone system at the Mosul Dam. At this point the QA Field Engineers were focused on identifying issues, if they occurred, and evaluating whether the contractor was following the correct drilling and grouting procedures to address the issues when they did occur. This focus meant that the forms could be revised again to reflect the current practices and procedures. It also provided an opportunity to migrate from the Microsoft Windows Forms to web-based forms. This change would make it much easier to the GoI to maintain and update the forms, if they wanted to and reduced the need for software updates due to operating system changes from Microsoft. Revising the forms would also flatten the learning curve for the Iraqis taking over the system.

The user-friendly forms focused on documenting issues, if and as they were observed. Forms 1 and 2, which checked the temperature, density, and marsh viscosity were updated to visually show if one of the parameters were out of range and were a failure. All QA Field Engineers and all others using the system were able to export all issues for all holes to be able to analyze data. Training and user guides were provided on using the forms (Figure 9).

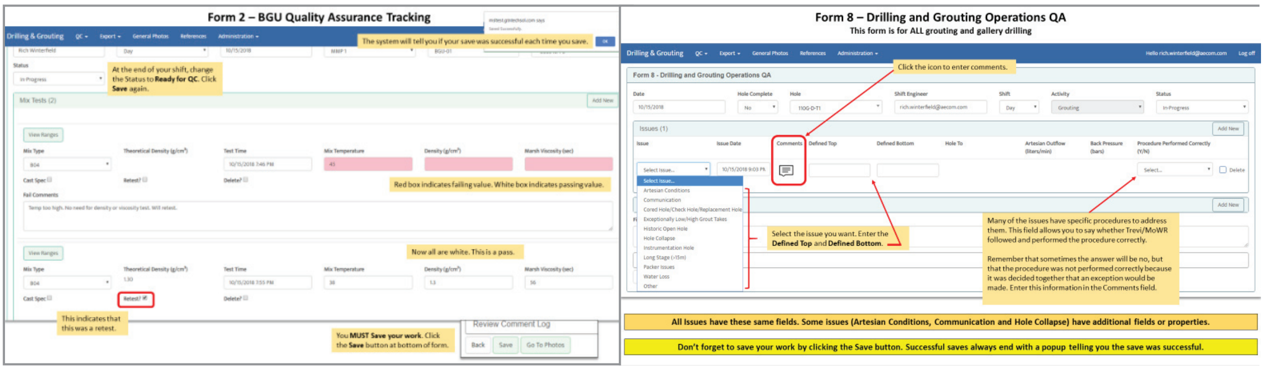
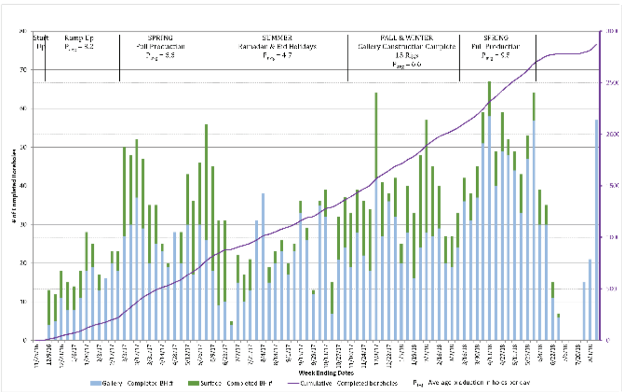


Figure 9 : User Guide for Training

5.1 Processing Data from Forms 3, 4, 6, and 7

Forms 3, 4, 6, and 7 provide information on production statistics for the project. These statistics include length of drilling, no of holes completed, and volume of grout injected into the foundation. The forms also provide information on the grout production and injection into the foundation. The rate of grout injection provides insights into future planning of the grouting materials needed.

Figure 10 provides the statistic on the number of holes completed (drilling and grouting) on a timeline. Figure 11 depicts the length of drilling and volume of grout emplaced each week. These plots help in analyzing the reasons if reduction in production is observed.



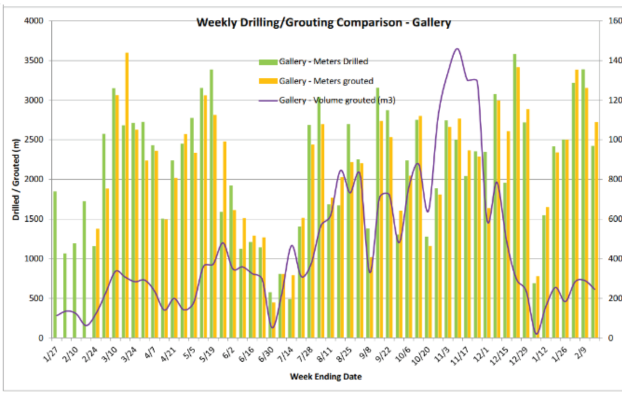


Figure 10 : Holes completed (drilling and grouting)

Figure 11 : Drilling and Grouting Statistic by Week

5.2 Processing Data from Forms 1,2, and 3

Data from Forms 1, 2, and 3 are processed to understand deviation of grout mixes from the specifications. Figure 12 shows a sample analyses of unconfined compression (UCS) test results of the cylindrical samples. A similar analyses was conducted using the various grout characteristic test results documented on Forms 1 and 2, to understand the deviations.

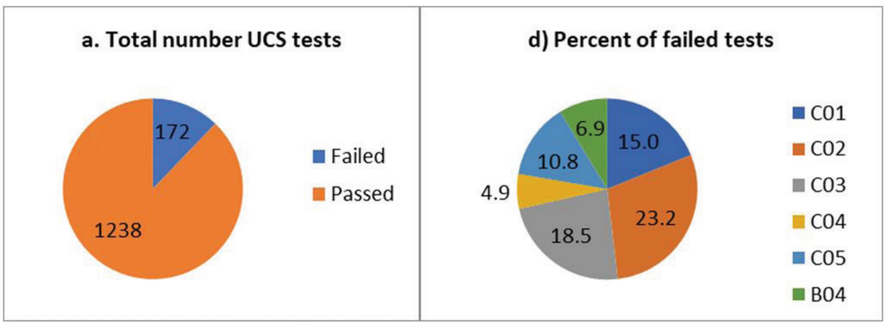


Figure 12 : Sample analysis of UCS Test Results

5.3 Processing Data from the DFR

Analyses of equipment usage, equipment location, and on-going infrastructure upgrade work related information documented on the DFR is used for future planning of the equipment location. This information was also used to establish the equipment efficiency and usage. Figure 13 shows the planned location of the equipment. This is important for planning drilling, grouting, and infrastructure upgrade work. Planning the equipment location was critical due to the limited gallery and maneuvering space. Figure 14 shows sample equipment usage analysis. The analysis includes equipment working time, idle time, and down time.

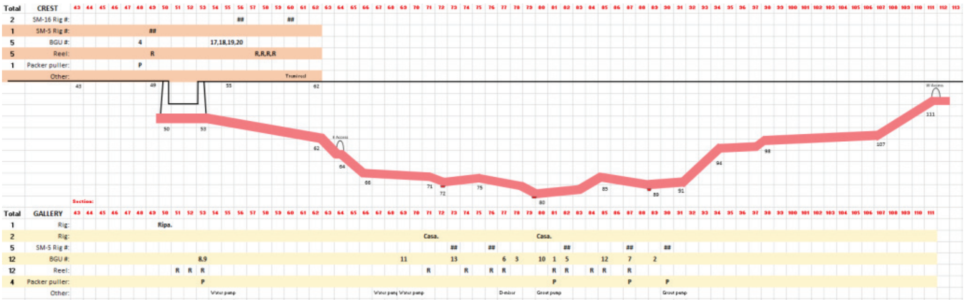


Figure 13 : Equipment Location along the Gallery

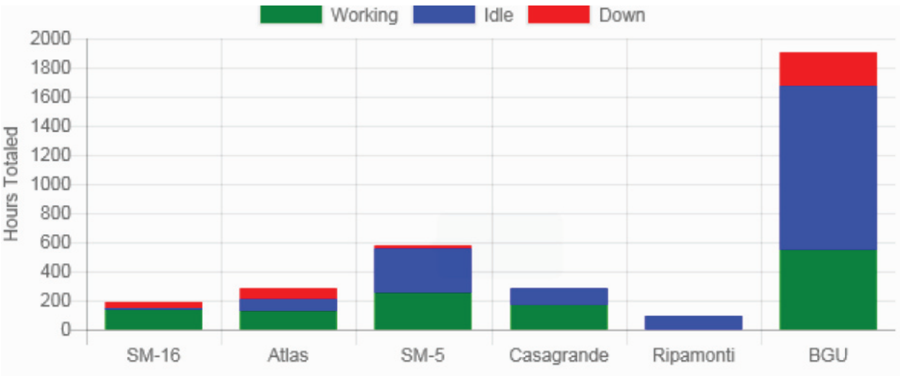


Figure 14 : Equipment Usage Over a Limited Time Period

6. CONCLUSIONS

Agile data management practices and processes were critical to providing the information needed to plan, execute, revise, and adapt drilling and grouting operations continuously on a 24-hours per day, 6-days per week basis. These data management practices and processes were structured so field personnel knew what information to collect and report and agile enough to quickly allow new information to be collected and incorporated for refined interpretation.

The implemented data management practices and processes provided real time information and analysis tools fundamental to the success of the Mosul Dam emergency grouting program as follows:

- Drilling and Grouting Methodology : Choice of drilling and grouting method selected was made based on understanding of geology and documented challenges.
- Equipment : Tracking the usage of drill rigs, drill bits, core barrels, packer sizes, grout reels, packer pullers, and other specialized equipment. Choice of equipment and handling techniques were heavily influenced by geology, documented challenges, and successful usage of specific equipment.
- Grout Mixes : A suite of mixes with different characteristics were used for grouting to address the variation in conditions across the site. The choice of grout mix was based on documented field conditions and challenges. The QA results of the grout mixes played a role in the choice of the mixes.
- Technology : Real time data collection using the grout monitoring database, along with analysis of grouting data using the tough pads allowed for real time adjustments to the processes and improved the results.
- Time : Planning, sequencing and implementation of drilling and grouting, to avoid possible challenges and wastage of time and resources, was based on documented observations.

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