MOSUL DAM – A MULTI-NATIONAL DAM FOUNDATION REHABILITATION EFFORT

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ABSTRACT

Mosul Dam, is one of the largest multi-purpose dams in the Middle-East. Located in Northern Iraq, the 3.4 km long earth fill dam is located on extremely problematic, karstic foundation, that has the potential to erode due to the presence of dissolvable anhydrite, gypsum and limestone layers extending to depth of several hundred meters below the dam. The gypsum dissolution has been shown to form interconnected openings in the foundation that could compromised the stability of the dam. This issue has been addressed by maintenance grouting over the years. However, the deteriorating foundation of the dam due to both geologic processes as well as hostilities in the past 5 years posed a risk that, if not addressed immediately, could result in catastrophic loss of life, economic damage, and geopolitical instability.

This paper discusses the multi-national approach undertaken to address the identified problems with the karstic foundation, including challenging socio-political conditions, limitations in adopting modern grouting technology, customization of drilling and grouting techniques, use of computer-based grout monitoring systems, and development of a comprehensive construction logging database. The paper also discusses the efforts involved in building a multi-national team to address rehabilitation of the dam foundation and integration of the Iraqi Ministry of Water Resources staff into a training program to ensure they can successfully operate and integrate the new equipment, software and techniques into their future maintenance grouting program. Best management practices used to address the aggressive schedules, production, and intensity of the grouting effort will be discussed in the paper.

1. INTRODUCTION

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

The dam is founded on a layered sequence of sedimentary 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. Four significant gypsum units were identified during design and construction. The dissolution and erosion of gypsum by water seeping under the dam, has created a significant void system and was a primary focus of the emergency grouting program.

The Ministry of Water Resources (MoWR), Government of Iraq (GoI), has been performing maintenance grouting since the original dam construction; however, the geo-political instability in northern Iraq interrupted maintenance grouting between 2014 and 2015 and it was believed to have impacted the foundation conditions of the dam.

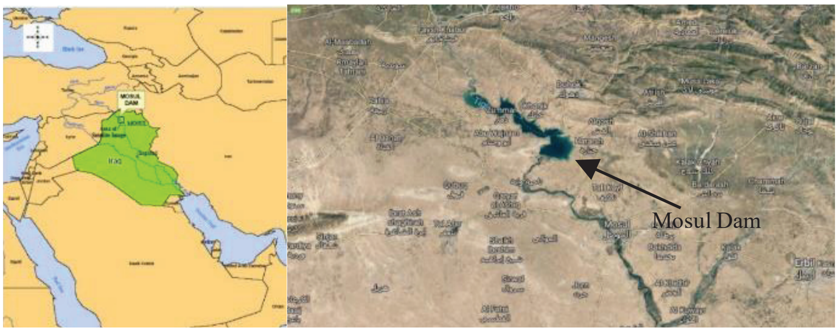


Figure 1 : Project location map.

1.1 Dam Design

Concern for underseepage and the associated risk of dissolution of gypsum in the foundation was identified during the original design of the dam. To address the issue, the design included a relatively shallow, grout blanket installed beneath the dam core combined with a deep grout curtain installed from a dedicated grouting gallery constructed at the base of the dam along the dam centerline. This 3.7 m tall and 3 m wide grouting gallery also provides access for continuous maintenance grouting of the deep grout curtain.

The presence of karstic terrain was confirmed during the site excavation for the core. Voids and large caverns were found under the river bed and abutments. There is evidence that the area may have high permeability conduits that carry river and ground water through the bedrock. The 113 m tall long embankment dam core includes multiple filters, an internal chimney drain and transition zones. A cross section (Fig. 2) of the embankment is shown below. The crest is at elevation 343 meters with 13 meters of freeboard at the normal pool elevation (330 meters).

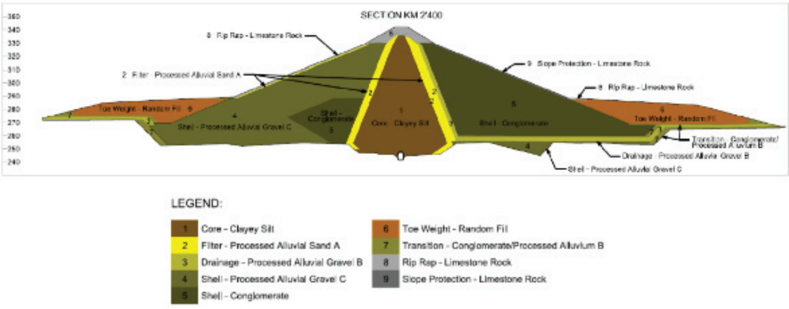


Figure 2 : Typical section of main embankment.

1.2 Dam Safety Risk

Mosul dam serves as a flood control structure protecting several million people residing in the flood plain from imminent threat. A risk-based study performed by the U.S. Army Corps of Engineers (USACE) in 2016, considered the likelihood of dam failure due to various Potential Failure Modes (PFMs) related to the foundation conditions combined with the predicted loss of life to determine a risk profile. When shown on the USACE risk chart (Fig. 3), the risks for Mosul Dam are high due in large part to the magnitude of the estimated life loss if the dam were to fail. If the risks are not addressed, failure could result in catastrophic loss of life, economic damage, and geopolitical instability.

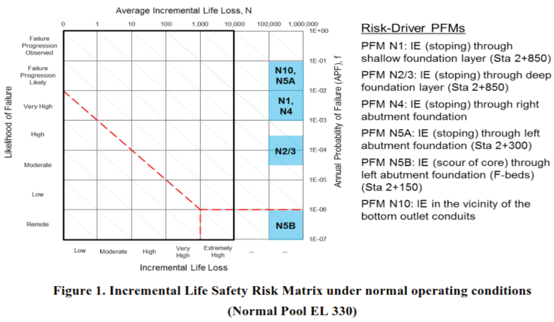


Figure 3 : Incremental Life Safety Risk Matrix Under Normal Operating Conditions (Normal Pool El 330)

2. Emergency Grouting and key objectives

The interruption to maintenance grouting due to the geo-political instability in northern Iraq between 2014 and 2015, led to the emergency grouting initiative to stabilize the dam foundation. In October 2015 the Iraqi Government issued an international invitation to tender for the emergency maintenance and safety of the dam. Trevi S.p.A. was awarded the tender (March 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 connecting curtains from the crest of the dam east of the spillway and west abutment. This task was completed in a phased approach with the key objectives of each phase as outlined below:

Phase 1 :

1. Reestablish at least a continuous single grout line, or one row of grout holes, across the length of the dam.
2. Grout holes to be advanced to a depth of 50 m beneath the gallery floor or 50 m below the contact between the dam embankment and foundation geology. Discovery of historical open holes had resulted in extending the depth of the planned holes to their previous grouted depths, to avoid leaving open vertical conduits in the foundation.
3. Complete stage pressure grouting on all holes.
4. Finish drilling and grouting with the highest priority given to stabilizing the foundation.

Phase 2 :

1. Complete the continuous double grout line or two rows of grout holes (the single line was completed and the second line was started during Phase 1), across the length of the dam, grouting around the bottom outlets (2), power plant intake tunnels (4) and Jezira tunnels, install a third (middle or downstream angled) row of holes in the lower gallery where geology and grout take indicate a need, complete check holes, and instrumentation/characterization holes.
2. Integrate 250 MoWR staff and workers into the grouting program at all levels so they are proficient in the drilling and grouting program and are able to take over the project when the USACE demobilizes from the site.

Phase 1 included drilling and grouting operations from November 2016 to August 11, 2018. Phase 2 included drilling and grouting operations from August 12, 2018 to July 11, 2019. The principal objective of the Phase 1 emergency grouting program was to install a continuous grout curtain, by drilling and grouting at least a single grout line, across the length of the dam. The single grout line (mostly downstream holes with middle line holes in some areas) was completed in addition to completing approximately 37% of holes on the second line (mainly upstream holes). The Phase 2 objective work was focused on completing the second line across the dam and drilling and grouting inclined (downstream) and middle line holes and grouting of the tunnel areas. This effort was scheduled to prioritize problematic areas identified based on a review of the dam geology and data collected during the Phase 1 work.

3. CHALLENGES

The conditions of the project presented multiple challenges, the primary ones are as follows:

- Need to replace entire grouting infrastructure (mixing, batching, distribution, etc.) as well as dewatering and electrical systems.
- Security situation in Northern Iraq limited the movement of the grouting staff to the site and within the site. Increased difficulty to recruit technical staff for the engineer and contractor.
- Complicated logistics to move equipment, tools, consumables, and supplies to project site.
- Difficulty in procurement of materials, tools and equipment due to "made on order" European approach.
- Change in the control of the area from the Kurdistan region to the central government of Iraq impacted the local work force, and some workers not being able to cross the check points or border to reach the site.
- Customization of modern grouting equipment to meet high productivity and site conditions.
- Overcoming the language barrier between the multinational team involving hundreds of onsite staff.
- Timely coordination between the on-site and reach back teams overcoming the time zone differences.

The need to upgrade the legacy grouting systems to meet the demanding production needs while concurrently drilling and grouting holes presented a significant challenge at the beginning of the project. 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 9 new drill rigs (plus 9 in the 2nd phase) 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.

4. TEAM SETUP

To accomplish the emergency grouting program, the project work was performed in accordance with Contract between the GoI and Trevi S.p.A. (Contractor). The GoI requested USACE serve as the Engineer of Record for rehabilitation of Mosul Dam and Bottom Outlets works and provide oversight of the contractor. This was accomplished through a Letter of Agreement between the GoI and the U.S. Government, outlined the roles and responsibilities of USACE in serving as Engineer of Record for the MoWR. USACE's construction management staff was composed of engineers and geologists from USACE supported by technical staff from AECOM and Versar – collective termed the s Mosul Dam Task Force "MDTF". This team included the necessary staff with experience in dam safety, risk analysis, and risk reduction.

To meet the aggressive production schedule, the contractor performed drilling and grouting 24 hours per day, six days per week. To direct, control and monitor this large round-the-clock operation, advanced communication and computer based monitoring systems were used to assess equipment, grout mixes, drilling and grouting methodologies. Innovative project management approaches to overcome communication barriers, planning of equipment use, sequencing of drilling and grouting to achieve the aggressive production targets, health and safety practices were applied to keep the project on track.

5. PROJECT MANAGEMENT

The MDTF team included approximately 70 to 80 staff on site, with an equivalent staff on the reach back (state side) team. The MDTF team provided the oversight on the emergency grouting program, guiding approximately 700contractor team. The aggressive production schedules involved multiple project management challenges as depicted in Figure 4.

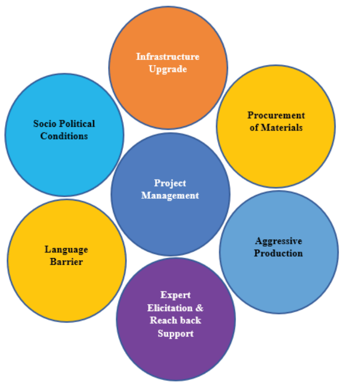


Figure 4 : Project management challenges

The aggressive production schedule needed a large team to accomplish the project objectives. Due to the existing socio-political situation in Iraq, the MDTF, and contractor staff were provided housing within a secure base camp constructed for this project. The project site and the base camp were secured to provide safe working environment.

The political and security situation necessitated continued assessment of prevailing conditions and inclusion into the project management plans. These conditions impacted procurement of materials, equipment, and movement of project personnel necessary to meet the project objectives. Instances needing immediate medical attention needed to be part of the management plans.

The project involved a multi-national team, speaking at least 3 predominant languages. The large size of the team needed effective communication, overcoming the language barrier for successful implementation of the project. The variations in management style of various teams had to be overcome through effective communication. The team experienced the Forming-Storming-Norming-Performing stages of the group development (Bruce Tuckman, 1965), before exceeding the minimum objectives set for the project.

The variations in the profile and configuration of the grouting gallery needed to be taken into account when choosing the customized drilling and grouting equipment to be used. The sequencing of the drilling and grouting was based on the project objectives but had to be managed around the gallery profile and configuration, equipment, challenging grouting conditions, and on-going infrastructure upgrade work in the grouting gallery. Finally, a significant factor that was emphasized during this program was the health and safety and welfare of the field personnel.

6. GALLERY CONFIGURATION AND EQUIPMENT MOVEMENT

The configuration of grouting gallery cross section and profile across the 2.2 km length varies and is shown in the schematic below (Fig. 5 and 6). The gallery cross sections are generally 3m wide and 3.7m tall and have either horse-shoe or circular configuration. The tunnel underneath the spillway is the narrowest (2m wide and 3.2m tall). The slope of the gallery profile varies across the length of the dam and is shown in Figure 6. The steep slopes (ranging from 0.5% to 41%) and configuration of the gallery cross section posed a significant challenge in terms of equipment configuration and maneuvering requirements.

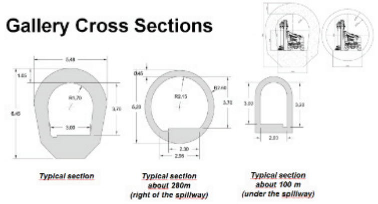


Figure 5 : Grouting Gallery Cross Sections

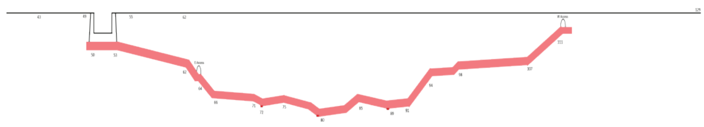


Figure 6 : Grouting Gallery Profile

The grouting units (pumps and dispensing hoppers) were designed to fit within the limited space. Customized drill rigs (designed and provided by Soilmec), specifically designed to fit within the gallery and traverse the slopes and tight turns were critical to the success of the project. Drill rigs capable of drilling through different types of geology, up to 150 m deep, core holes, and work through artesian groundwater conditions were designed for this project. Rigs were equipped with drilling parameter recording (DPR) capability to collect and provide various parameters for analysis. Figures 7 and 8 shows the drill rigs being used in the gallery and their configurations.

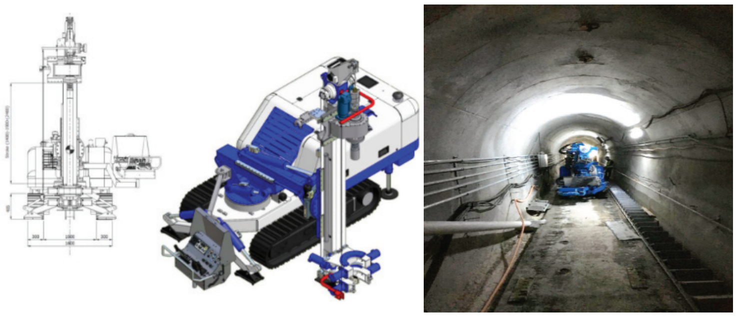


Figure 7 : SoilMec SM-5 Drill Rig for Gallery Operation

Figure 8 : SoilMec SM-5 EM Drill Rig for Gallery Operation

The batching and grouting units are also custom designed to operate in the gallery with potentially high artesian pressure conditions and with the ability to pump at high pressures and flow rates, see Figure 9.

Figure 9 : Soilmec Batching and Grouting Unit (BGU)

The varying gallery configuration, profile, and anticipated challenges determined the choice of the equipment to be used in sections of the grouting gallery. The positioning of the equipment needed careful planning for future maneuvering and personnel movement. These aspects needed to be synchronized with the grouting objectives, and planned infrastructure upgrade ahead of time to achieve maximum equipment utilization and high productivity.

7. INFRASTRUCTURE UPGRADE

The infrastructure in the gallery that was in-place at the beginning of this contract dated from the original construction of the dam and needed to be replaced in its entirety. The infrastructure upgrade included new electrical, water/wastewater, grout conveyance, grout mixing plants, communication/internet, lighting, ventilation, and concrete delivery installations. Figures 10, 11, and 12 show typical views of the gallery with legacy and upgraded infrastructure, respectively.

Figure 10 indicates the legacy Iraqi standpipes set into the concrete floor in the gallery through which GoI conducted grouting. The risk of damage to the tracks of the new drill rigs existed due to the protruding 5-inch diameter legacy standpipes. Therefore, the original standpipes were cut and new 4-inch threaded standpipes inserts were grouted in place that are flush to the grouting gallery surface. The threaded standpipe assists in attaching auxiliary equipment to the collar, and to cap it if needed. The new standpipes were installed flush to the surface for easy movement of equipment and personnel. Figures 11 and 12 show the upgraded infrastructure in the gallery.

Figure 10 : Grouting Gallery with Legacy Infrastructure and Standpipes

Figure 11 : Grouting Gallery with Updated Infrastructure

Figure 12 : Gallery with Standpipes Cut Flush to Surface

Details of the infrastructure upgrades included:

- Electrical: Removal of over 3000m of old cables and installation of new cables (170,000 m), cable trays, transformers, and generators to supply power to the gallery and crest of the dam.
- Water/wastewater: Over 4500 m of new pipelines were installed (and 2000 m relocated) to carry fresh water and wastewater in and out of the gallery. New submersible pumps to circulate fresh water across the 3.4 km dam were installed. This upgrade also included installation of new sump pumps that carry the wastewater from the sumps to the siltation tanks outside the gallery.
- Grout mixing plants: Three permanent grout mixing plants that operate on weight-based batching, were constructed and positioned across the length of the dam to assist in mass production of grout. The mixing plants have silos to store cement, dry bentonite, bentonite slurry, and water. The grout batching units at the mixing plants can prepare 1500 L of base grout mix per batch. The plants are equipped with grout pumps with a capacity to pump 300 L/min. The pumps have the capacity to keep the grout in continuous circulation in the grout line circuit, 3000 m long. See Figure 13 below for a photo of one of the mixing plants and a typical setup schematic.

Figure 13 : Typical Mixing Plant Setup at Mosul Dam Project

- Grout conveyance systems: Given the limited space constraints in the gallery, hauling the material and batching the grout mixes adjacent to the injection hole is not practical. The grout mixed at the mixing plants is conveyed to the gallery and crest through the grout delivery and distribution system. The system includes a series of pipes to keep grout and bentonite slurry in continuous circulation. The grouting units (BGU) positioned at the injection holes draw the base mix, bentonite slurry, and water from the conveyance pipeline systems and use localized volumetric batching to prepare the desired mix. The conveyance system initiates and ends at the grout mixer at the mixing plants. The conveyance system has been designed to be easily configured in multiple loops of varying length each. This facilitates grout delivery to where it is needed at the required volumes. Loops in excess of 2 km in length were successfully used at the site.

- Communication/Internet: A robust communication network was critical to conduct a complex grouting operation of this magnitude. The entire gallery and crest were equipped with a Local Area Network (LAN) using 2500 m of newly installed fiber optic cable. This facilitated computerization of the operations. Wireless hotspots with Internet connection were set up across the entire dam to enable communication among teams working simultaneously throughout the dam. The entire communication network is connected to a centralized operations center ("Control Room"), from where the entire drilling and grouting operations are supervised.
- Lighting: New lighting systems were provided in the gallery and crest for safer and more effective operations.
- Ventilation: A new ventilation system was designed and installed to draw fresh air in through the right access gallery, circulate it throughout the gallery and then out through the left access gallery.
- Concrete delivery system: The concrete delivery system was established through vertical shafts constructed in the dam to deliver concrete mix from the crest to the gallery.
- Quality Control Laboratory: An on-site quality control laboratory was set-up to perform the quality control activities. The lab is equipped with tools and equipment to design and test grout/concrete mixes. The laboratory has capacity to establish temperature, density, viscosity, bleeding, setting time, pressure filtration and unconfined compression tests.

8. COMPUTER BASED GROUT MONITORING SYSTEMS

A centralized operations center ("Control Room") was setup to monitor the grouting operations across the dam from a single location. The entire grouting operations have been automated using sophisticated grouting software. Automated manifolds were set up near the injection hole to gather pressure and flow data and transmit it to the grouting software. The gathered data is analyzed by the software that helps it to manage the grout pumps. The grouting software triggers mix changes based on pre-set criteria for pressures or volumes within the bounds of the refusal criteria.

The grouting units (BGU) are designed to communicate with the computer-based monitoring systems and to be remotely managed by grouting software. Figure 14 shows the mechanism of how the different components of the computer monitoring system interact with each other. On-site QA personnel equipped with the tablet, can monitor and control the grouting operations if needed.

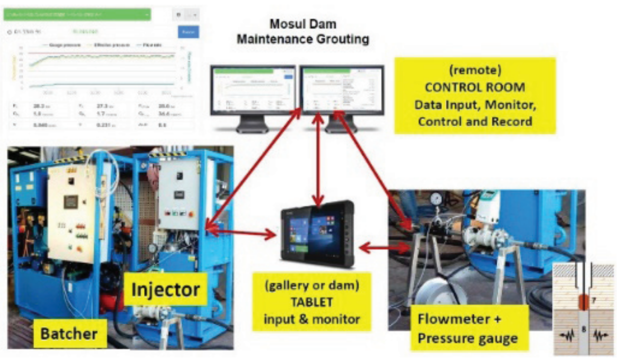


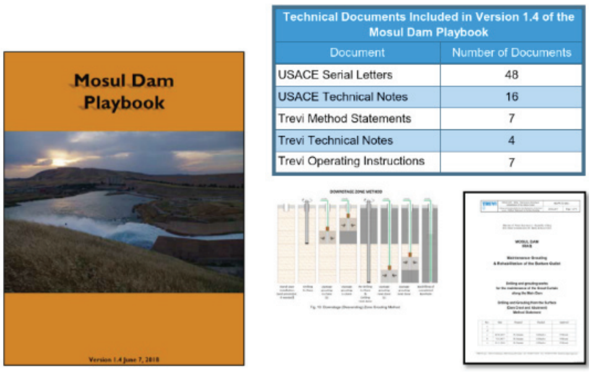
Figure 14 : Computerized Grouting Control, Monitoring and Recording System

9. CONSTRUCTION QA DATABASE AND CUSTOMIZATION OF TECHNIQUES

A comprehensive construction database (Fig. 15) was built to document the field observations. The database included multiple forms to digitally document the drilling, grouting and quality control observations. The database also included features to develop daily field reports capturing equipment usage and personnel involvement. The database is customized to capture information in a format for easy integration into other software programs, graphic display and analysis. The database was installed as an application on field tablet computers for field personnel to capture the information which is available for review immediately and for easy access to the staff on the next shift.

Figure 15 : Construction Database

The adopted grouting methodology has varied across the dam based on encountered geology and field observations documented drilling and grouting operations. Issues encountered during drilling, like hole collapses and water loss were reviewed and analyzed and the results of the analysis were used when planning the grouting methodology and customization of techniques for each section. The upstage method was the most preferred grouting method to keep up with the aggressive production schedules. However, the downstage and downstage-zone methods were also used based on field observations and geology. Each hole was generally pressure grouted in 5 m intervals using a single packer. The grouting techniques implemented on this project including serial notes, technical notes, method statements and operating instructions were inventoried and compiled into and overall manual for construction that was termed the "Mosul Dam Playbook" (Figure 16).



Technical Documents Included in Version 1.4 of the Mosul Dam Playbook	
Document	Number of Documents
USACE Serial Letters	48
USACE Technical Notes	16
Trevi Method Statements	7
Trevi Technical Notes	4
Trevi Operating Instructions	7

Figure 16 : Mosul Dam Playbook

10. PROGRESS TRACKING

The data collected from the field was used to track multiple aspects of the grouting program on a periodic basis (daily and monthly) to make informed decisions on the course of the grouting program. Some of the key information collected include total production tracking, equipment usage and efficiency, explorations for new instrumentation installation, and progress on MoWR integration program. The production tracking includes drilling and grouting operations. As of July 11, 2019, a total of twenty drill rigs were utilized on the project in areas that included the surface (crest), the gallery, and other sites for exploratory drilling throughout Mosul Dam. The emergency grouting program, from November 16, 2016 through July 11, 2019, included drilling and grouting of 5,393 holes to the target depth. About 40,800 m3 of grout were pumped from the holes drilled form surface and gallery. Other production parameters being tracked are listed as follows:

- Total holes grouted = 5393 (1145 on the crest and 4248 in the gallery)
- Total grout volume = 40,800 m3, corresponding to 27000 tons of cement
- Meters drilled = 667,800 m plus 8500 m of coring
- Highest take in a hole = 422 m^3

11. TRAINING AND INTEGRATION OF MOWR STAFF

Integration of MoWR staff with adequate technical training was part of the program objectives. This task was complicated by establishing effective approaches for knowledge transfer to the Iraqi staff, overcoming the language differences and bridging technical barriers. About 155 MoWR staff were trained in technical, critical organization, and functional areas. About thirteen (13) workshops were organized covering topics on instrumentation, dam safety, GIS, rig safety, health and safety, grouting software, mix designs, geology and QA/QC procedures.

The infrastructure upgrade was a significant task that required a good understanding of the condition of the current dam infrastructure, as well as planning for the future needs of the dam. The engineer also had a significant role in planning and training the MoWR staff on modern technology, latest equipment and integrating them into the workforce. U.S. Army Corps of Engineers (USACE), as the engineer on record for this project, served in planning, coordinating, and supervising the emergency grouting operations, in association with the MoWR officials. USACE, in its role not only brought the technical expertise, but also bridged the gap between the GoI and the contractor.

12. CONCLUSION

The emergency grouting program of Mosul Dam has been one of the most challenging projects of recent times. The rehabilitation of the dam is significant for the stability of the Middle-East, given the high consequences associated with the potential failure of the dam. The prevailing and continuously changing socio-political conditions in Northern Iraq, made it extremely difficult to procure skilled labor, equipment, materials, and modern technology at a fast pace. Innovative management practices needed to be adopted to achieve the project objectives. This was essential to address the issues present at Mosul Dam in a time-sensitive fashion in order to reduce the risk of dam failure and prosperity of Iraq.

ACKNOWLEDGEMENTS

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