MOSUL DAM CONCLUSIONS POST 3 YEARS EMERGENCY DRILLING AND GROUTING

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ABSTRACT

Over the past two decades numerous publications have presented the conditions and challenges at Mosul Dam and most were based on limited information from previous work by others without the benefit of direct site knowledge. Those publications consistently and sometimes inappropriately, used the phrase "The Most Dangerous Dam in the World" to refer to Mosul Dam, a phrase that was recycled numerous times in media reports.

The recent drilling, grouting and exploration in over 5,000 holes and the creation of a comprehensive three-dimensional GIS foundation model has allowed development of detailed knowledge of the complex geology at the dam. This was further supported by extensive original construction records that only became available as the work progressed. Detailed modeling and analyses of construction data has supported a risk analysis that determined which areas on site present the highest risk for solutioning, identifying the most significant risks to the site and producing a more certain and improved risk assessment. The combination of the work completed, access to detailed foundation treatment records and detailed modeling greatly improved the understanding of the site and was key in the change in the risk assessment at the conclusion of emergency grouting.

The geology was found to be more complex than the limited information originally available indicated with rock ranging from massive intact anhydrite to soft karstified limestone to soft clay like marls. The stratigraphy of the site was known but the variability of the rock layers and structure was more uncertain. Although voids were found, they were filled with grout and multiple grout curtain lines were established.

Mosul Dam will remain a very high-risk dam due to the extremely large downstream population at risk, however, given the improved understanding of the design and construction of the dam, the foundation exploration and grouting performed, Mosul Dam should no longer be referred to as the most dangerous dam in the world.

1. INTRODUCTION

Mosul Dam, originally named Saddam Dam, is located on the Tigris River, 50 km upstream of Mosul and 350 km upstream of Baghdad, Iraq. The dam is also located approximately 60 km downstream of the Iraq-Syria border and 100 km downstream of the Syria-Turkey border.

Figure 1 : Map of the Regional Location of Mosul Dam

The 2.21 km long embankment dam was completed in 1985 and is owned and operated by the Government of Iraq Ministry of Water Resources (MoWR). The project was designed by the Swiss Consultants Group and constructed by the German Italian Mosul Dam Joint Venture (GIMOD). The dam's main features include a 113-meter high zoned embankment, a service spillway, a 750-megawatt hydropower facility, outlet works (referred to as the bottom outlet tunnels), a saddle dam, and a fuse plug emergency spillway.

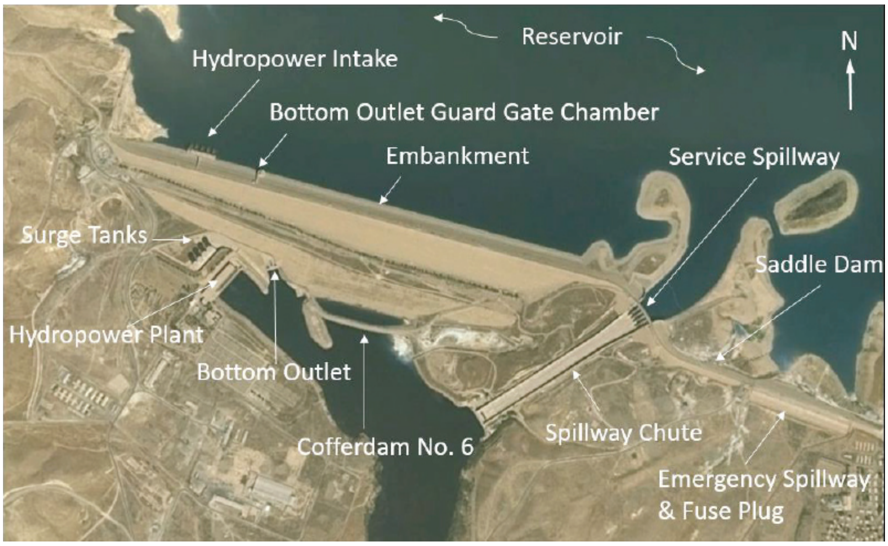

Figure 2 : Mosul Dam Main Project Features

The goals of the project are to provide significant water and irrigation supply, flood control management, hydropower generation, and environmental benefits to Iraq. Full capacity design storage volume of the dam is 11.1 billion cubic meters.

The bedrock that makes up the dam foundation is marl, limestone, gypsum and anhydrite, all of which can be either intact or brecciated. The layers of gypsum, gypsum breccia and anhydrite are subject to dissolution over time, forming solution cavities and potentially large interconnected voids that can form problematic seepage paths in the foundation. Water flow through these seepage paths within the foundation has the potential to cause foundation and embankment materials to erode into these openings resulting in internal erosion of dam materials that can threaten the dam's ability to retain the reservoir water.

The original designers, fully aware of the problematic foundation, incorporated a reinforced concrete grouting gallery at the base of the dam at the foundation/embankment contact along the dam's centerline. This grouting gallery begins under the service spillway structure on the east end and extends to the west abutment on the west end of the dam. This somewhat unusual feature for an embankment dam was intended to facilitate continual maintenance grouting of the foundation for the life of the project in order to combat the formation of seepage pathways through the erodible foundation over time (Washington International/Black and Veatch, 2004). This requirement is different from dams on limestone or other karst foundations where grouting may be needed periodically, as the dissolution rate of the gypsum/anhydrite at this site dictates that much more intensive monitoring and grouting are needed in order for the dam to function as designed.

2. EMERGENCY SITUATION AND USACE INVOLVEMENT

Over the past decade, armed conflict in Iraq resulted in shortages of equipment, materials and manpower at the project site. This resulted in periods of decreased levels of maintenance grouting and periods where no grouting was performed. Because of this reduced grouting effectiveness, an increased risk developed for significant voids and seepage pathways to coalesce in the foundation. In addition, there were identified signs of distress such as surface depressions and sinkholes that developed progressively more near the footprint of the dam than in the past. To further complicate matters, one of the two bottom outlets was inoperable due to a damaged gate position indicator rod, the condition and reliability of the entire bottom outlet system, including the conduits and joints, was of concern to the MoWR and potentially required repairs. The bottom outlet system was built to allow the controlled release of water through Mosul Dam at all reservoir elevations. The bottom outlet system is the sole means of passing water through the dam when the reservoir level falls below the intakes to the hydroelectric power plant.

USACE estimated that several million people, along with infrastructure worth tens of billions of dollars to the national economy, are within the floodplain. A breach of the dam at full storage capacity could result in substantial life loss and economic impacts. Mosul Dam also provides a significant portion of the country's drinking and irrigation water supply that would be lost should the dam no longer be able to hold a pool.

The foundation conditions, distress indicators, reduction in maintenance grouting activity, condition of the bottom outlets, and potential consequences all raised concerns of increased seepage pathway development and increased risk of dam failure. In 2006, the media had identified and publicized the conditions at the dam and referred to the dam as “The Most Dangerous Dam in the World.” In 2015, Mosul Dam was evaluated by USACE in accordance with International and U.S. dam safety standards. It was determined that the dam would be assigned a USACE Dam Safety Action Classification (DSAC) of DSAC I - Very High Urgency. A DSAC I is assigned to those dams where progression toward failure is confirmed to be taking place under normal operations. At that time, the risks were driven by not only the potential performance of the foundation, but also by the exceptionally large downstream population at risk.

Early visits and reviews of the project identified areas adjacent to the project where sinkholes and large cavernous features existed in the area. For example, on the west bank just upstream of the dam, a cave and conduit network exist in the anhydrite and gypsum. Surface expression of collapse features are 90m long and 40m wide with a vertical collapse of 3 to 4 meters exist to the north of the cave and numerous smaller collapse features exist east of the cave. The cave was known to exist at least back to approximately the year 2000, but the size of the cave appears to have increased since that time based on one photo that was in previous summary documents. Figure 3 are photos of the cave on the right bank. Early assessments did not have the benefit of numerous drill logs from the site which showed a different existing condition in the rock beneath the gallery than seen in the cave.

Figure 3 : Photos of large cave opening on right bank

While this cave does not pose a threat to the dam, as it is too far in the west abutment, it does represent what the foundation could look like without intervention by grouting. Indeed, drilling along the downstream left abutment of the dam near the dam toe, but within the toe weight footprint (see Figure 5 for a cross-section and toe weight feature), revealed a pattern of voids similar to what was observed in this cave. Many of the boreholes showed one to three-meter voids with one borehole having a void up to 6 meters tall.

The downstream left abutment void space took over 900 cubic meters of grout. Accessible portions of the west upstream cave would likely be closer to 400 cubic meters for comparison. However, it is unknown what other chambers deeper into the hillside or deeper into the foundation might be connected by smaller passageways that the team was not willing to enter, and grouting was not completed in the west abutment cave for comparison since it did not pose a threat to the dam.

The presence of the cave, as well as evidence of surface depression features at various location in the area of the dam however, led to the conclusion that large voids could be present beneath the dam due to potential flaws and interruptions in the grouting program.

While the presence of large voids was confirmed on the downstream side of the dam, no voids of this size were found underneath the center of the dam along the grout curtain treatment area during 2016-2019 drilling and grouting nor under the core of the dam. This finding supports the choice of the original designers to include the grouting gallery under the embankment as 30 years of maintenance grouting prevented the coalescing of large voids directly underneath the gallery along the centerline of the dam.

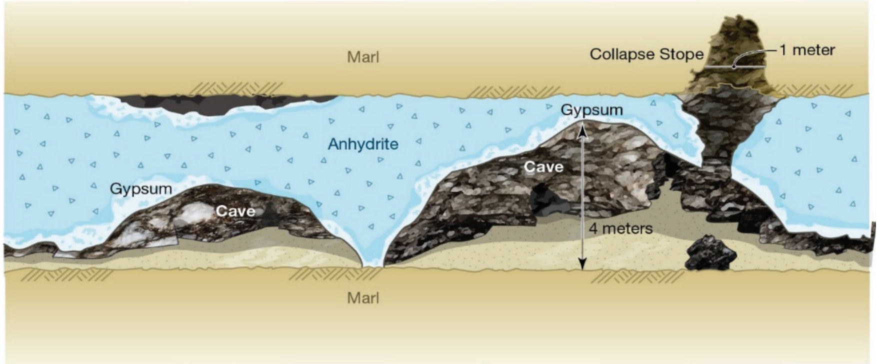

Figure 4 : Conceptual drawing of cave network and collapsing roof.

In 2016, the Government of Iraq (GoI) contracted with Italian firm, Trevi to repair the bottom outlet indicator rod and to bring state-of-the-art grouting equipment, supplies and additional labor to provide emergency grouting repairs to the project. The US Army Corps of Engineers (USACE) was requested by the MoWR to be the Engineer of Record and oversee the contract. The Engineer and the Iraqi Ministry of Water Resources aggressively worked with Trevi to complete as much work as possible to provide a robust foundation grout curtain, repair of the west bottom outlet and repair and maintenance of virtually all features of the dam to restore full operation capabilities and provide state of the art equipment, significant stockpiles of high quality supplies, materials and replacement parts and to provide a highly skilled work force and engineering team fully capable of leading Mosul Dam, the Ministry of Water Resources, the Tigris River basin and the country of Iraq into the future.

3. EMERGENCY DRILLING AND GROUTING AND OUTLET WORKS REPAIR

The three years of emergency efforts onsite resulted in a stabilized foundation, trained labor force using state of the art techniques, improved monitoring program, repaired and fully operational outlet works, as well as an increased understanding of the foundation conditions across the project. The result also included an understanding by USACE that although the foundation conditions are complex and problematic, the Mosul Dam should no longer be referred to as the "Most Dangerous Dam in the World."

As active operation, rehabilitation, drilling and grouting, subsurface exploration, and monitoring of the dam was ongoing, the USACE worked to better characterize and understand the project design, condition, and associated risk that led to their conclusions. An improved understanding of the quality of the original design and construction, foundation conditions, and effectiveness of the emergency grouting efforts led to a better evaluation of risk at the dam.

3.1 Original Design and Construction.

At the start of USACE involvement, there was minimal information available concerning the project construction details and foundation conditions. Original construction exploration records, maps and drawings were later identified, but many of these were not available before the first row of grouting or first phase of subsurface investigations were completed. As time on the project progress, information was provided and reviewed in detail. Documentation of foundation treatment was key in changing the risk assessments. Previous assessments assumed that no treatment had been performed, or that it was completely ineffective. Detailed review of documents obtained from MOWR during the emergency grouting, led to the conclusion that the dam was exceptionally well designed to deal with its problematic geologic foundation. Features such as appropriate materials selection, embankment size, embankment zoning, filters, extensive foundation treatment and an aggressive initial grouting program were all included. Detailed maps and analyses were generated and compared with drilling and grouting results. This work revealed that the foundation rock under the core was completely exposed during original construction and extensive treatment including dental concrete, slush grouting, blanket grouting, and the initial grout curtain was performed. The original designers were located and they were able to confirm design and construction features. This additional information was a key factor that influenced the latest risk assessment of the dam.

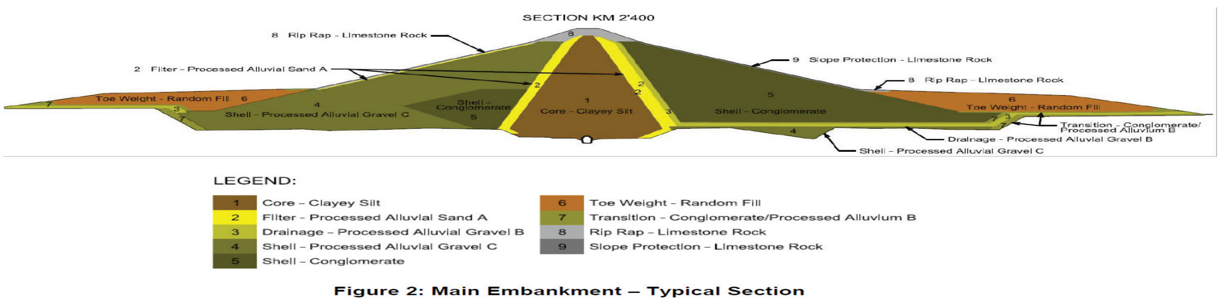

Figure 5 : General Cross-Section of the Dam

3.2 Foundations Conditions Along the Grouting Gallery

Early in the project, there was an understanding that there was a higher risk of seepage and piping potential through the foundation where undissolved gypsum was at or near the base of the embankment or where there was significant brecciation of the gypsum. The primary areas and geologic units of concern near and/or in contact with the embankment along the centerline of the dam at the grouting gallery are identified as GB1, GB2 and GB3, at the locations shown in Figure 4.

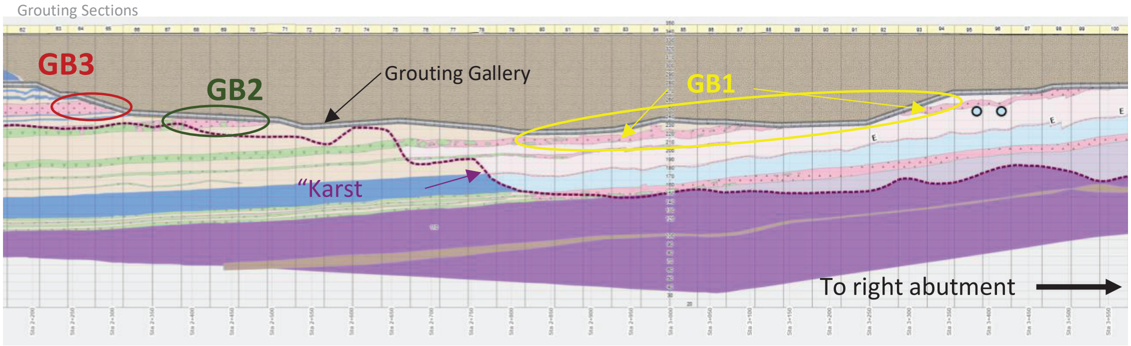

Figure 6 : Generalized geologic profile along the axis of the dam showing the locations where gypsum (GB) was near the embankment contact (after Morel, 1982)

The original designers tried to capture the difficulty of explaining the heterogeneous conditions of these GB layers by drawing a "karst line" that was a 2D dividing line between what was judged to be the more intact, vs. altered/more brecciated gypsum layers. This line was a delineation based on the drilling and grouting at the time and was a record of where higher and lower grout takes could be expected. At the time of construction of the dam, higher grout takes were above this "karst line" and lower grout takes were below this line. This distinction was also represented by the coloration of the GB layers (as shown in Figure 6). Where they are green, they were considered more intact. Where they are pink there was more developed brecciation. Thus, near the contact with the grouting gallery and embankment the GB layers were shown to have areas of intact gypsum/anhydrite within an overall brecciated and altered layer.

Exploration as well as drilling and grouting during the three-year emergency drilling and grouting program confirmed the designer's interpretation and provided a much better appreciation for the foundation material properties, historic grouting efforts, and nature of void spaces. One key tool for evaluation the foundation conditions was the Optical Televiewer used in both cored and destructively drilled holes. This provided a 360-degree view of the in-situ material that was otherwise unavailable. An example image from the OPTV of a borehole before and after grouting is shown in Figure 7. (Reference Hlepas and Bateman 2018).

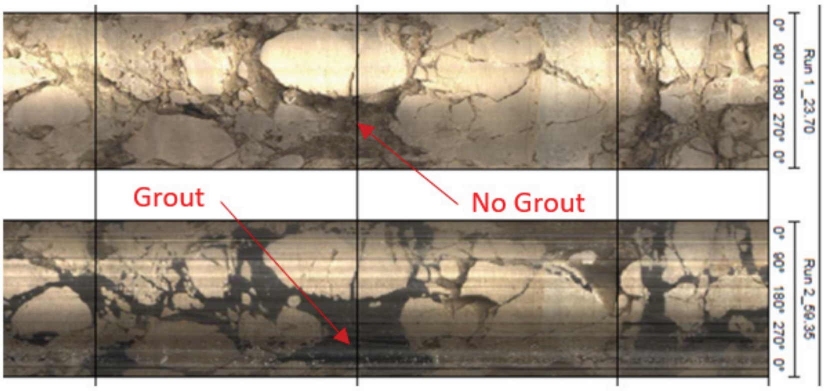

Figure 7 : OPTV Images of a 2 m length zone before grouting (top) and after grouting (bottom).

Detailed records of the maintenance grouting program since the end of original construction were not available, however, general information of large grout take areas, and the total amount of grout placed in a gallery section for specific years were provided. The MoWR used a grouting technique where pressure was only applied at the top of the grout hole and packers were not used.

Over the course of the USACE's involvement, it was discovered that there were numerous locations that had large rod drops during drilling. Initially, it was thought that these were substantial solution feature voids. However, most of the rod drop locations were determined to be unassociated with solution features but were instead old boreholes that were only partially grouted. Previous grouting efforts only applied pressure from the top of the borehole was unable to move grout into lower portions of the many of the boreholes in several sections of the grouting gallery.

Repeated historic episodes of grouting have interrupted the karst network development. However, the emergency grouting program showed that the ground was still accepting grout, despite the amount that had been put in from previous programs. Modern understanding of karst development in gypsum supports the hypothesis that this karst development will continue until the gypsum/anhydrite is completely solutioned or removed.

The recent grouting program revealed that the originally defined "karst line" has changed since original construction. The dissolution front was defined by the 2016-2019 exploratory and grouting efforts as being located further west that from the original analysis. This indicates that there is ongoing solutioning in the foundation which increases the permeability of the foundation over time. The contact between the gypsum/anhydrite units and the adjacent limestone units were also identified as having high permeability and void spaces, supporting the understanding that solutioning is ongoing. High grout takes in the brecciated limestone layers after 30 years of grouting also support this conclusion. High gradients across the grout curtain contribute to this dynamic situation resulting in ever changing foundation conditions and a continued need for grouting until all the vulnerable layers are replaced or until a foundation structural cutoff wall is constructed.

Core borings and optical televiewer logs from recent investigation and instrumentation programs were compared with historic boring logs made available after drilling and grouting was well underway. This comparison indicated that some rock layers, particularly the marl and highly altered GB layers near the grouting gallery and the bottom outlet tunnels on the western portion of the dam were significantly softer than what was originally logged. As opposed to a hard marl material, it was greatly decomposed with very low shear strength similar to a soft clay.

In addition, there were areas identified in the original grouting program with substantial grout takes. The emergency grouting efforts yielded significant grout takes in these same areas. Cavity and anomaly maps generated from original construction boring logs and from the recent emergency grouting program revealed variable sized openings in the foundation that have been treated by the drilling and grouting operations and filled with grout. All these voids identified during drilling were subsequently filled with grout.

The results of the verification program after the three year of grouting effort and over 5,000 grout holes yielded a foundation along the length of the dam with low permeability and satisfactory performance (as measured by water pressure tests and upstream and downstream piezometers). The dam experienced a record low pool and a high pool near the original operating pool level while USACE was on site and the dam performed well under all loading conditions.

3.3 Foundations Conditions Downstream of the Grouting Gallery

Little information outside the dam alignment was available at the early stages of the emergency grouting program. Given the heterogeneous nature of the foundation layers, this resulted in significant uncertainties as to their condition both upstream and downstream of the centerline of the dam. Additionally, the extensive foundation treatment under the core footprint was not applied across the rest of the dam.

Between 2016 and 2019, an exploratory program was performed that revealed two areas of large voids downstream of identified high-risk areas. The first was located along the downstream left abutment contact near the toe of the toe weight (Figure 5 shows a typical cross-section), where an active surface depression feature was identified. The second was within the foot print of the toe weight and along the bottom outlet tunnels. Both these areas revealed voids up to 6m in height during drilling operations. Drilling and grouting efforts were concentrated in these areas to determine the extent of the void features and indicated a complex and hydraulically interconnected network of voids. These areas were extensively drilled and grouted. Grout takes in the left abutment area were in excess of 900 cubic meters of grout and near the bottom outlets in excess of 185 cubic meters. Although these areas were treated with grout, it is uncertain how far and how many more cavernous type voids may exist. Drilling under the upstream portion of the embankment was not permitted. Further, even after the significant amount of grout material placed within these voids, surficial settlement slowed, but continued. In addition, voids up to 0.5m were ubiquitous and instrumentation indicates that the downstream foundation is nearly instantaneously responsive to tail water fluctuations. This is indicative of a very permeable downstream foundation. However, the foundation treatment beneath the dam core, a satisfactorily performing grout curtain, a robust instrumentation system, and the downstream toe weight (consisting of a rock fill shell which can choke a void formation) all mitigate the potential for internal erosion.

3.4 Bottom Outlet Condition

The Bottom Outlet Works consists of a concrete intake structure located in the reservoir, a guard gate chamber located on the upstream side of the dam, and a concrete discharge structure located on the toe of the dam. These structures are connected by two steel lined concrete conduits creating two independent paths for water to pass through. The system included bulkheads, which were designed to be placed inside of the concrete intake structure in the reservoir using a barge and divers. This would allow the entire bottom outlet system to be drained such that repairs and inspections of the structural condition of the system could be performed.

In 2015, it was understood that one of the bottom outlets was damaged and unusable due to a broken gate position indicator rod. The bottom outlet system required unwatering in order to make necessary repairs. In addition, there were reports that the joints between the conduit sections may be leaking and require repairs.

However, at the start of USACE involvement, the condition of the upstream intake bulkheads was entirely unknown as they had not been used and been stored underwater, inside of the bottom outlet intake structure, since the original construction. The barge used to remove/install the bulkheads had also never been used for that purpose and its condition was unusable.

By the end of the emergency program, the indicator rod was completely replaced, and an improved design was implemented to reduce the potential for future inoperability. The bulkheads were inspected and restored to full operational condition. The outlet works tunnels were inspected and the leaking joints were sealed. The bottom outlets were ultimately brought into full operational condition. This improved the operational condition of the dam and removed the concern of limited discharge capacity.

4. CONCLUSIONS

During the time that the Engineer was on site, the record low lake level occurred, and a 15-year record high lake level was experienced. The spillway was operated for the first time in 15 years and twice in three spring seasons. In addition, the bottom outlets were both tested to full capacity. The dam performed satisfactorily to lake levels up 4.8m below full storage in the spring of 2019 while the USACE was on site.

USACE found that the design and construction of Mosul Dam was very specifically tailored to the challenges of the site and the likelihood that anhydrite/gypsum dissolution would occur under the dam. As part of the design and construction, features such as an extremely large embankment section with toe weights, blanket grouting, cutoff trench dental concrete treatment and extremely well thought out embankment zoning were very specifically implemented to limit the impact that any foundation rock problems that might develop would have on the dam itself. These original design and construction features, in combination with the extensive foundation treatment and other construction recently completed, contribute to the current stability of Mosul Dam.

As part of the work on Mosul Dam, in 2019, USACE published a Dam Safety Modification Study that included an updated risk assessment and an evaluation of alternatives to permanently address the foundation challenges at Mosul Dam. This study was conducted in general accordance with USACE Engineering Regulation (ER) 1110-2-1156, March 31, 2014. This study considered the risk associated with the dam and numerous potential alternatives to address the risk in detail. It was determined that a structural concrete cutoff wall would be the most appropriate and effective alternative to permanently address risk at Mosul Dam and maintain the benefits that the dam provides to the country.

As of the final evaluation of the dam performance in April 2019, the USACE determined that the dam was in full operational condition and the foundation was stabilized. However, because of its dynamic foundation condition, grouting provides a time-limited solution which must be continuously reinforced. Without implementation of a permanent solution such as a structural foundation seepage cutoff wall beneath the dam, effective continuous maintenance grouting will continue to be required throughout the life of the dam. The future stability of Mosul Dam is also dependent continued exploratory programs and dam safety monitoring by the Ministry of Water Resources. The Ministry has all the skills and state of the art tools necessary to be fully effective at both grouting and monitoring of the dam. Appropriate budgeting and effective procurement and management will also be critical to the future of Mosul Dam. Currently, the dam presents a much lower risk to the downstream community than it did in 2015 and the label of "the most dangerous dam in the world" is not applicable.

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