CASE HISTORY AND LESSONS LEARNED AUTOMATED INSTRUMENTATION SYSTEM MOSUL DAM, IRAQ (2015-2017)

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ABSTRACT

In 2015, there was an effort led by the Government of Iraq Ministry of Water Resources (GoI MoWR) and US Army Corps of Engineers to learn more about the current performance status of Mosul Dam. As part of this effort, AECOM was retained to design and remotely assist with installation of an early warning instrumentation system that would be targeted to key performance areas of the dam. The automated data acquisition system (ADAS) needed to be easy to install, work the first time, and communicate remotely using an advanced satellite network. In addition to requirements for specific geotechnical and structural instrumentation, the system was required to include remotely operated video cameras. The video cameras needed to be viewable over the satellite network and show key locations of the upstream and downstream dam embankment and spillway areas.

This paper will provide an overview and lessons learned from the design challenges, approach to fabrication, testing and installation of the ADAS and instrumentation equipment. The data management and presentation solutions that were developed for the project will also be described. The paper will discuss the initial early warning system (2015-2016) and cover the extended long-term performance monitoring ADAS that includes about 500 instruments to monitor the rehabilitation grouting program (2017-2019).

1. INTRODUCTION

In 2015, there was an effort led by the Government of Iraq (GoI) and the US Army Corps of Engineers (USACE) to learn more about the current performance status of Mosul Dam. As part of this effort, AECOM was retained to design and configure data acquisition equipment and remotely assist USACE and GoI MoWR personnel during initial system installation and commissioning.

2. PROJECT BACKGROUND

Mosul Dam is a zoned earth-fill embankment dam with a power house, bottom outlet, concrete-lined gated spillway, and fuse-plug secondary spillway. The dam was constructed in the 1980s on the Tigris River about 48 km northwest of Mosul, Iraq for irrigation, flood control, water supply, and hydropower (refer to Fig. 1, Mosul Dam Location Map). The dam is 113 meters (m) high and 3650 m long including its spillway. It contains graded filters in the upstream and downstream shells, with an inclined-chimney drain and a blanket drain.

Figure 1 : Mosul Dam location map.

The foundation and abutments of Mosul Dam are karst bedrock consisting of alternating layers of limestone, marl, and highly soluble gypsum and anhydrite. Several layers of the foundation bedrock are highly fractured and undergoing dissolution. Several sinkholes are visible downstream of the dam and on the left abutment. Concerns about the instability of the foundation and abutments have led to a long-term maintenance program of grouting that began soon after dam construction was completed. The grouting was performed from within a reinforced concrete grouting gallery constructed at the base of the central clay core of the dam, parallel to dam centerline. The grouting gallery is 2.3 m wide by 3.7 m high and is entered through access galleries from the downstream toe on the left and right abutments. The gallery is divided into 36 m-long grouting sections. These sections extend from the spillway on the left abutment, across the old river channel, and into the right abutment.

The longstanding maintenance grouting program was interrupted during the summer of 2014. In 2015 USACE contracted AECOM to design and fabricate an instrumentation automated data acquisition system (ADAS) to monitor the condition of the Mosul Dam foundation. Our Dam Safety Systems team designed the instrumentation data acquisition system and procured and fabricated the necessary data acquisition units, various types of telemetry equipment, and geotechnical and structural instrumentation. Once the equipment was configured and tested it was shipped to the dam site for installation by USACE and GoI MoWR personnel.

3. AUTOMATED DATA ACQUISITION SYSTEM (ADAS) OVERVIEW

The primary design principles for the Mosul Dam ADAS were that it needed to be easy to install, work the first time, and communicate remotely using an advanced commercially available satellite system. In addition to a specific requirement for geotechnical and structural instrumentation, the system was required to include remotely operated video cameras. The cameras needed to be viewable over the satellite network and show key locations of the upstream and downstream dam embankment and spillway areas. All equipment had to operate reliably in a harsh environment.

The ADAS design incorporated industry-standard data acquisition equipment that had been deployed successfully on several large ADAS projects for the USACE in the past. Principal system components included:

- Instrumentation network (piezometers, crackmeters, weirs, water quality sensors, deformation loops);
- Five IP-based video and still image cameras;
- Remote monitoring units (RMUs);
- Remote wireless input/output (RIO) units;
- Remote multiplexer (RMX) units;
- Local radio frequency (RF) network;
- Broadband global area network (BGAN) satellite terminals;
- Wide area network (WAN);
- Virtualized central network monitor (CNM);
- Web-based project portal; and
- Grounding and lightning protection systems

An ADAS instrumentation plan is shown below in Figure 2. It shows the locations of automated instruments as well as ADAS components, including cameras, RMUs, and RIOs. The automated piezometers, crackmeters, and weirs use vibrating-wire sensors. There are automated open-standpipe piezometers located on the downstream embankment, left abutment, grouting gallery, and spillway gallery. There are automated closed-system piezometers (uplift cells) located in the grouting gallery. The crackmeters are used to monitor displacement across construction joints in the grouting gallery. The water quality units (sondes) have various water quality sensors as well as strain gauge sensors to measure water levels. The sondes are used to monitor the pool and tailwater water quality and the seepage flow rates at weir locations. The deformation loops are used to monitor potential sinkhole formation at several locations in the downstream embankment.

Figure 2 : ADAS instrumentation plan.

A high-level diagram of the system architecture schematic is shown below in Figure 3. The BGAN provides communication links between the RMUs at the dam and the CNM, which is located offsite. The WAN consists of a BGAN satellite network and the terrestrial virtual private network (VPN). The RF network consists of radios that serve as routers and/or repeaters. The network provides wireless communication links at the dam between the dataloggers (RMUs) and those automated vibrating wire instruments that use a RIO interface. The RF network includes two repeaters for improved signal range and stability.

The RMUs are rugged enclosures that house dataloggers, multiplexers, and radios. There are five primary RMUs and one secondary RMU. The primary RMUs include radios for access to the RF network. In addition, each primary RMU is connected to a dedicated BGAN satellite terminal for access to the WAN. The BGAN units are IP-based. The RIO units consist of fiberglass enclosures with a Campbell Scientific, Inc. (CSI) AVW-206 wireless vibrating wire datalogger. They are used for instruments located too far from an RMU for a hard-wire connection. They provide a wireless communication link between remote instrument locations and the RMUs. The RMX units are housed in fiberglass enclosures with multiplexers that allow hard-wire connections of multiple piezometer and crackmeter sensors to the dataloggers. These units are only used in the grouting gallery.

The initial system included five surveillance cameras at the dam. They are IP-based cameras hard-wired to various RMUs via a power over ethernet (PoE) connection. The cameras provide views of the upstream embankment, dam crest, downstream embankment, left abutment, right abutment, and seepage outfalls. Camera images are transmitted via the BGAN network on an hourly basis.

The web servers and database servers were located at a commercial hosting center. This system included software to manage the dataloggers, store the data, configure the cameras and satellite terminals, generate trend plots, and monitor for rate-of-change alarms. All information was provided on the web-based project portal accessed by all project team members worldwide. Instrumentation readings were updated every 15 minutes. Routine cameras images were updated on an hourly basis.

The ADAS includes redundancy in major system components to minimize the likelihood of downtime. There are always multiple ways to route ADAS radio traffic around the project site. Since the design included dedicated BGAN satellite terminals at each RMU, there were five individual communication options for remote access.

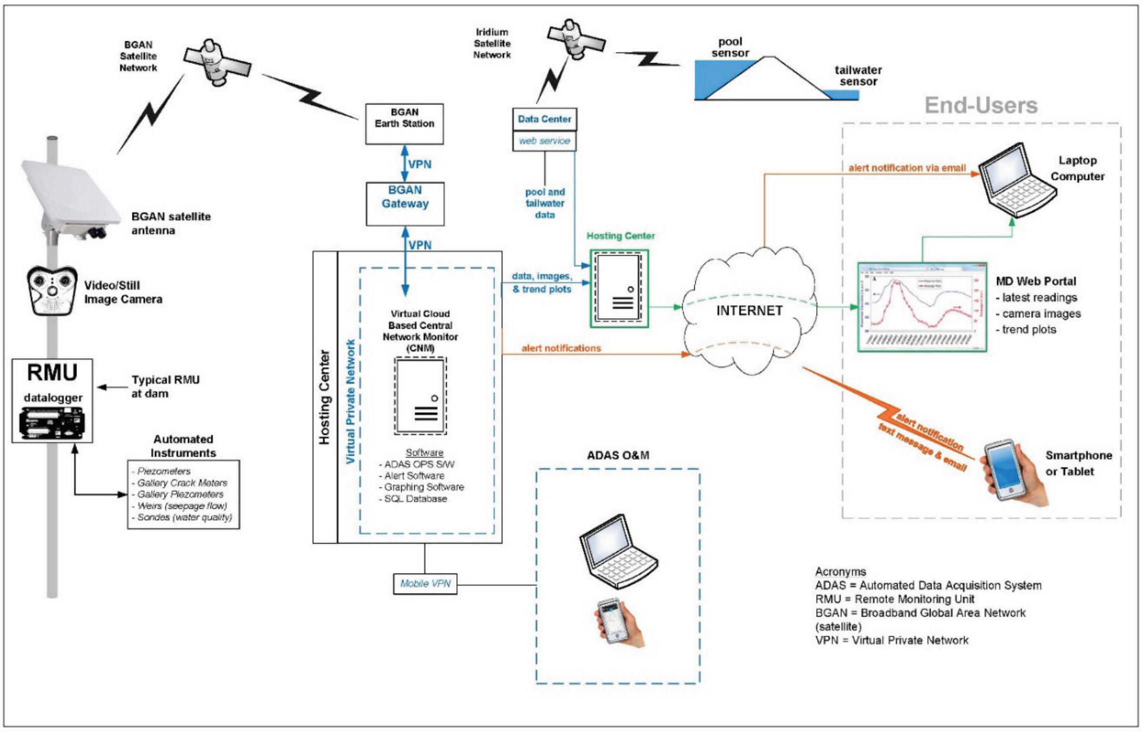

Figure 3 : Mosul Dam phase 1 system architecture diagram

As shown above on Figure 3 the ADAS dataloggers, CNM and web portal were programmed and configured to perform the following tasks automatically:

- Acquire instrument readings every 15 minutes and transmit them to the CNM;
- Update the instrumentation readings and short-term trend plots on the web portal every 15 minutes;
- Transmit a single image from each camera to the CNM at the top of each hour and update it on the web portal;
- Update the long-term trend plots on the web portal once per day; and
- Compare each top-of-the-hour instrument reading with the readings collected at 15, 30, 45, and 60 minutes after the hour. If the difference exceeded the rate-of-change threshold levels, the system would send alert notifications via text message and email to project team members.

The threshold levels for alert notifications were set for piezometers, crackmeters, and the deformation loops but not for the weirs. A two-tier, color-coded alert system was implemented. Threshold levels initially were set for a lower tier (yellow alert) and an upper tier (red alert) for rate-of-change levels. A yellow alert indicated that an instrument reading was out of normal range. In this case a text message was sent to an instrumentation support team for evaluation. Often the yellow alert level was explained and cleared. A red alert indicated that a critical limit had been exceeded. In this case the alert messages were sent to a larger group of stakeholders for further action.

4. GEOTECHNICAL, STRUCTURAL, AND ENVIRONMENTAL INSTRUMENTATION

The initial Phase 1 ADAS at Mosul Dam included the following instruments:

1. Twenty-eight (28) open-standpipe piezometers. These existing instruments were located on the downstream embankment, left abutment, and in the grouting and spillway (Fig. 2). They include open-standpipe piezometers that were automated using non-vented vibrating wire pressure transducers. These instruments are used to monitor changes in phreatic surface on the downstream side of the existing grout curtain.

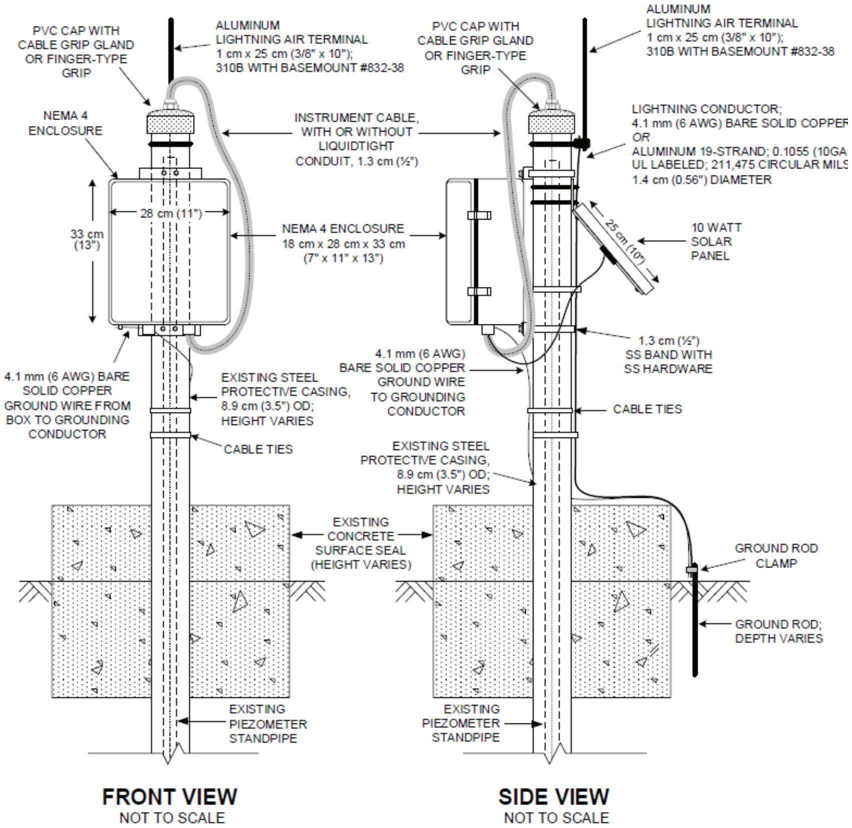

Figure 4 : Typical solar powered RIO.

2. Thirteen (13) closed-system piezometers (uplift cells). These existing instruments are in the grouting gallery. They are closed-standpipe piezometers with non-vented vibrating wire pressure transducers connected to the existing steel risers. The purpose of these instruments is to monitor uplift pressures in the dam foundation materials.

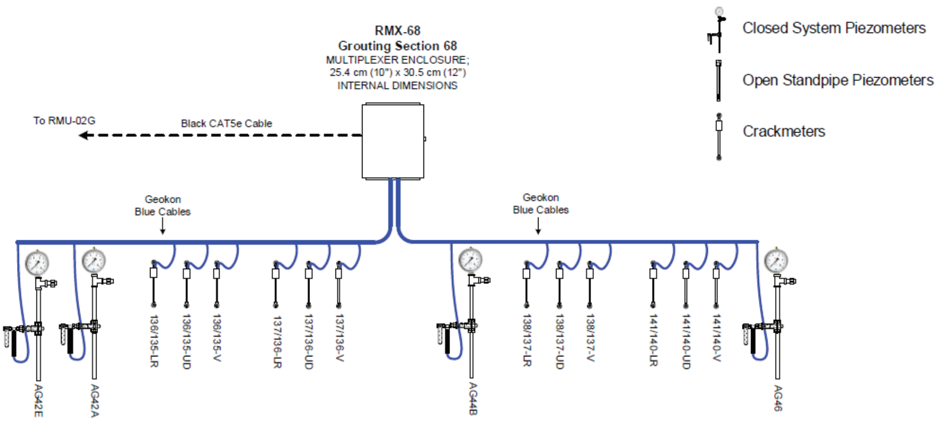

Figure 5 : Typical RMX in the grouting gallery (closed system piezometers and crackmeters)

3. Forty-seven (47) crackmeters. New vibrating wire crackmeters were installed across construction joints in the grouting gallery. Most were installed in groups of three for 3D monitoring of displacement across a joint. These instruments were installed to monitor potential deformation of the grouting gallery.

4. Four (4) Deformation loops. A set of four cables of varying lengths were extended across an area of the downstream embankment to monitor for potential sinkhole formation and/or embankment deformation. Installation details are shown below on Figure 6A. To detect a break in an individual loop, the leads are connected to the datalogger in conjunction with 1 kΩ and 100 kΩ resistors. If the loop is broken, the datalogger detects a very large voltage drop (~ 2475 mV) across the 100 kΩ resistor. A break in one or more cables could indicate surface deformation resulting from sinkhole collapse.

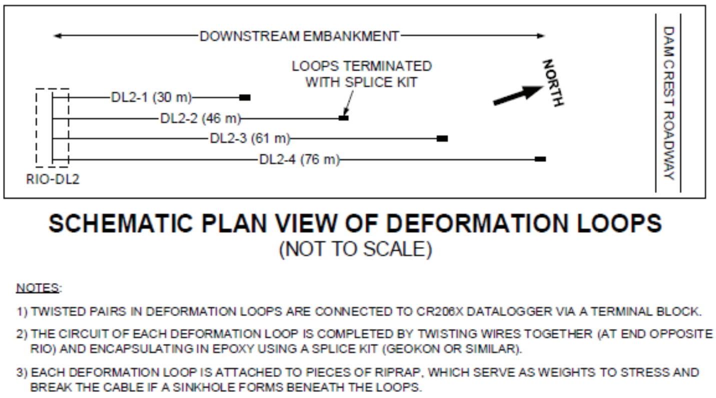

Figure 6A : Schematic plan deformation loops.

5. Three (3) weir sensors. There were three seepage collection channels with contracted rectangular weirs and outfalls located near the base of the auxiliary spillway on the left abutment. The weirs were automated using vented vibrating wire pressure transducers with a 0.17 bar (2.5 psi) range. The transducer at each location measures the total water depth in the canal upstream of the weir. These readings are used together with the height and length of the weir crest to calculate the seepage flow.
6. Three (3) seepage water quality sensors. The three seepage outfalls equipped with automated weirs also have sonde units that measure the seepage water quality. The sondes are In-Situ TROLL 9500 units installed in stilling wells. The sondes are configured to measure temperature, barometric pressure, conductivity, pH, turbidity, dissolved oxygen, water pressure, and battery voltage.
7. Pool and tailwater water quality and level sensors. The pool and tailwater sondes are connected to an Iridium satellite telemetry system that transmits data to a remote data center. These initial pool and tailwater sensors were installed by USACE.
8. IP-based video cameras: A total of five cameras were installed to monitor the dam. Cameras are co-located with RMUs and BGAN satellite terminals to facilitate image transmission to the project web portal. The cameras provide views of the upstream embankment, dam crest, downstream embankment, left abutment, right abutment, and two of the seepage channels. Camera images are acquired hourly and transmitted to the web portal for display.

5. PROJECT WEB PORTAL

The Mosul Dam project web portal provided a secure means for remote viewing of instrumentation data, camera images, and trend plots from any location worldwide with internet access. The website was maintained by AECOM at a data hosting center with industry-standard cybersecurity, backup power, and redundant internet connections.

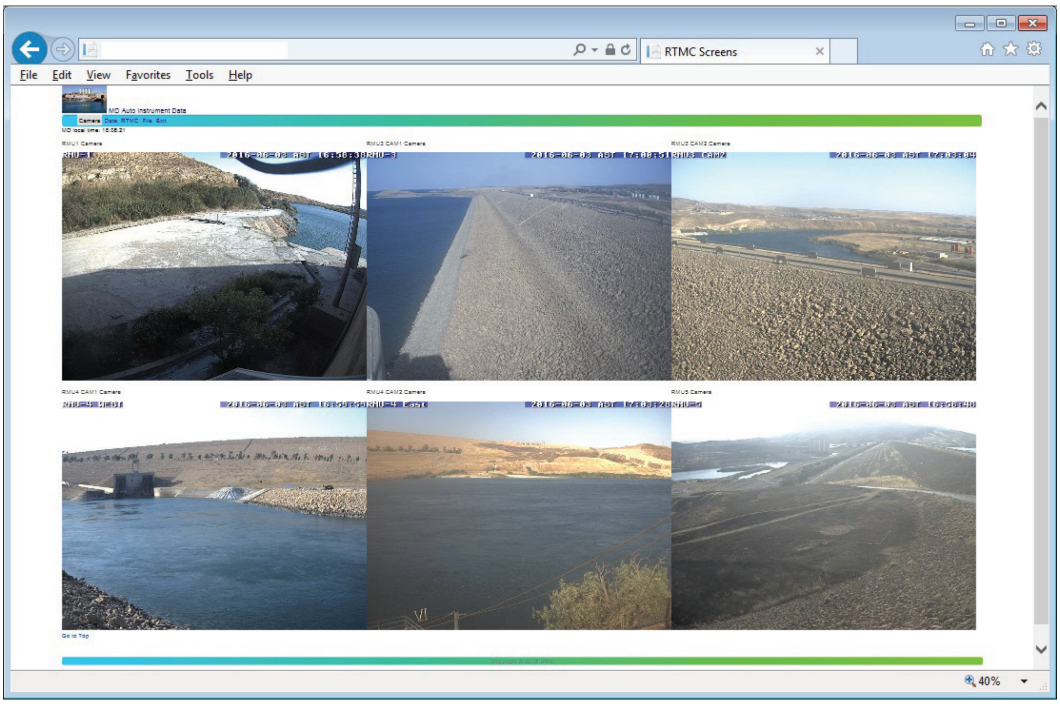

Figure 7 : Images from the six IP-based cameras installed at the dam.

Another feature of the web portal was the interface with Google Earth that was used to show current instrument levels and threshold values for licensed users. These online images were updated every 15 minutes.

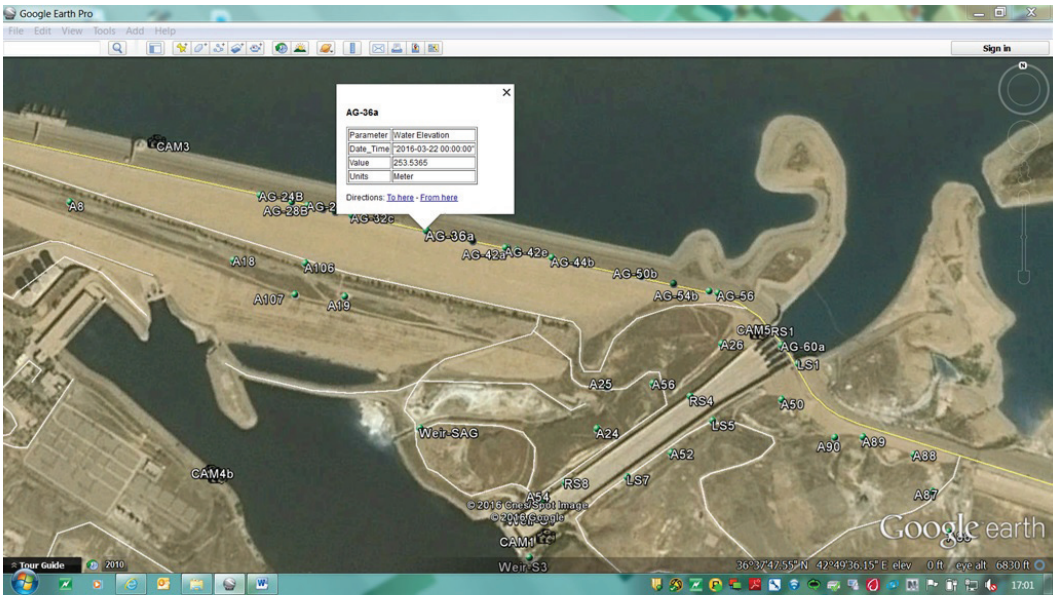

Figure 7 : Google Earth instrumentation map, Mosul Dam web portal.

6. AUTOMATED DATA ACQUISITION SYSTEM OPERATION AND DATA FLOW

Operation of the ADAS was predominantly automated using datalogger control programs, custom configuration of system software, and custom-developed programs on the web server and database server. The frequency for acquiring instrumentation readings and camera images was controlled by the RMU dataloggers.

Once an RMU datalogger acquired a new set of raw instrument readings, it immediately reduced the values to engineering units and stored both the raw and calculated values in a data table along with related parameters such as the barometric pressure and datalogger battery voltage. The data was saved in the LoggerNet database (LNDB).

Table 1 : Threshold levels for piezometers, crackmeters, and deformation loops

Instrument Type	Yellow Alert Threshold Level/Hour	Red Alert Threshold Level/Hour
Piezometer	1.5 m	3.0 m
Crackmeter	0.5 mm	1.0 mm
Deformation Loop	1.0 V	1.5 V

Alert notifications were sent automatically to all project team members using text messages and email.

7. CONCLUSIONS AND LESSONS LEARNED

Based upon our experiences while working on the Mosul Dam ADAS project, we offer the following conclusions and lessons learned for your consideration:

(1) The Mosul Dam ADAS provided reliable service from a remote site in harsh conditions using commercially available data acquisition equipment and instrumentation.

(2) All RMUs and RIOs were fabricated, programmed, and tested before being packed for shipping and field installation. The radio networks and BGAN terminals were also tested before shipping to the dam. This approach reduced the amount of time spent in the field during installation.

(3) The lithium iron phosphate batteries that were used for each of the RMUs performed very well. These batteries were 100Ahr capacity and weighed around 14 kg (conventional batteries weigh about 34 kg) which facilitated the installation since all equipment had to be hand-carried.

(4) This was the first time a remote CNM was virtualized, using cloud-based servers instead of being installed onsite. This approach worked very well and will likely be considered for projects we design in the future.

(5) The dual wireless networks were very helpful and kept the data flowing uninterrupted even when a satellite terminal or radio went offline. The ability to reroute RMU traffic over the radio networks was very helpful.

(6) The design of appropriate lightning protection systems and grounding systems resulted in a reliable ADAS. Even though there were several storms during the first 12 months of operation there was no loss of instrumentation or communication equipment.

(7) A key benefit of an ADAS is the ability to detect instrument reading trends or changes very quickly if deformation is occurring.

CURRENT STATUS OF THE MOSUL DAM ADAS

Since the original system was installed in 2015 there have been two expansions oif the ADAS at Mosul Dam. We were involved with the 2017 Phase 2 system expansion that increased the number of automated instruments from 97 to about 360. The system is currently being expanded by the GoI MoWR to include over 520 instruments.

ACKNOWLEDGEMENTS

We would like to acknowledge and thank the project teams with GoI MoWR and USACE that worked closely together to make sure the initial system performed as intended.