AEG/USSD Workshop
December 6-8, 2021
Ft. Lauderdale, Florida

Emergency Repairs to Mosul Dam
A High Risk Dam on a Karst Foundation
2014 BATTLE FOR WATER RESOURCES OF IRAQ

MOSUL DAM
August 2014

DEVELOPING STORY
ISIS SEIZES IRAQ'S LARGEST DAM
Mosul dam is upstream from Tikrit, Baghdad
ISIS control of Tigris and Euphrates River
Tabqa dam, Syria Since February 2013

This is the ISIS held main hydroelectric plant, main flood control gates and spillway and dam control room. It's been inoperable since last week. NO SDF/ISOF personnel have ever been here to inspect anything. Syrian Government Dam engineers reportedly killed by U.S. airstrike Sunday. Central room on either side of dam destroyed by obvious U.S. airstrike. Condition is serious. NOBODY is operating this facility and ISIS still holds. SDF/ISOF guessing that everything is OK.

Oil spill
Water as a Weapon
Military, financial, infrastructure, irrigation, food supply, drinking water, public health
Dam Safety Risk
Communication Behind ISIS Lines
The Phone Call

• Within hours, requests for support came to USACE.
  • Department of State.
  • CJTF.
Airstrikes Support Kurdish Ground Forces

three days, U.S. forces have conducted 35 airstrikes against Islamic State of Iraq and Syria (ISIS or ISIL) terrorists around the Mosul Dam complex.

“In all, we destroyed over 90 targets including a range of vehicles, equipment, and fighting positions,” said Pentagon press secretary Rear Adm. John Kirby in statement. “Iraqi forces have cleared the dam and are working to further expand their area of control.”
Kurdish Forces Take Back Mosul Dam
SECURITY

- KRG Peshmerga
- Syria
- Italian Security Force
- KRG Referendum
- Iraqi Forces Replace Peshmerga
- US Replace Italian Army
Largest dam in Iraq, 4th largest in Middle East
~18 km upstream of Mosul City
Storage Capacity – 11.1 Billion cubic meters
40% of Iraq’s water supply
Inflow from Turkey and Iran
Largely snow melt reservoir
Hydropower Plant rated at 750 MW
4 million population at risk
Name: Mosul Dam
River: Tigris River
Height: 113 m (371 ft)
Length: 3.4 km (2.1 mi)
Capacity: 11,100,000 m³
(9,000,000 acre-ft)
Year Complete: 1984
Age: 33 Years
Owner: Iraq Ministry of Water
TYPICAL SECTION

EMBANKMENT LEGEND

1. CLAY CORE: Clayey Sand and Sandy Clay soils derived from Terrace Deposits and River Channel Alluvium. Unknown compacted density, psi. 150 psi. LL=55. PL=25. MC=35%.
2. FILTER (Zone A and B): Zone A - Fine Filter. Sand and Fine Gravel from 0 to 3 cm. Zone B - Coarse Filter. Sand to Medium Gravel. Overall filter media D50=1.4 mm, depth = 1 meter. Processed Gravel.
3. DRAINAGE: Gravel, Medium to Coarse grained, D50=7.5-25 mm, D95=25-100 mm. Processed Gravel.
4. SHELL MATERIAL: Sand, Gravel, and Cobble. Produced from processed Alluvium. Fine Sand and Silt removed using static Air-Flotation Plant in 24 cm sized bins with 4 passes from niter. Only 2.5% of material had size smaller than 0.63 mm.
5. SHELL MATERIAL Produced from processed Gravel and Cobble. Borrow area often required blending. Material judged to be coarse grained and free-flowing.
6. TOE WEIGHT: Presumably constructed using Matt and Alluvium Combination, lift thickness and composition unknown.
8. RIP RAP: Limestone produced from JR 1 Limestone quarry. Blocks up to 1500 kg.
9. SLOPE PROTECTION: Limestone produced from JR 1 Limestone quarry. Blocks ranging from 5 to 60 kg.

FOUNDATION LEGEND

- SANDY SILT: PRESUMABLY LOOSE OR SOFT TO FIRM RECENT ALLUVIUM.
- SANDY GRAVEL: CONGLOMERATE WEAKLY CEMENTED.

LOWER MARL SERIES: CHAINAGE 2+400 MARKS THE TRANSITION BETWEEN THE VALLEY SECTION AND THE LEFT ABUTMENT. AT THIS LOCATION, THE LOWER MARL SERIES CONSISTS OF MARLS AND BS BEGINS 552 AND 603. BS IS NEAR THE BASE OF THE GROUTING GALLERY FROM 2+380 TO 2+400. THE FOUNDATION HERE IS CHARACTERIZED AS VERY DISTURBED, WEATHERED, DISCOLORED, AND FREQUENTLY INTERLITRED BY SUB-VERTICAL SNICKLES FILLED WITH BRECCIATED MARLS OR CONCRETE. ALLUMINUM FROM ABOVE THE ROCK IN HIGHLY FRACURED AND HIGHLY KANKED. OVERLAIN BY PLAIN MARL. MARL IS PARTLY OR COMPLETELY DISCOLORED WITH NUMEROUS COLLAPSE FEATURES. MANY POCKETS OF GRavel CONGLOMERATE WERE FOUND IN THE TOP FEW METERS. MARLS EXPOSED IN THE VALLEY SECTION.

NOTES:
1. THE FOUNDATION GEOLOGY SHOWN UNDER THE Core OF THE DAM IS TAKEN FROM THE PROFILE (DRAWING NO. 30/G2#-008).

Job No. 1
Prepared By: dg
Date: 9-30-2016

MOSUL DAM
CHAINAGE 2+400
CROSS SECTION
POOL RESTRICTION OF 11 METERS SINCE 2006
National Impacts
$25 million Contract for training and equipment executed by Gannett Fleming

Equipment is still onsite

Entire system never used

Required:
- Consistent high quality materials logistics chain
- Trained personnel
- New drill rigs
- 100 people/12 drill rigs
MOSUL DAM TASK FORCE

- Letter of Agreement (LOA) between US and GoI
- USACE Serves GoI as Engineer for Contract
- Cost Reimbursement Contract - $300 million Iraq Funded
- 70 people – Military, USACE, and AECOM

Unprecedented Project for US Government
Critical Infrastructure in Conflict

- Emergency response is challenging; add armed conflict.
- Infrastructure devastated.
- Borders, air, ground movements complicated/often impossible.
- Thousands displaced from homes, population resettlement.
Partnership

3 Governments

2 USG Departments

Security

Planning, Engineering & Construction Management
International team

USACE MDTF/Trevi: 16 Nations
Critical infrastructure in conflict

- USACE Requested by Iraqi Government to oversee grouting contract.

- Iraq paid for contract; US paid for oversight; Italy paid for security.

- Contract was required to resume grouting; Trevi.
- Contract required to support USACE oversight; AECOM.

- Incredible coalition formed under difficult circumstances.

- ISIS to Solicitation 12 Months.
- Solicitation to Award 9 Months, including 2 major alterations.
- Mobilization started within a month.

- Talent acquisition and retention.
MOSUL DAM TASK FORCE (MDTF)

• USACE Engineer of Record and Oversee Contract with Trevi for Emergency Drilling and Grouting and Outlet Works Rehab

MDTF consists of USACE, AECOM, and Versar
TREVI CONTRACT SCOPE

Grouting Infrastructure Upgrades

Drilling and Grouting 24/6

Bulkhead Repair

Guard gate – Elec/Mech Repair

HPUs

Refurbish 5 Cranes
EMERGENCY GATE REPAIR – BOTTOM OUTLETS

MOSUL DAM
BOTTOM OUTLETS
GUARD GATE REPAIR
• Right BO open for first time since 2013
BOTTOM OUTLETS

Diving Barge & Bulkheads
BOTTOM OUTLETS

Bottom Outlets Inspection
February and June 2017
BATHYMETRY AND LASER SCANNING
PLUNGE POOL HYDRAULICS MODELING

Velocity ~5 m/s from surging (Note: model has not completed)

Downstream end of concrete apron
Surge of flow up the rollercrete face

Max. Stream power ~20 kW/m² on concrete apron

Max. Stream power ~100-120 kW/m² on rollercrete.
The location of high stream power moves with surging

High stream power in area of erosion of rollercrete (repaired Mar. 2016)

Outlet Gates

Dentates
DAM SAFETY RISK

MOSUL DAM
2016 USACE PFMA/SQRA

24 potential failure modes were identified by the Risk Assessment Team

- **PFM N1** – Internal Erosion through the Shallow Main Valley Rock Foundation
- **PFM N2/3** – Internal Erosion through a Deep Flaw in the Main Valley Foundation
- **PFM N4** – Internal Erosion through the Right Abutment Rock Foundation
- **PFM N5A** – Internal Erosion (Stoping) through the Left Abutment Rock Foundation
- **PFM N5B** – Internal Erosion (Scour) through the Left Abutment Rock Foundation F-Bed
- **PFM N10** – Internal Erosion through Rock Defects in the Vicinity of the Bottom Outlet Conduit
Downstream Consequences

Consequences associated with dam failure based on restricted pool elevation 319 m

Population at Risk
3,850,000

Potential Life Loss
400,000+

Economic Consequences
$15 - $20 billion

Wave Arrival: 3 to 4 hours
Wave Height: 12 to 15.5 meters

Wave Arrival: 6 to 10 hours
Wave Height: 9 to 18 meters

Wave Arrival: 56 to 70 hours
Wave Height: 3 to 6 meters
Internal Erosion along the Bottom Outlet Conduits

Load Occurs (reservoir elevation 319 m)

Interconnected system of open features from vicinity of centerline to the outlet works plunge pool

Flaws expose embankment to erosion or collapse

Material from embankment or foundation moves through voids by collapse or contact erosion starting a stope

Open stope to embankment surface below reservoir

Continued material transport lower crest below reservoir

Intervention unsuccessful

Breach occurs

No PZ elevation data available

No
Highest Risk Dam in the World? Comparison to USACE Portfolio

Loss of life and economic risks posed by Mosul Dam are extreme.

Even a dam incident could be catastrophic.

Grouting, although critical, does not bring risk to tolerable levels.
GENERAL GEOLOGY AT MOSUL DAM

• Multiple layers of soluble carbonate and sulfate (gypsum and anhydrite) rocks are interbedded in the foundation.

• Varying degrees of dissolution have resulted in a wide range of karst conditions in the foundation.

• Potentially significant voids may have formed in the foundation.

• Some karstic rock units extend to and daylight in the tailrace.

• The foundation has been grouted continuously from the grouting gallery beneath the main embankment since construction to mitigate continuing dissolution of the carbonate and sulfate rocks.
FOUNDATION GEOLOGY

- Pleistocene conglomerate
- F-Bed Limestone
- Lower Fars Group (Lower Marl Series)
  - Foundation is Mostly Marl (calcareous claystone)
  - Multiple thin limestone layers
  - Gypsum Breccias – WIDE range of properties. Four thick units in the Lower Fars Group originally composed of gypsum/anhydrite that either remains intact or has partially or completely solutioned out designated GB-3, GB-2, GB-1, and GB-0
  - Multiple thinner unnamed gypsum layers

Each of the GB layers are separated by marl and limestone
As anhydrite is exposed to water it turns to gypsum and dissolves, leaving voids, cavities and beds of collapse breccia.
GEOLOGISTS FOR SCALE
Foundation behavior controlled by gypsum dissolution and karstic limestone
GEOLOGY
One Dam, Two Foundations

Foundation behavior controlled by gypsum dissolution and karstic limestone

Foundation behavior controlled by chalky limestone
POTENTIAL DISTRESS FEATURES

• 71+ Potential Distress Features were identified by various means at Mosul Dam

- Aerial/Satellite Imagery
- Site Assessment and Drilling
- Observation and Anecdotal Reporting
- Bathymetry
INTERFEROMETRIC SYNTHETIC APERTURE RADAR MONITORING
INTERFEROMETRIC SYNTHETIC APERTURE RADAR MONITORING

Three Years of Ground Truth
GYPSUM DISSOLUTION FRONT
MOSUL DAM

NEW INSTRUMENTATION
**NEW INSTRUMENTATION**

- New Core Holes: 75
  - Core Holes in Gallery: 43
  - Core Holes on Surface: 32

- New Piezometers: 325
- Existing Piezometers to be Automated: 80
- New Inclinometers: 3
- New Crack meters: 45
- Weather Station: 1
- Accelerographs: 2
- Pendulums: 3
- Lake and River level sensors and Regulating Dam pool sensors
  - Lake levels displayed in powerhouse as well.
GALLERY PIEOMETERS - East Side

Mosul Dam Exploratory Holes and Instrumentation

Plate 2d - Profile Geology and Proposed Boreholes and Instrumentation

Proposed Borings and Piezometer Installations

Legend
Piezometers
Automation of Existing PZ
- Automated
- Manual
- Proposed Phase 2 EWS Automation
- Abandoned
Proposed for Installation
- Borehole GS
- US Proposed Borings

Distress Indicators
- Crack
- Great Emergence
- Monolith Movement
- Overtake Separation
- Structure
- Wall Separation
- Active Depression
- Espandrite
- Collapse + Historical, Non-Active
- Great Emergence
- Landslide
- Minor Deformation
- Potentiel Wedge
- Sinkhole, Post-construction
- No Action
- Soil Cracks
- Spring
- Steepened Slope
- Water Supply

Geotechnical Materials

1985 Condition

Note: Upstream piezometers will not be automated with the exception of the new installation, existing upstream piezometers are not labeled on this drawing.
MOSUL DAM

HISTORICAL GROUTING
MoWR HISTORICAL GROUTING

- Continuous Grouting for over 30 years
  - Need for continuous grouting established during original design.

- MoWR allowed access to Mosul Dam Library in January 2017.

- MoWR provided historical grouting information in June 2017.

- MoWR Nipple grouting since 1990
  - Flow rate – 50 l/m.

- Piezometer readings.

- Original Equipment from Original Construction.
HISTORICAL GROUT LINES

- Right Bank Extension (4+045 to 4+453)
- Main Dam (1+738 to 4+045)
- Boat Launching (Sections 1 to 17)
- Left Side of Spillway (Sections 1 to 17)
- Left Bank/Saddle Dam (0+532 to 1+738)
- Outside U/S Curtain (0+550 to 1+630)
- Left Bank Extension (1+505 to 0+531)
GEOLOGY

One Dam, Two Foundations

Foundation behavior controlled by gypsum dissolution and karstic limestone

Foundation behavior controlled by chalky limestone
Historical Grouting INSTANCES

Number of Grouting Per Section From (2000 to 2016)

- X-axis: Section No.
- Y-axis: Number of Grouting

The bar chart shows the distribution of grouting instances per section from 2000 to 2016.
Historical takes - total over time

- From 1991 to 2016, 860 Km of grouting length were completed.
- A total of 81,500 Tons of solids (includes sanded grout) injected.
- Generally, in upper 20 meters, takes have decreased with each grouting event.

**Notes:**
1. Data from Sections 45-111
2. Dry Materials include Cement, Bentonite, and Sand.
EMERGENCY GROUTING

MOSUL DAM
GROUTING GALLERY INFRASTRUCTURE

- **Removed**
  - 3,000 m electrical cable
  - 2,000 m grout lines
  - 2,000 m water lines

- **Relocated**
  - 2,000 m dewatering lines

- **Installed**
  - 170,000 m electrical cable
  - 15,000 m grout lines
  - 3,500 m water lines
  - 3,000 m fiber optic lines
  - 2,000 m dewatering pipeline
  - Dewatering pumps
GROUTING GALLERY

- New fiber optic system for computerized grout monitoring system.
- New power distribution system.
- New piping system for grout, water, bentonite and cement slurries.
- Robust/redundant communication system.
- New delivery system for sanded grout and gravel mixes.
- Complex sequencing of the work.
Drilling started in 16 Oct 16. The first liter of grout was injected on 22 Nov 16.

Production grouting was “declared” started on 10 Jan 17.

T-Grout software monitors and controls all grout delivery equipment with instantaneous feedback.
T - GROUT CONTROL ROOM
MAIN MIXING PLANT 1
LEFT ABUTMENT
## GROUT MIXES

<table>
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<tr>
<th></th>
<th>MIX A</th>
<th></th>
<th>MIX B</th>
<th></th>
<th>MIX C</th>
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<td>Mix B04</td>
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<td>MIX C01</td>
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<tr>
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<td>lit</td>
<td>kg/m³</td>
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<td>1000</td>
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<td>900</td>
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<td>270</td>
<td>500</td>
<td>161</td>
</tr>
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<td>27.0</td>
<td>30</td>
<td>13.0</td>
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<td>2.5</td>
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<td>1111</td>
<td>1.199</td>
<td>1533</td>
<td>1176</td>
</tr>
<tr>
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<td></td>
<td>3.0%</td>
<td></td>
<td>1.0%</td>
</tr>
<tr>
<td><strong>C/W</strong></td>
<td>30.0%</td>
<td></td>
<td>50.0%</td>
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<td>100.0%</td>
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</table>
GROUTING CRITERIA

➢ Utilizing existing grout holes
➢ Pressure grouting by stages
➢ Grouting pressures as high as two and half times historical pressures
➢ Initial boring depths were adjusted based on geology and historic grouting depths
➢ Refusal pressures based on USBR “rule of thumb”
➢ Stage refusal: Achieve the effective refusal pressure and flow rate less than 1 l/min and maintained for 2 minutes.

Grouting Flow Chart, for each stage

- R: Refusal pressure – Stage Completed
- X% R: Rate of Refusal (target) pressure
- P: Measured pressure
- Pa: Target pressure in the stage immediately above (upstage method only)
- VN: limitless Volume

NB: V is the cumulative Volume in each Step
V1 = example = 0.1 m³/m
V2 = example = 0.2 m³/m (0.1+0.1)
V3 = example = 0.3 m³/m (0.2+0.1)
V4 = example = 0.4 m³/m (0.3+0.1)
V5 = example = 0.6 m³/m (in step C only)
V6 = example = 2.0 m³/m (in step D only)
DRILLING AND GROUTING
Phase 1 – EXPLORATORY GROUTING

- 12 Months, One Row Across 3 km, 1.5 m centers/150 m depth
- Utilizing Existing Holes (Historical Grout Lines)
- T-Grout Computer Monitoring System
- NO LUGEON CLOSURE CRITERIA
- Higher Pressures, Stage Grouting (5m)
- New Work Force of 700 persons
- Training MoWR Staff
GROUTING PROGRAM – PHASE 2

- U/S Row Across 3 km, 3m/1.5 m centers/100 – 150 m depth
- 2000 holes +/-
- D&G under 7 tunnels
- Additional angle holes U/S and D/S
- T Grout Computer Monitoring System

- LUGEON CLOSURE CRITERIA
  - 3-5 Luegon in upper 50 meters
  - 5-10 Lugeon 50-100 meters

- INTEGRATION OF TRAINED MoWR STAFF
GROUTING SUMMARY

- Over 40,000 stages completed/5 meters stages
- 5,000 + grout holes
- 100-150 tons cement consumption daily

**Equipment and Operations**
- T-Grout computer monitoring system/GIS system
- 3 Mixing Plants/20 drill rigs/20 BGU’s (secondary pumps)
- 24/6 operations
DRILLING & GROUTING SUMMARY

- 4,850 holes drilled & grouted
- 348,652 m length of drilling (216 miles)
- 39,227 m³ of grout (22,177 tons of solids)
  - More than the last 13 years combined
  - (1.3 Washington Monuments)
- 63000 m³ previous 30 years
  - (2 Washington Monuments)
- Re-established two continuous grout lines across 2.7-km length of the dam
- Added center line and downstream angled holes at critical locations
GEOLOGY

One Dam, Two Foundations

Foundation behavior controlled by gypsum dissolution and karstic limestone

Foundation behavior controlled by chalky limestone
GROUTING RESULTS
GEOLOGY
One Dam, Two Foundations

Foundation behavior controlled by gypsum dissolution and karstic limestone

Foundation behavior controlled by chalky limestone
2017 PSTQ Analysis

Sec. 79-91 - Solids: kg/m

- Primary: 40
- Secondary: 35
- Tertiary: 59
- Quarternary: 51

Sec. 91-113 - Solids: kg/m

- Primary: 60
- Secondary: 50
- Tertiary: 45
- Quarternary: 4
- Quint:
Summary Findings

1. No preferential seepage paths from U/S to D/S encountered. However, high takes point to potential paths within at left abutment contact.

2. Historical grouting effectiveness limited by equipment and technique.

3. Historical grouting was generally been successfully in reducing permeability of the first 20m of foundation below the gallery floor

4. **Multiple high take sections have been identified to guide future grouting.**

5. **Artesian conditions West of Section 79 (Vuggy Limestone) require careful grouting procedures**

6. F-Bed, Limestone and Marl layers more difficult to grout than gypsum layers.

7. **Gypsum dissolution front remains a dam safety concern.**
BOTTOM OUTLET REPAIR FROM GROUTING

MOSUL DAM
Discovery – West B.O. Tunnel

- Last Inspected: March 31 2017
- 15 Nov 2017: Dewater West Bottom Outlet
- 17 Nov 2017: Discover Deformation in Steel Liner on East Side of Tunnel
- 28m downstream of Guard gate
  - Length=13m
  - Width= 3.9m
  - Height=1.1m
Discovery - East B.O. Tunnel
BOTTOM OUTLET REPAIR

EXISTING CONDITIONS
Bottom Outlet Repair

Features shown are an approximation of existing conditions. Use record drawings for more accurate depictions of the actual conditions.
RETURN TO NORMAL OPERATIONS
2019 15 YEAR RECORD POOL

Mosul Dam No Longer on Brink of Catastrophe

By Elkar Hanooti
May 15, 2019 04:43 PM

Engineer insists Mosul Dam not in danger despite heavy rain
3:34 AM 19 Jun 2016
Rudaw

Mosul Dam

Mosul Dam, Iraq

Tags: Mosul, Mosul Dam, Kurdistan, water crisis
MOSUL DAM

RISK ASSESSMENT
RISK ASSESSMENT RESULTS

Multiple 4 to 6 meter voids

Internal Erosion
Along Bottom
Outlet Tunnels

Internal Erosion
Along Left
Abutment Contact
RISK ASSESSMENT RESULTS

Normal Pool Elevation: 330; With Intervention

In general, risks fell 2 orders of magnitude. Still very high risk due to downstream population.
Why have the risks changed?

– We have MUCH more data to inform our judgment

  • Historic construction data
  • Maintenance data in the intervening years between construction and 2016 (still scarce)
  • Recent grouting data, recent exploration data, piezometer data

– The result is we have a better understanding of the geology from construction and the recent exploration and a better understanding of how the dam was built

– There has been a significant amount of grout (solids) put in the ground that has improved the overall condition of the foundation
DAM SAFETY MODIFICATION STUDY

MOSUL DAM
GROUTING IS NOT A PERMANENT SOLUTION

DAM SAFETY MODIFICATION STUDY

DSMS Alternatives

Cutoff Wall

Pool

Restriction

New Dam - Badush

Grouting
RELATIONSHIPS WERE KEY
Acknowledgements

- COL Michael Farrell, USACE, Commander, Mosul Dam Task Force
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- AECOM
Thank You!
Discussion

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