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


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Mosul
Mosul Dam
DEVELOPING STORY
ISIS SEIZES IRAQ'S LARGEST DAM
Mosul dam is upstream from Tikrit, Baghdad
CNN
KOSPI


Mosul
Dam
Crisis

ISIS control of Tigris and Euphrates River Tabqa dam, Syria Since February 2013

Water as a Weapon

Military, financial, infrastructure, irrigation, food supply, drinking water, public health

Dam Safety Risk Communication Behind ISIS Lines

The Phone Call

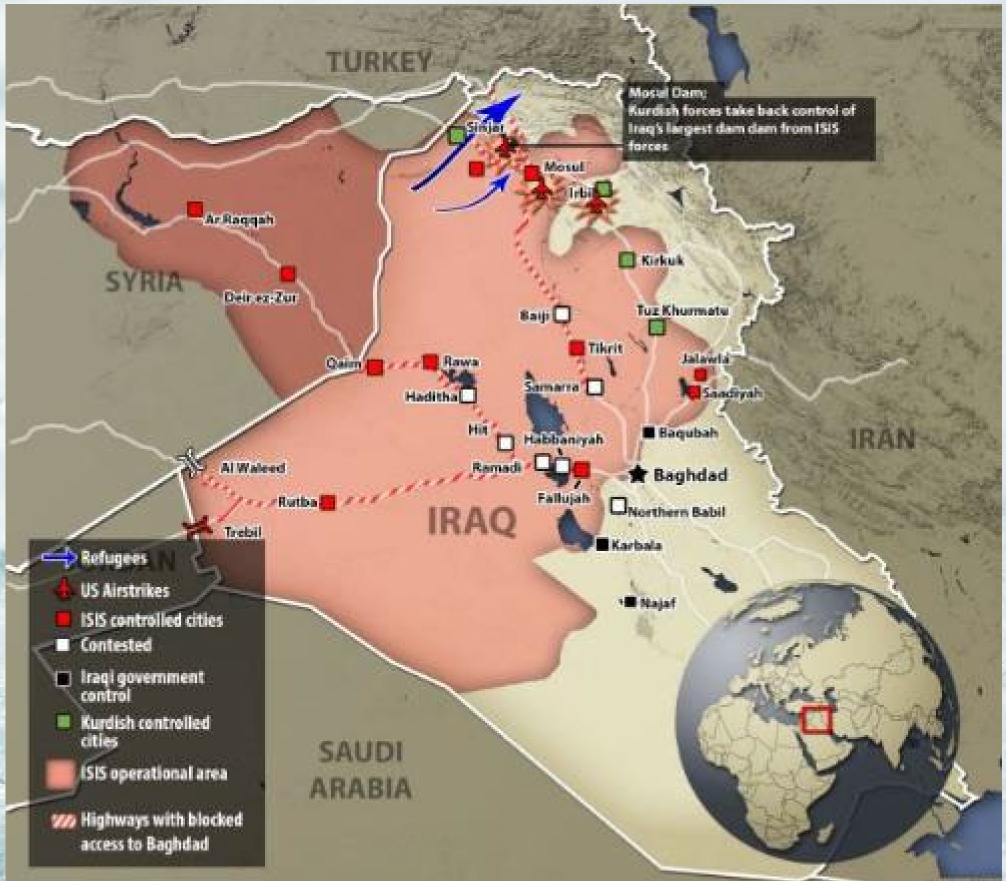
- **Within hours, requests for support came to USACE.**
  - **Department of State.**
  - **CJTF.**

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.

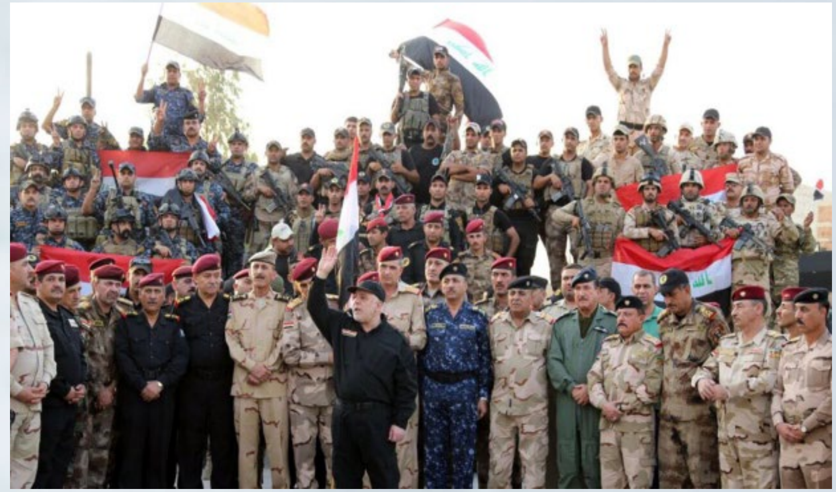
"In all, we destroyed over 90 targets including a range of vehicles, equipment, and fighting positions," said Pentagon press secretary Rear Adm. John Kirby in statement. "Iraqi forces have cleared the dam and are working to further expand their area of control."

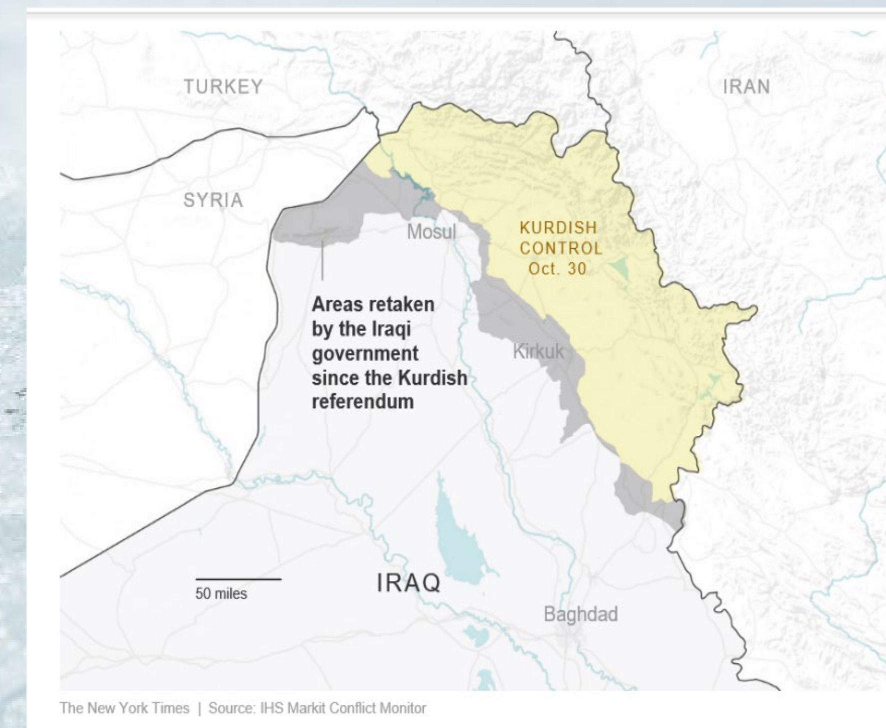
Kurdish Forces Take Back Mosul Dam



SECURITY

- ➢KRG Peshmerga
- ➢Mosul Operation began Oct. 2016
- ➢Syria
- ➢Italian Security Force
- ➢KRG Referendum
- ➢Iraqi Forces Replace Peshmerga
- ➢US Replace Italian Army





BACKGROUND

MOSUL DAM

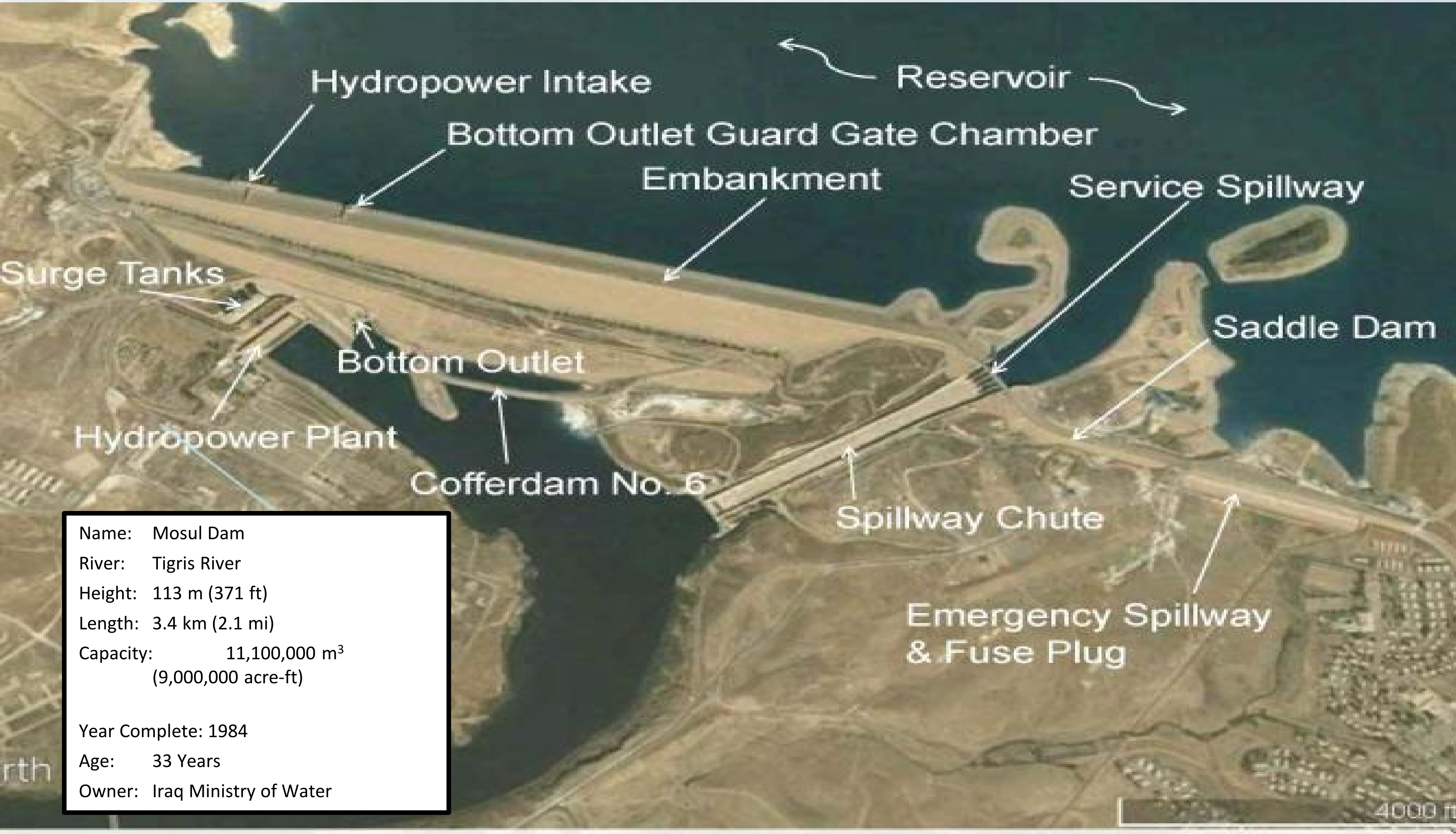
DAM FACTS

- Water Supply
- Irrigation
- Hydropower
- FRM

- Completed 1985
- 2.2 km long
- **Well Designed**
- **Bad Foundation**

- 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**

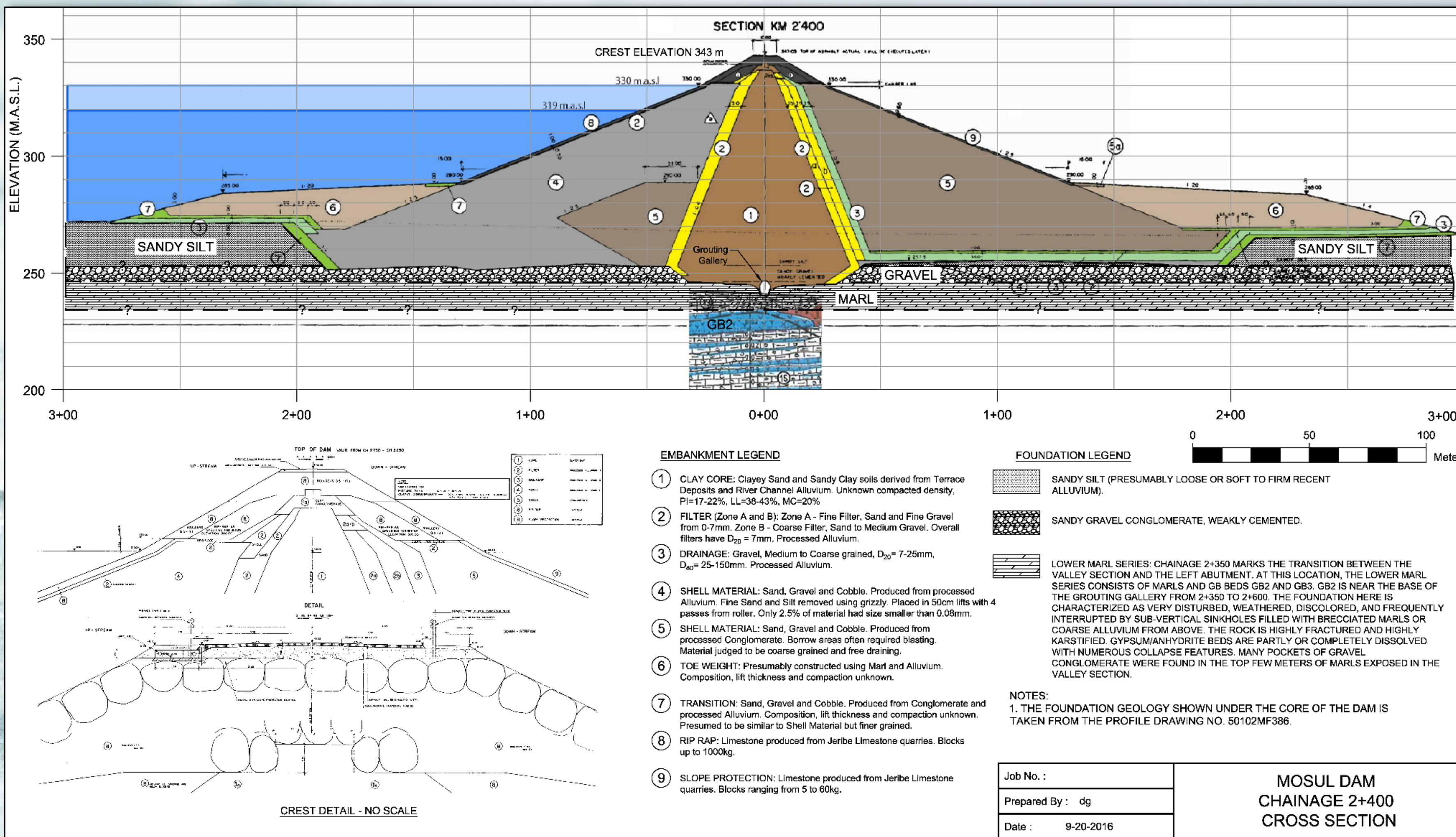
MOSUL DAM FEATURES



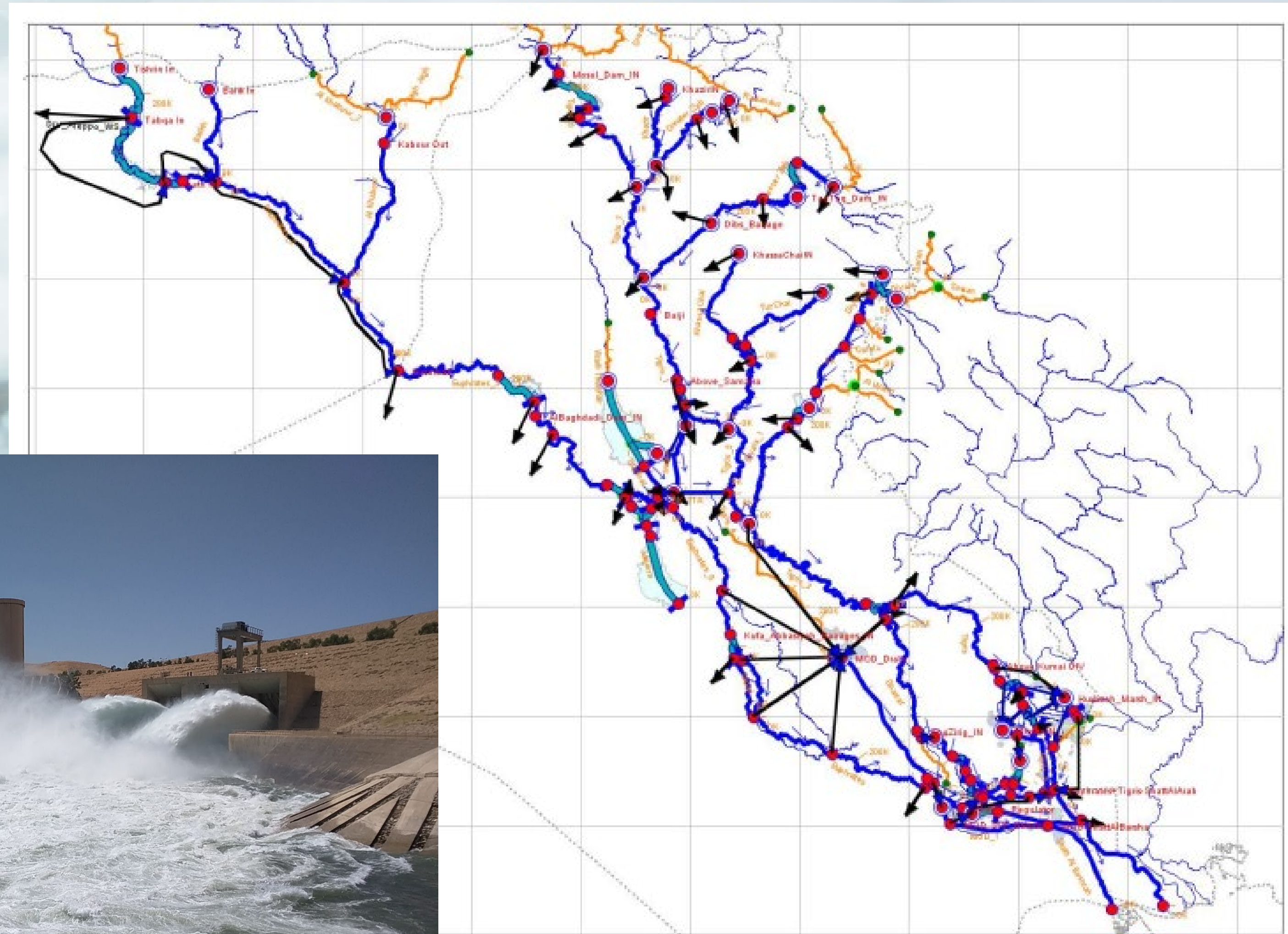
Name: Mosul Dam
River: Tigris River
Height: 113 m (371 ft)
Length: 3.4 km (2.1 mi)
Capacity: 11,100,000 m^3
(9,000,000 acre-ft)

Year Complete: 1984
Age: 33 Years
Owner: Iraq Ministry of Water

TYPICAL SECTION



POOL RESTRICTION OF 11 METERS SINCE 2006
National Impacts



2006-2008 Drilling and Grouting Support Effort

- $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

Security

U.S. ARMY

Planning, Engineering & Construction Management

US Army Corps of Engineers

AECOM

VERSAR

TREVI

3 Governments

2 USG Departments

TREVI

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

USACE Engineer & Oversight

Risk Assessment & Mobilization

Preliminary Drilling and Grouting

Phase 1

Phase 1 Extension

DSMS

Phase 2

May 2016

Nov 2016

Jan 2017

Jan 2018

Aug 2018

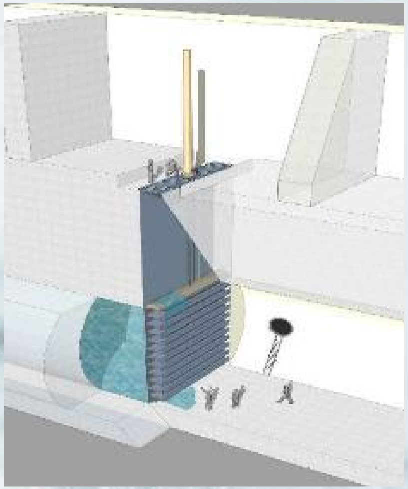
Jul 2019

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

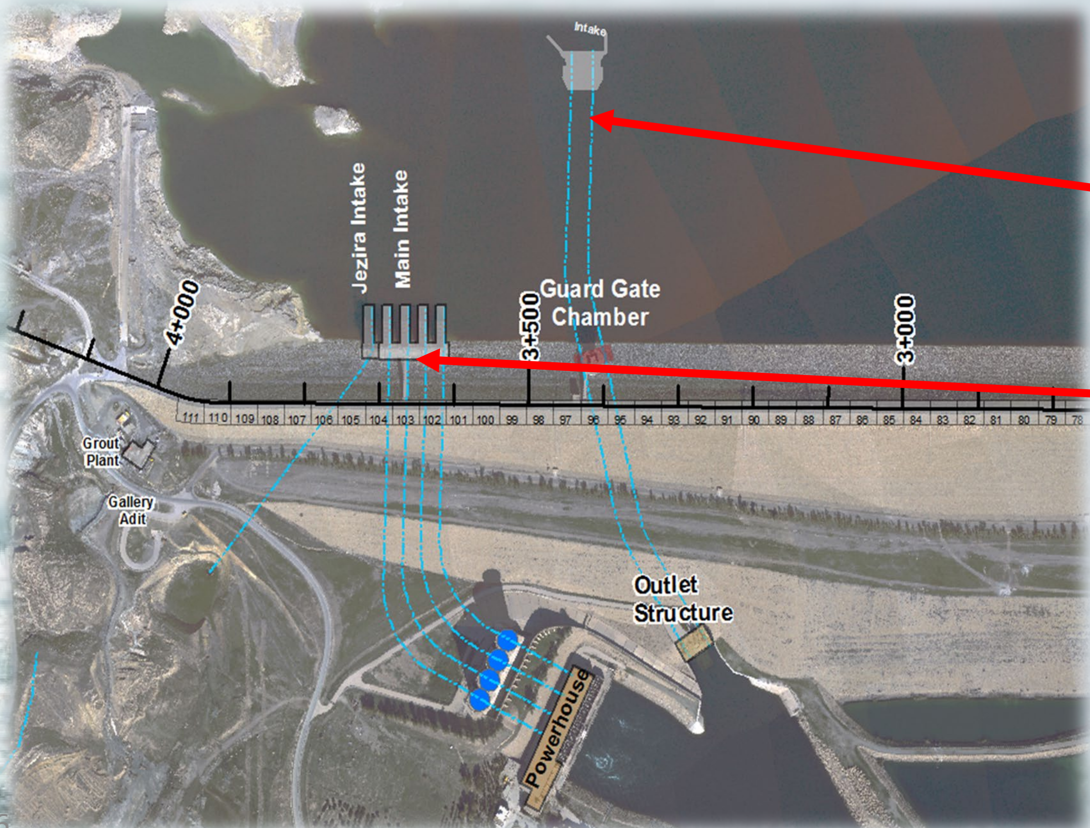
Refurbish
5 Cranes

HOUSING COMPLEX

EMERGENCY GATE REPAIR – BOTTOM OUTLETS

MOSUL DAM

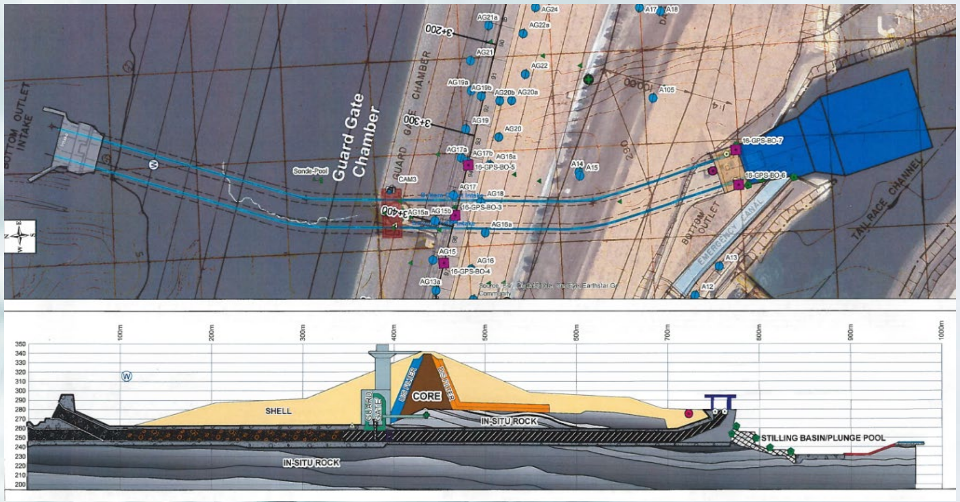
BOTTOM OUTLETS

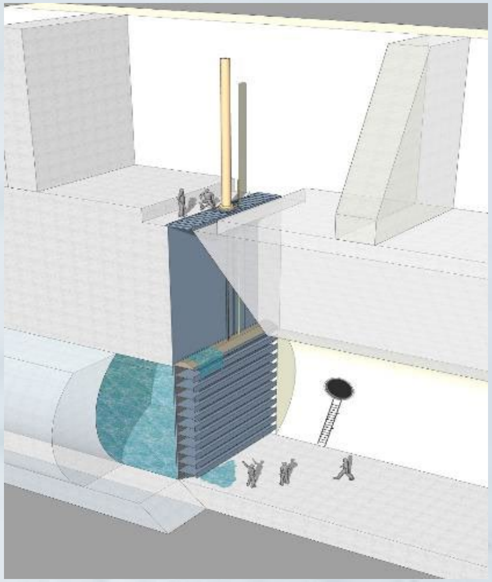


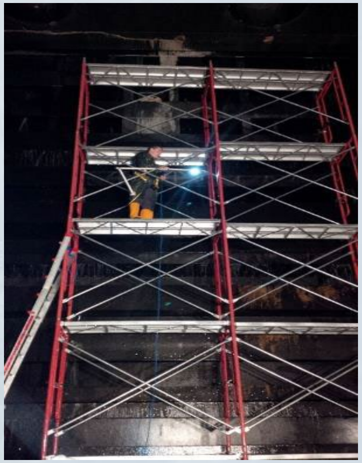
Bottom Outlet Tunnels

Power Tunnels

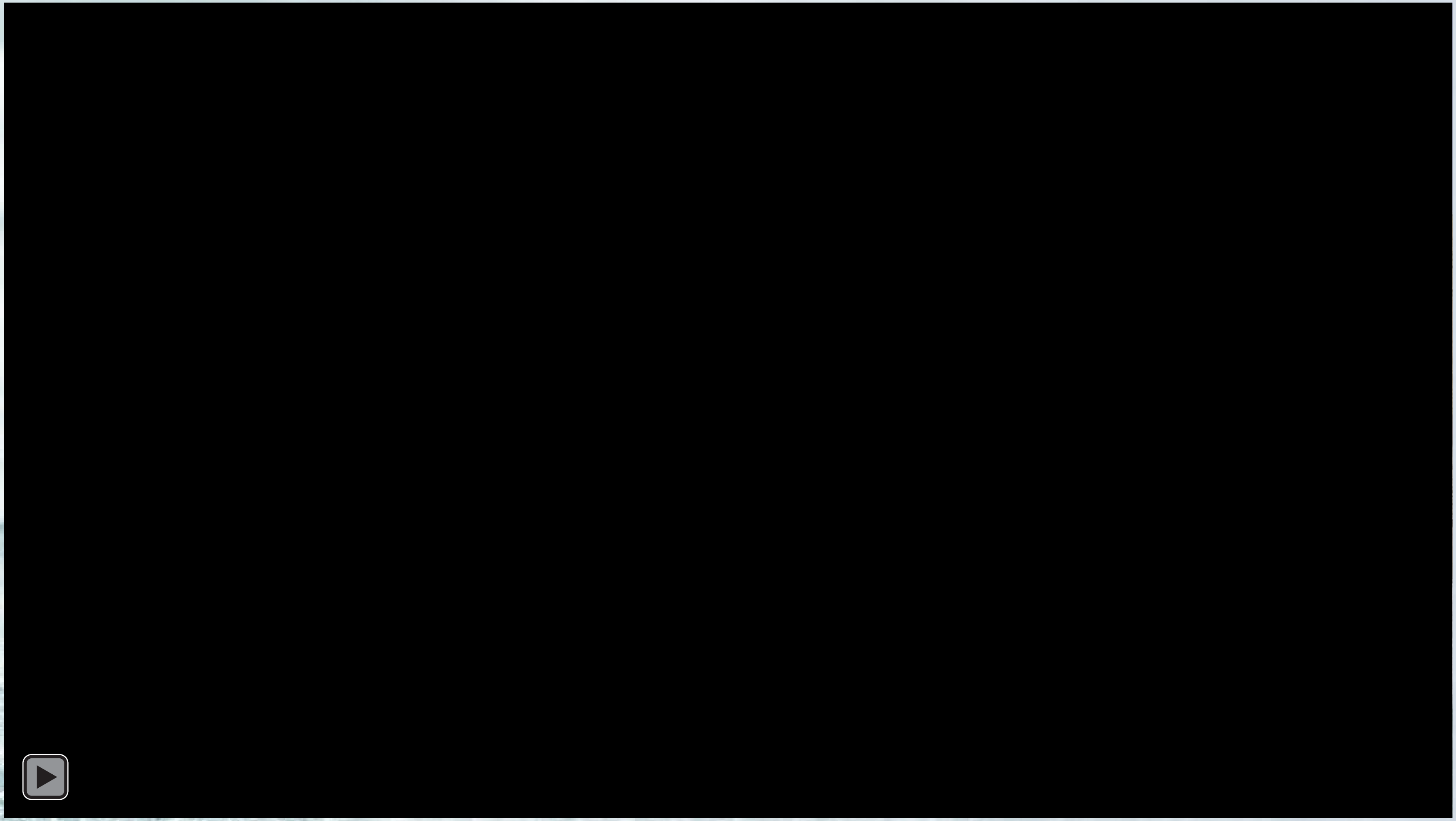
GUARD GATE REPAIR







BOTTOM OUTLETS



- Right BO open for first time since 2013

BOTTOM OUTLETS

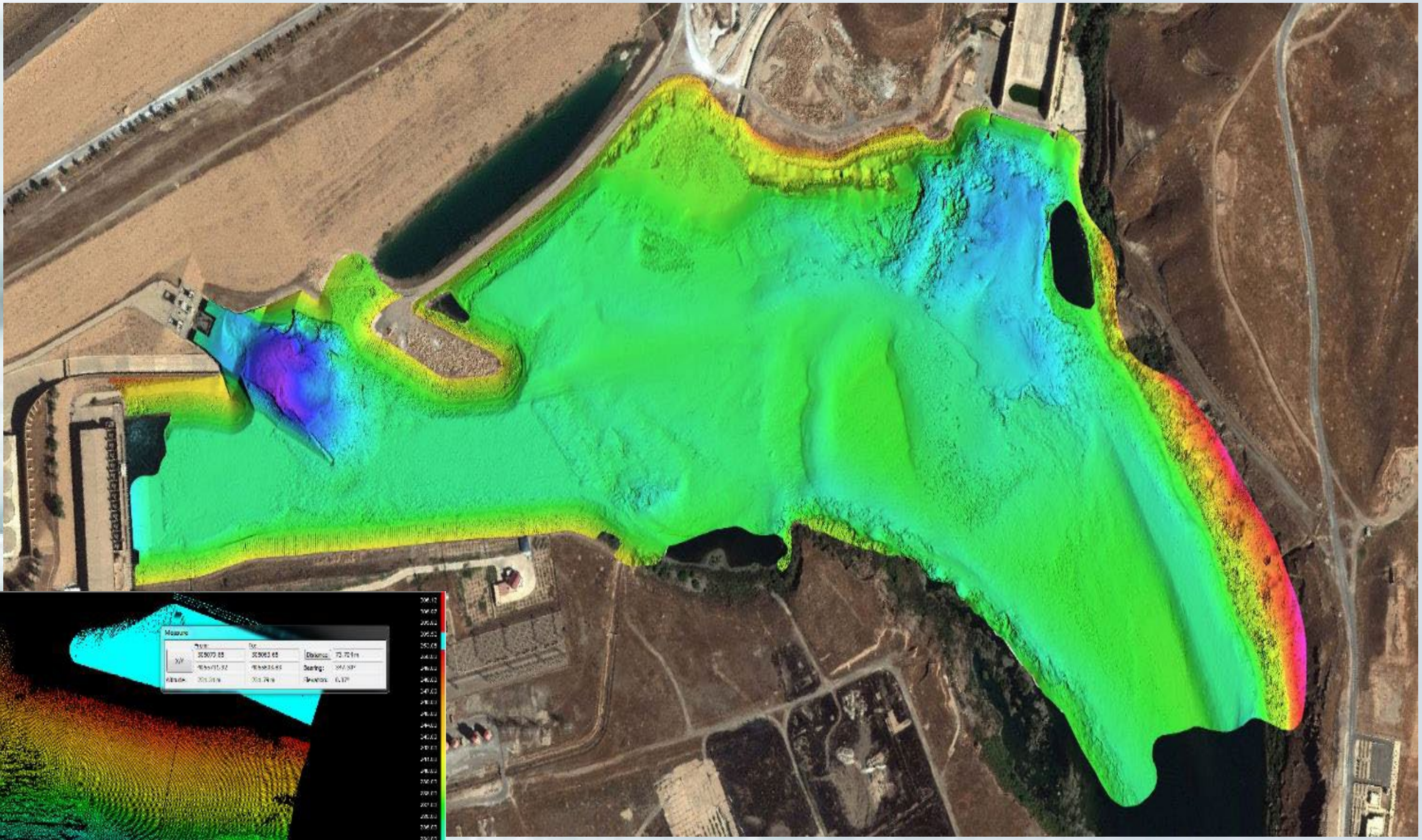
Diving Barge & Bulkheads

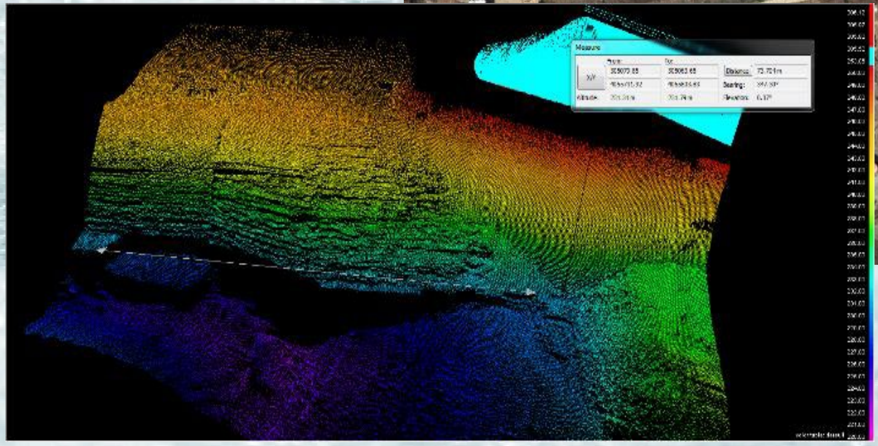
BOTTOM OUTLETS

Bottom Outlets Inspection

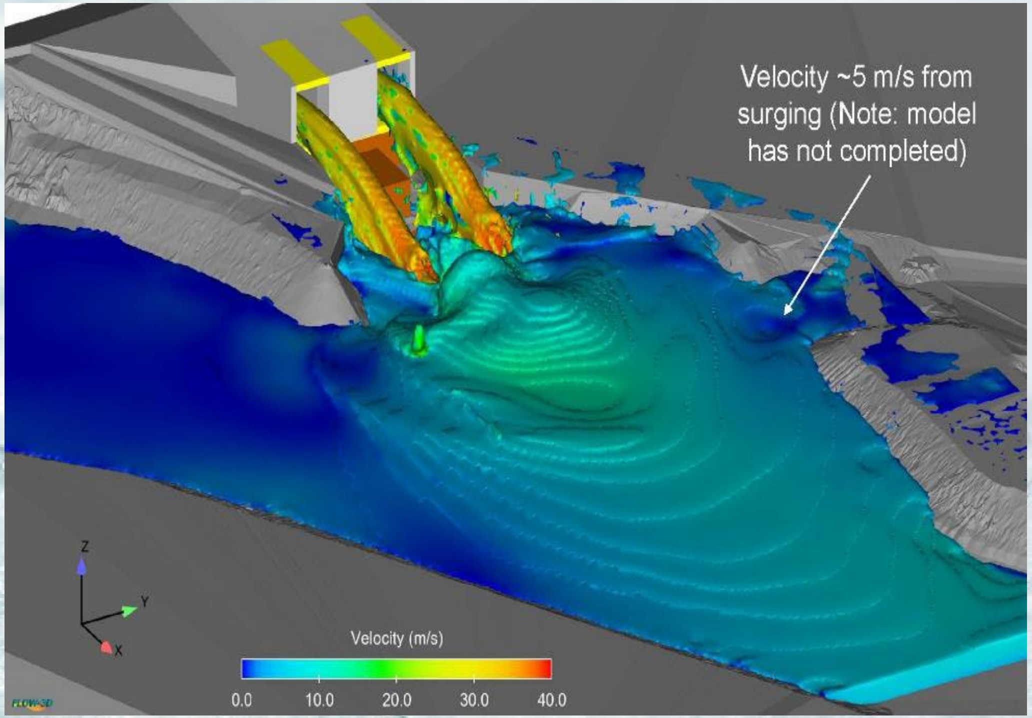
February and June 2017

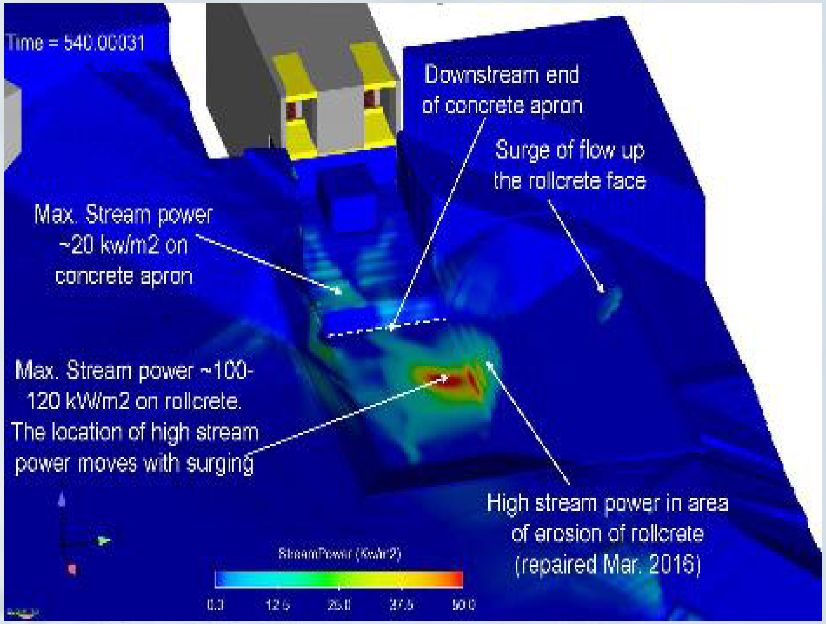
BATHYMETRY AND LASER SCANNING

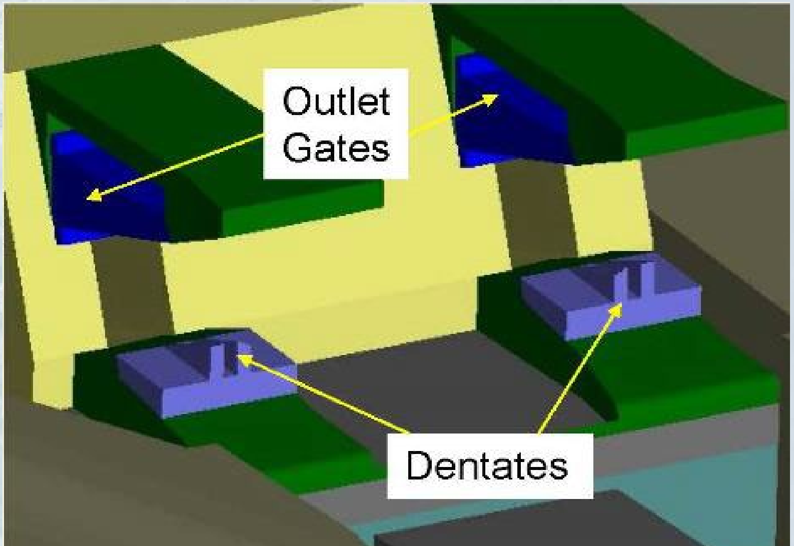




PLUNGE POOL HYDRAULICS MODELING







DAM SAFETY RISK

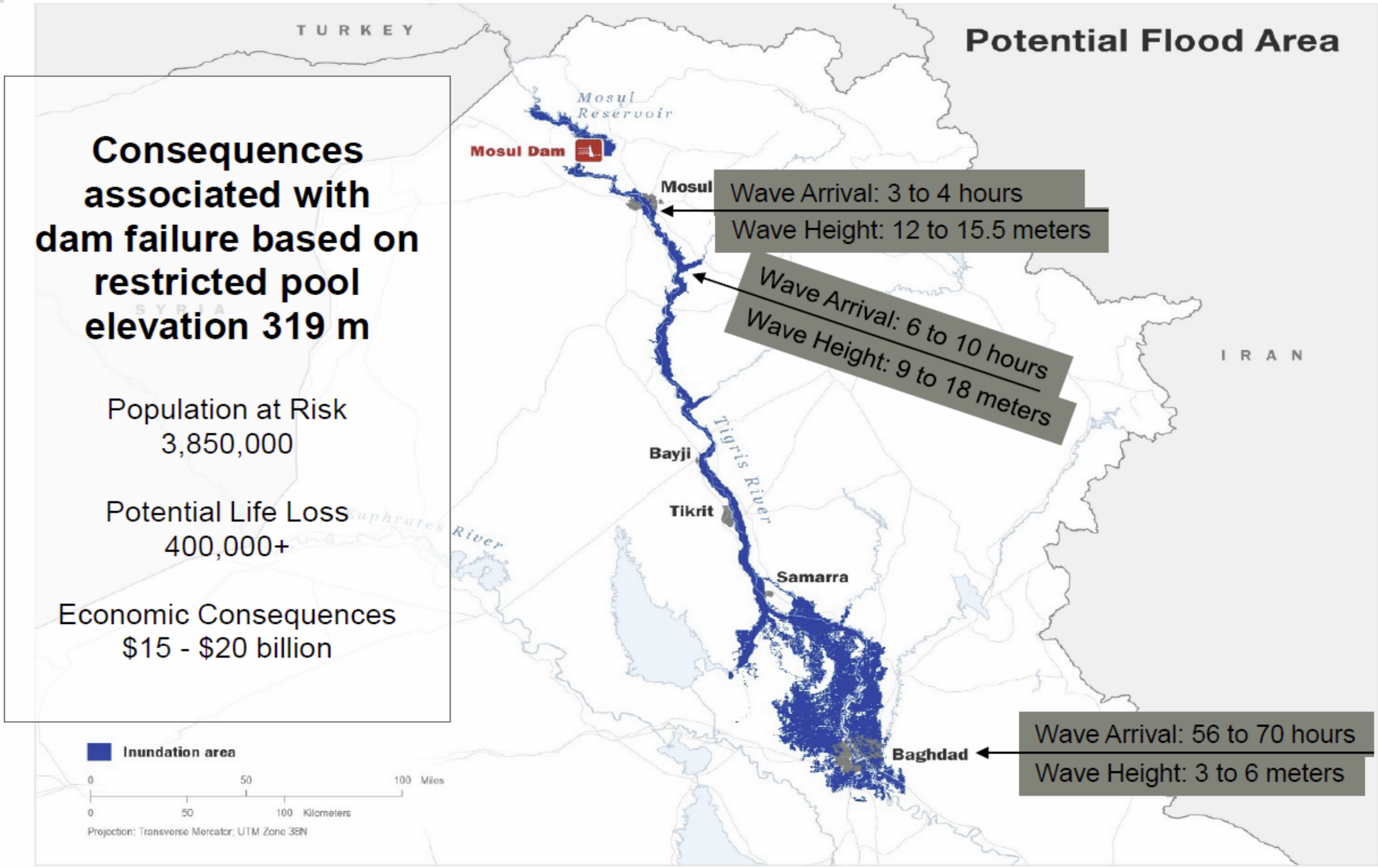
MOSUL DAM

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

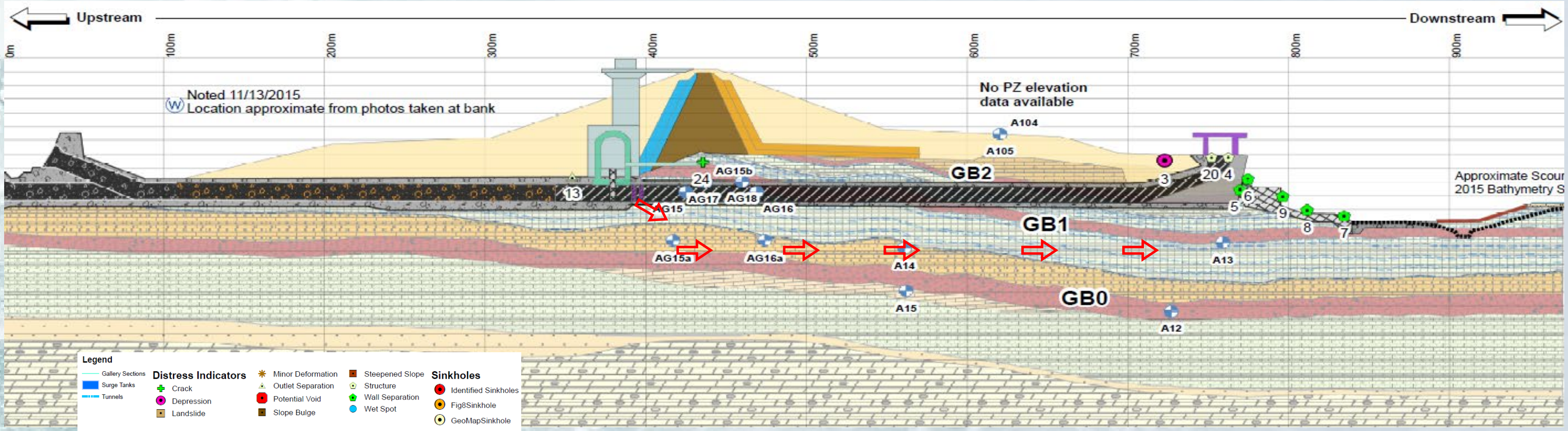


US Army Corps of Engineers.

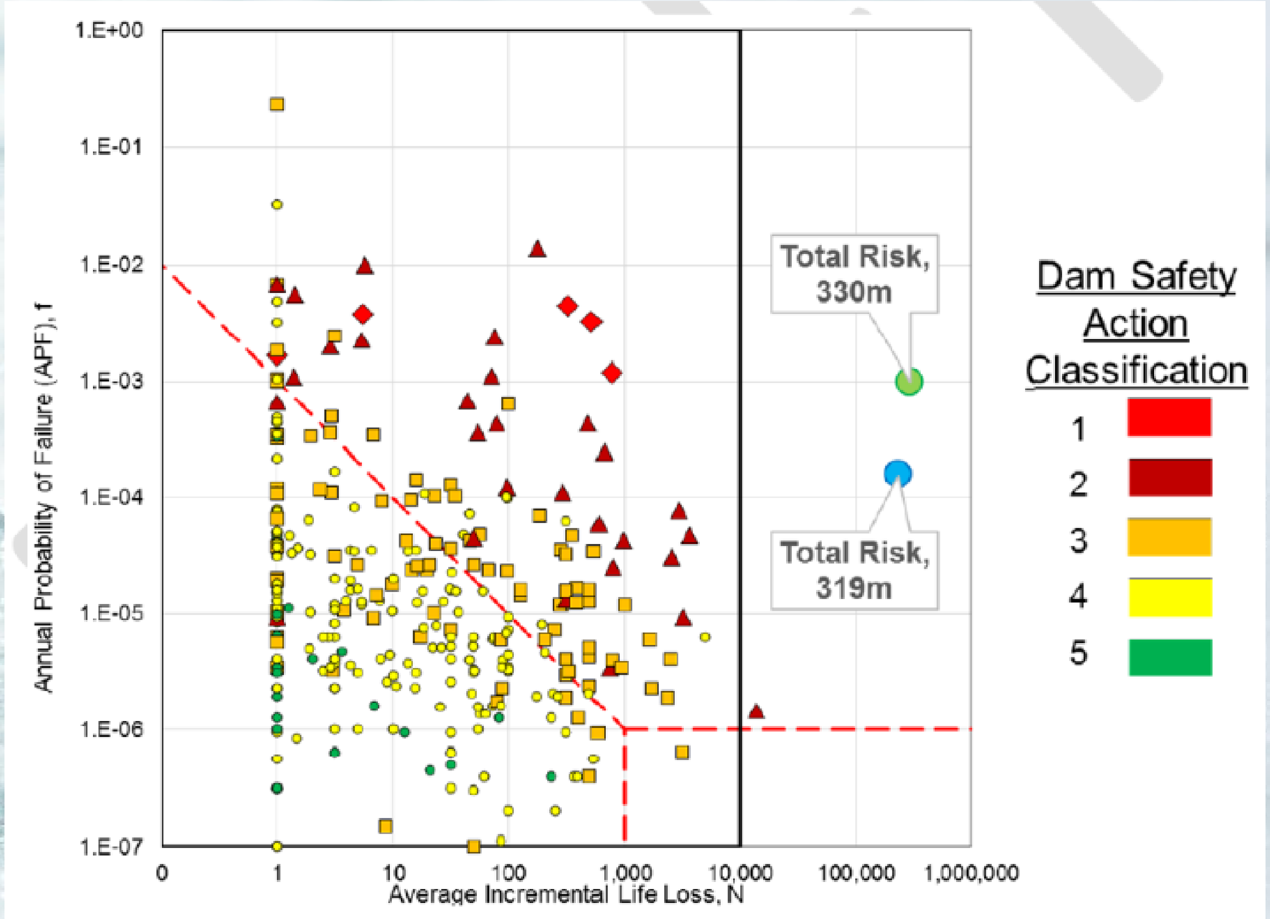
Internal Erosion along the Bottom Outlet Conduits

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
No
No
No
No
No
No



Highest Risk Dam in the World? Comparison to USACE Portfolio



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

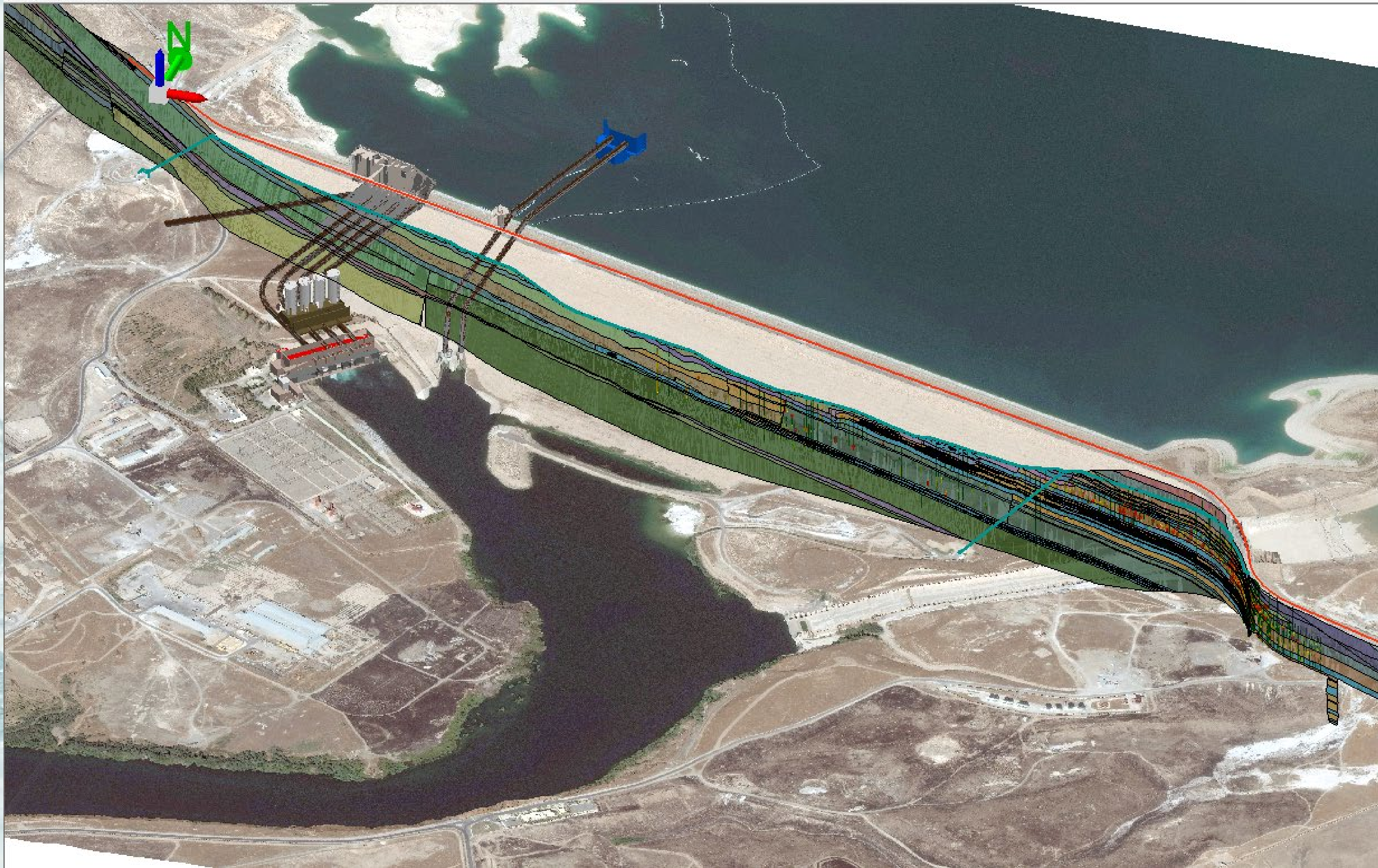
Even a dam incident could be catastrophic.

Grouting, although critical, does not bring risk to tolerable levels.

GEOLOGY

MOSUL DAM

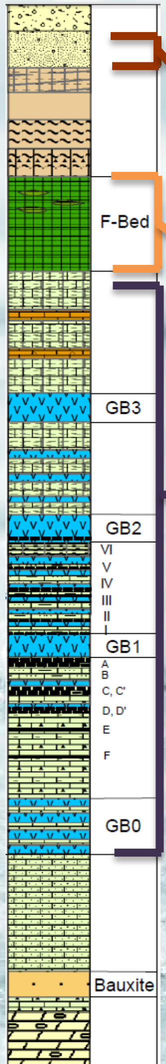
GEOLOGIC MODEL



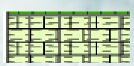
GENERAL GEOLOGY AT MOSUL DAM

- 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)

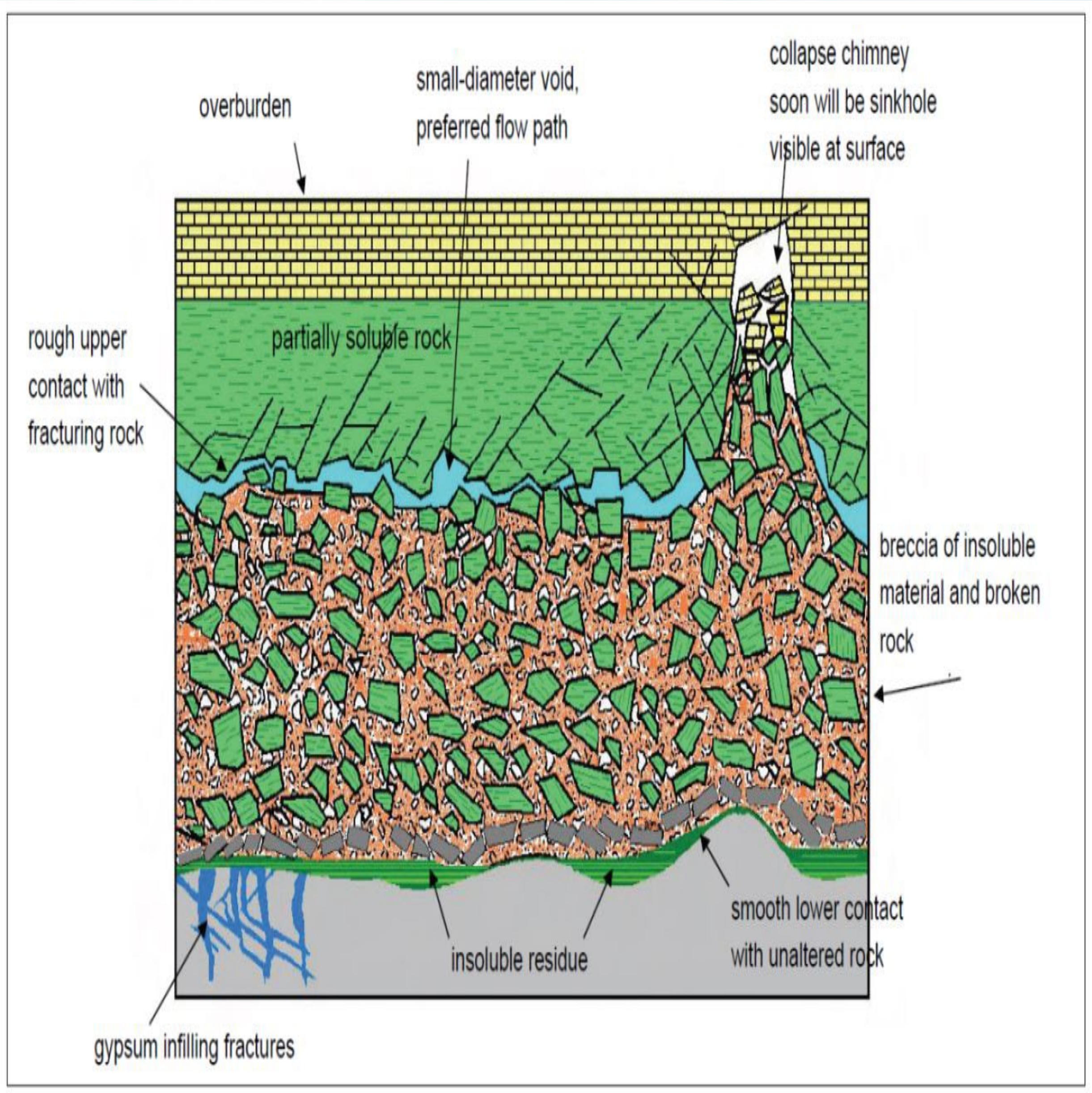


  - **Foundation is Mostly Marl (calcareous claystone)**
  - **Multiple thin limestone layers**

  - **Gypsum Breccias** – <u>WIDE</u> 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**

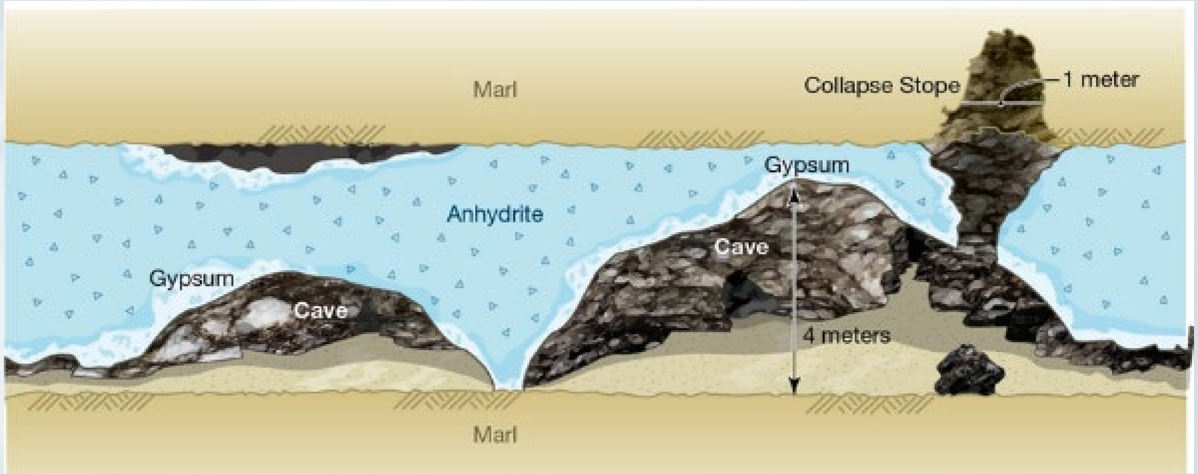
Each of the GB layers are separated by marl and limestone

EVAPORITE GEOLOGY



As anhydrite is exposed to water it turns to gypsum and dissolves, leaving voids, cavities and beds of collapse breccia

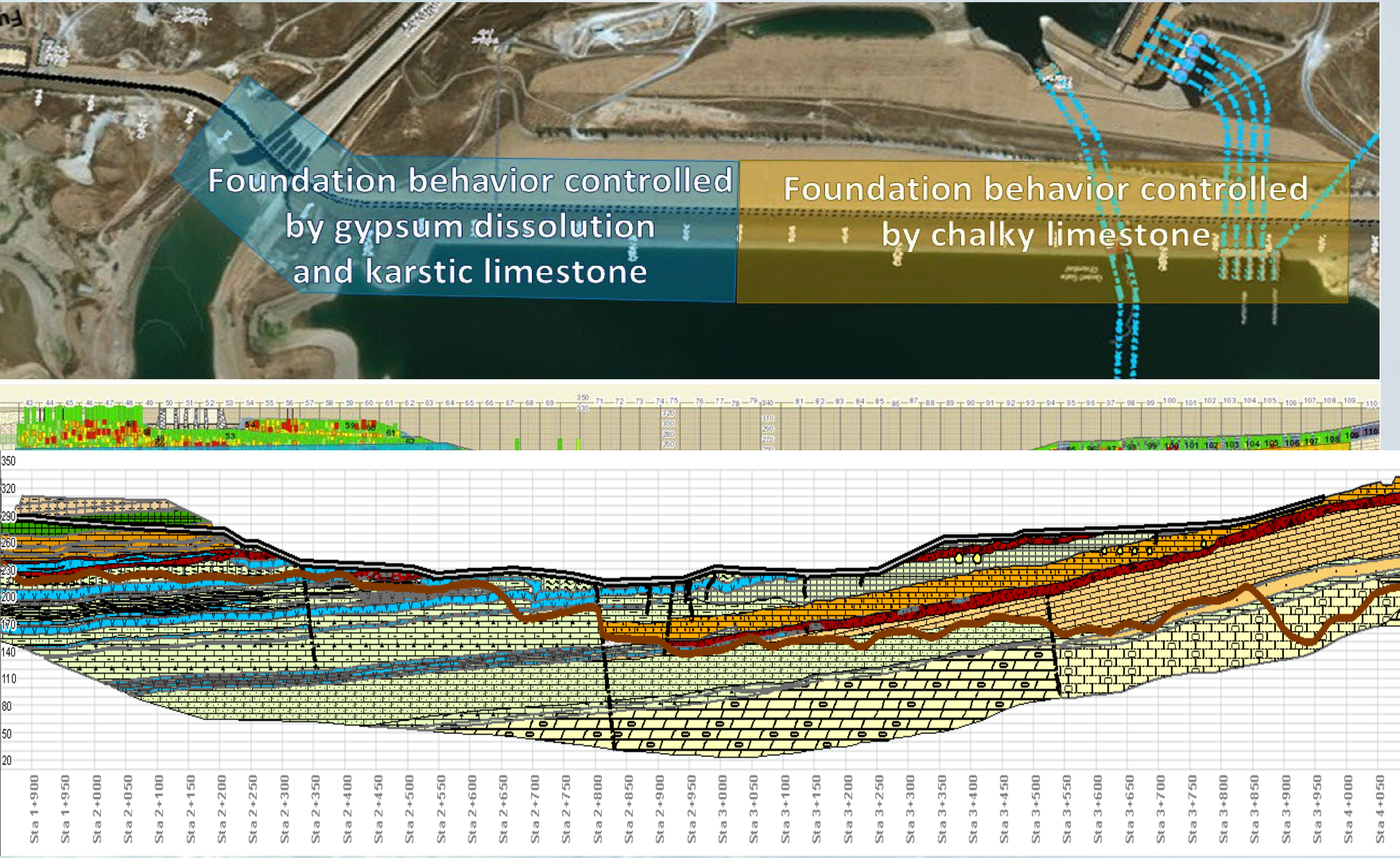
GYPSUM DISSOLUTION FRONT



GEOLOGISTS FOR SCALE

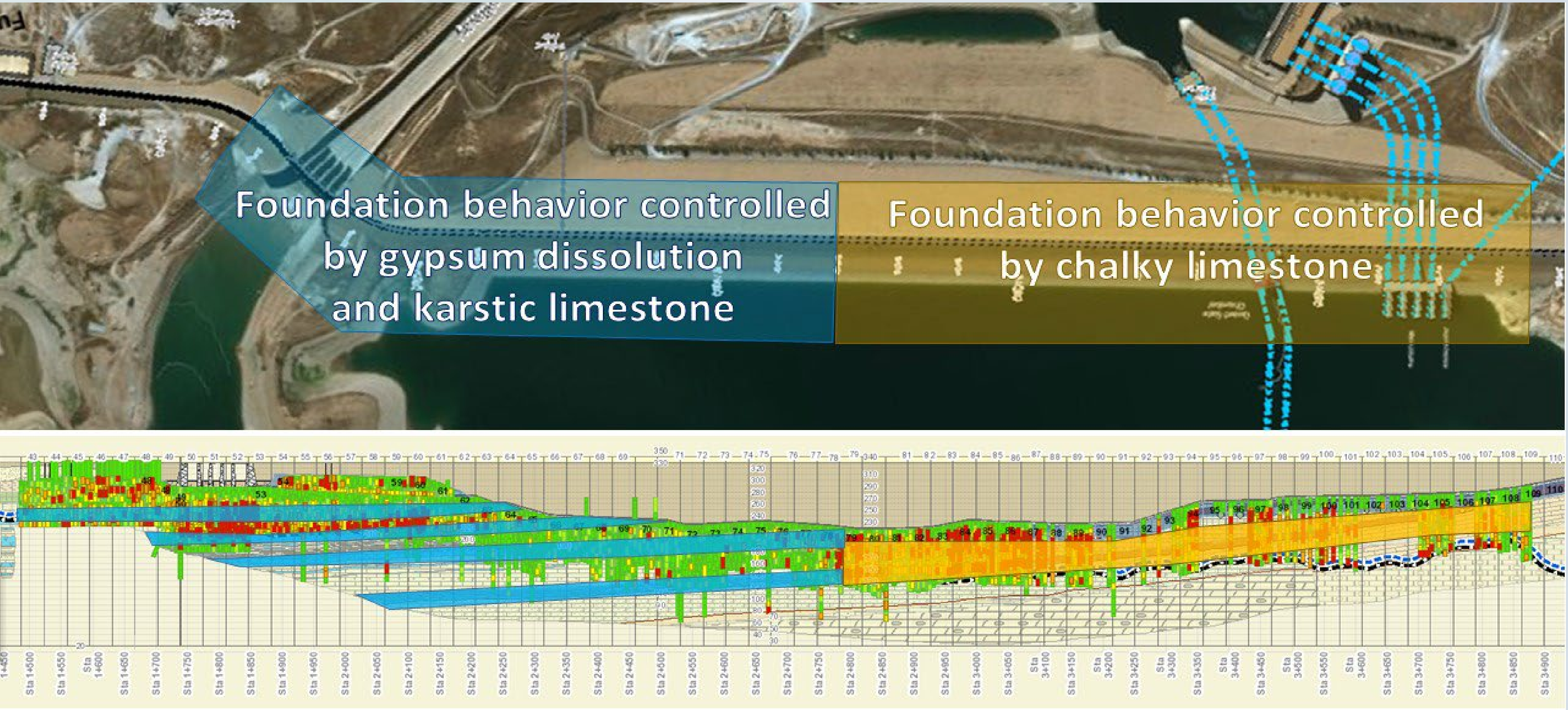
GEOLOGY

One Dam, Two Foundations



GEOLOGY

One Dam, Two Foundations



DISTRESS INDICATORS

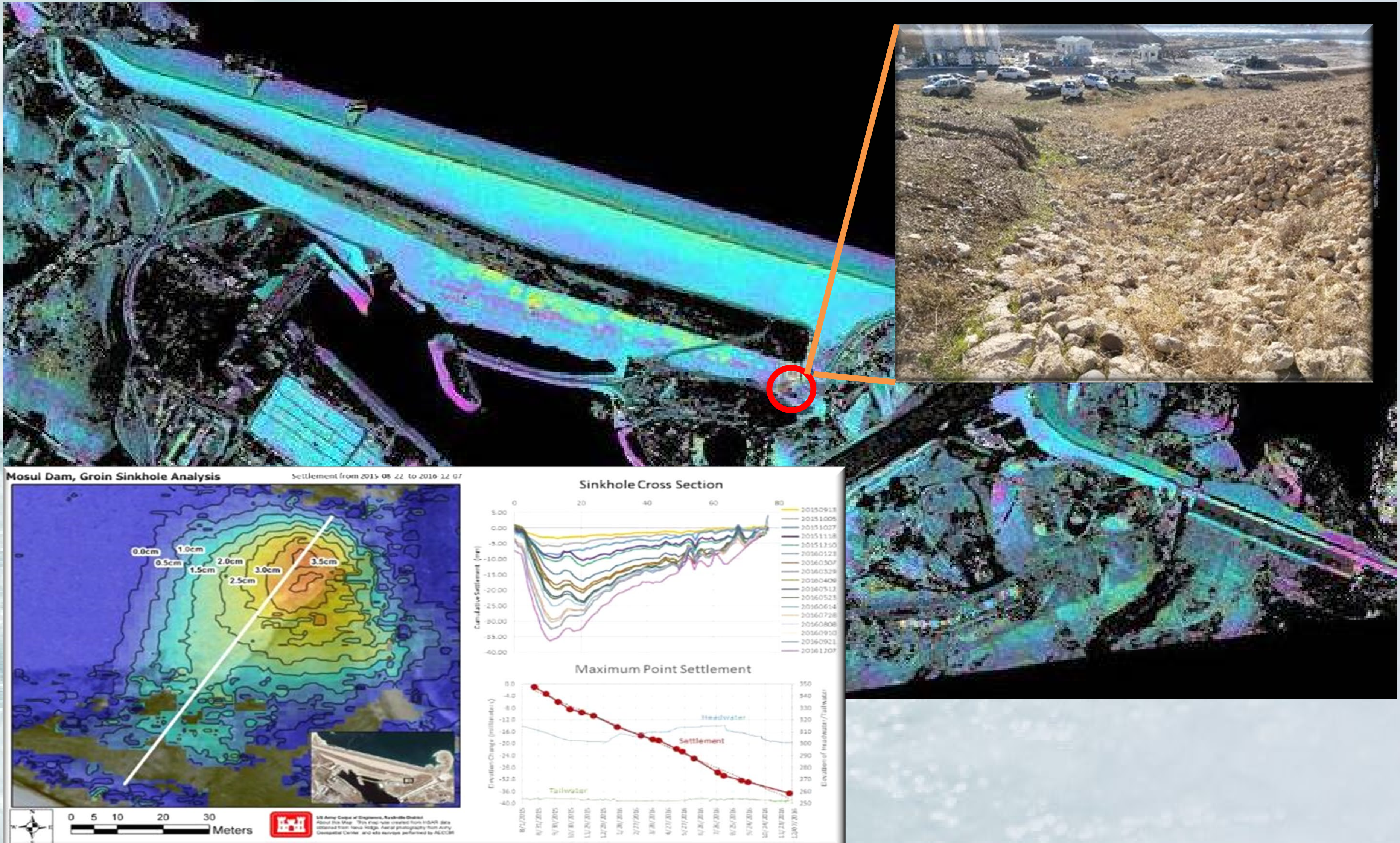
MOSUL DAM

POTENTIAL DISTRESS FEATURES

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

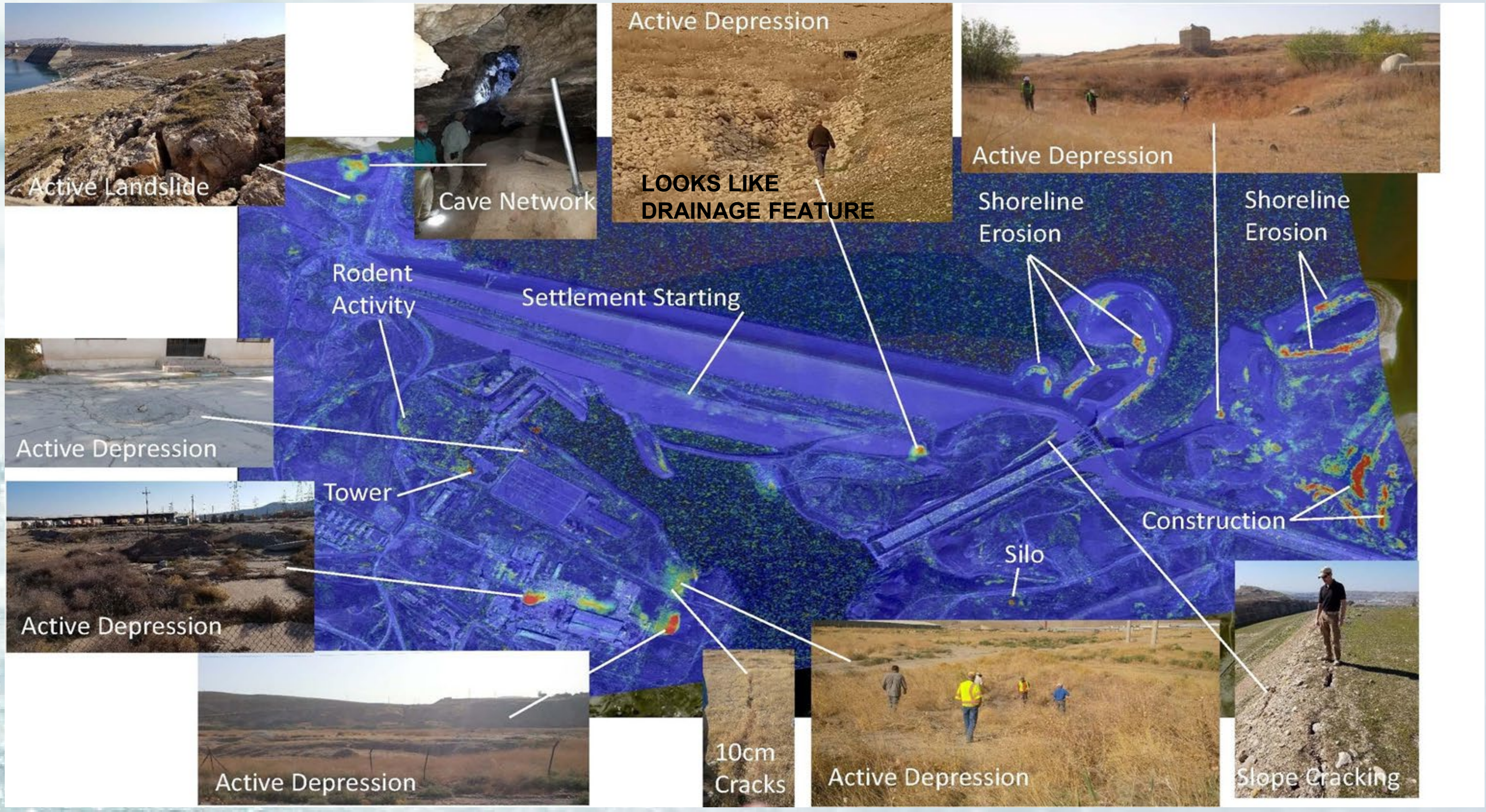
- Aerial/Satellite Imagery
- Site Assessment and Drilling
- Observation and Anecdotal Reporting
- Bathymetry

INTERFEROMETRIC SYNTHETIC APERTURE RADAR MONITORING

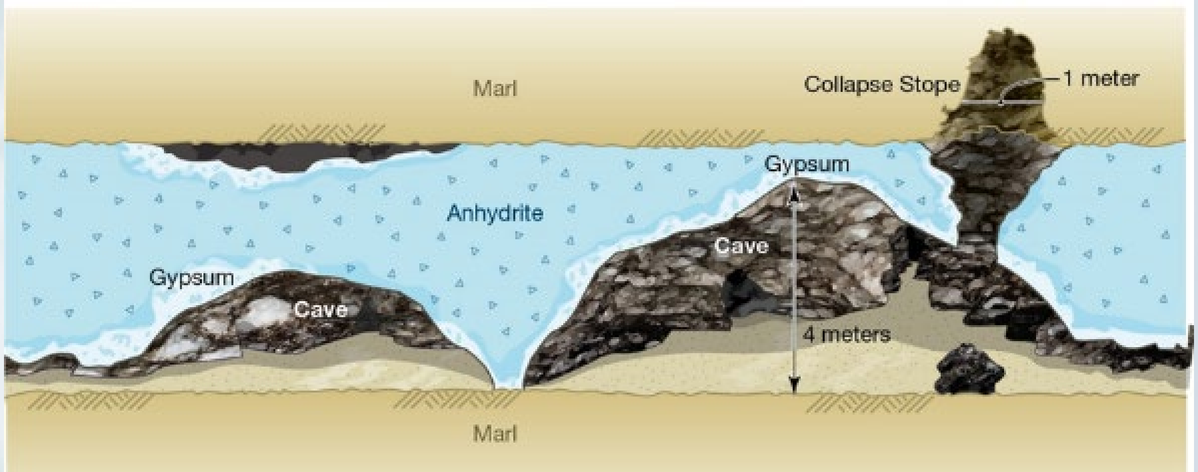


INTERFEROMETRIC SYNTHETIC APERTURE RADAR MONITORING

Three Years of Ground Truth



GYPSUM DISSOLUTION FRONT



NEW INSTRUMENTATION

MOSUL DAM

NEW INSTRUMENTATION

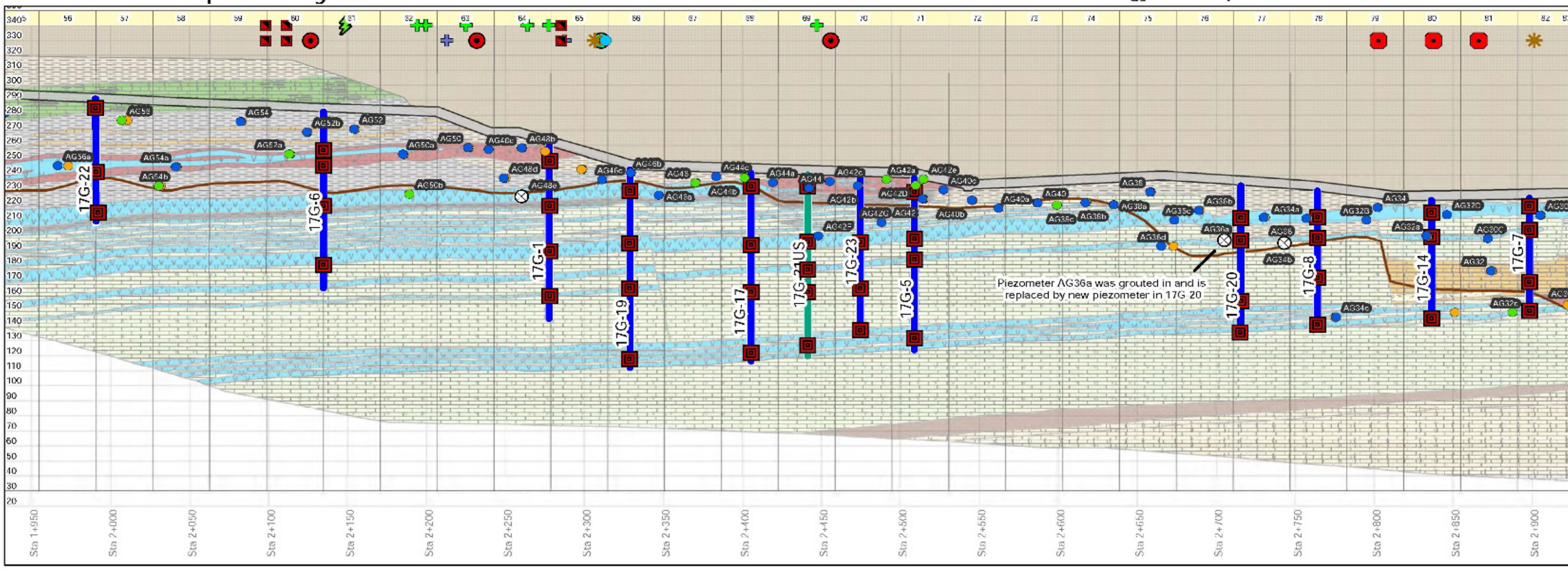
➢ New Core Holes:	75
➢ Core Holes in Gallery:	43
➢ Core Holes on Surface:	32
➢ New Piezometers:	325
➢ Existing Piezometers to be Automated:	80
➢ New Inclinometers:	3
➢ New Crack meters	45
➢ Weather Station:	1
➢ Accelerographs:	2
➢ Pendulums:	3

- 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

Proposed Piezometers

Borehole_ID	Gallery Section	Top El (m)	Bottom El (m)	Depth (m)	Bottom Geology	PZ Elevations
17G-22	56/57	290	215	118	GB1	285, 242, 211,
17G-6	60/61	282	165	115	GB2	260, 245, 220, 185
17G-1	64/65	260	145	115	Below GB1	250*, 220, 190, 160
17G-19	66	244	112	135	GB0	230, 195, 165, 116
17G-17	68	242	116	135	GB0	232, 194, 165, 122
17G-21US	69	240	120	120	GB0	233,196,184,165,127
17G-23	70	240	134	106	Top of GB0	196, 165, 136
17G-5	71	237	125	112	GB0	228, 197, 184, 132
17G-20	76/77	233	127	106	GB0	212, 196, 157, 135
17G-8	78	230	130	100	GB0	210, 190, 165, 135
17G-14	80	225	144	81	GB0	215, 198, 144
17G-7	82	225	148	77	GB0	220, 204, 170, 150

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

Legend

Piezometers

Automation of Existing PZ

- Automated
- Manual
- Proposed Phase 2 EWS Automation
- Abandoned
- Proposed for Installation
- DS Proposed Borings
- US Proposed Borings

Dam Features

- Grouting Sections
- Gallery
- Embankment
- Conduits

Distress Indicators

- Crack
- Grout Emergence
- Monolith Movement
- Outlet Separation
- Structure
- Wall Separation
- Active depression
- Cave
- Collapse - Historical, Not Active
- Grout Emergence
- Landslide
- Minor Deformation
- Potential Void
- Sinkhole, Post-construction, Not Active
- Soil Crack
- Spring
- Steepened Slope
- Wet Spot

Geotechnical Materials 1985 Condition

Pervious or Erodible Materials

- Alluvium
- Gravel or Conglomerate
- Clay
- Soft Marl
- F-Bed Limestone, Highly Karstified
- Sandy Marl
- Limestone, Highly Karstified
- Gypsum/Anhydrite, Pervious
- Gypsum Breccia, Marly Breccia
- Jeribe-Euphrates Limestones and Dolomites, Pervious
- "Bauxite"

Impervious Materials

- Hard Marl
- Bituminous Hard Marl
- Limestone, Impervious, with Gypsum
- Hard Marl, Marly Limestone
- Hard Marl Interbedded with Gypsum
- Anhydrite, Impervious

US Army Corps of Engineers
Nashville District, Geology
Map No. LRN.MD.G.PROFILE.V3.P1.20170111
Last Updated 4/8/17

HISTORICAL GROUTING

MOSUL DAM

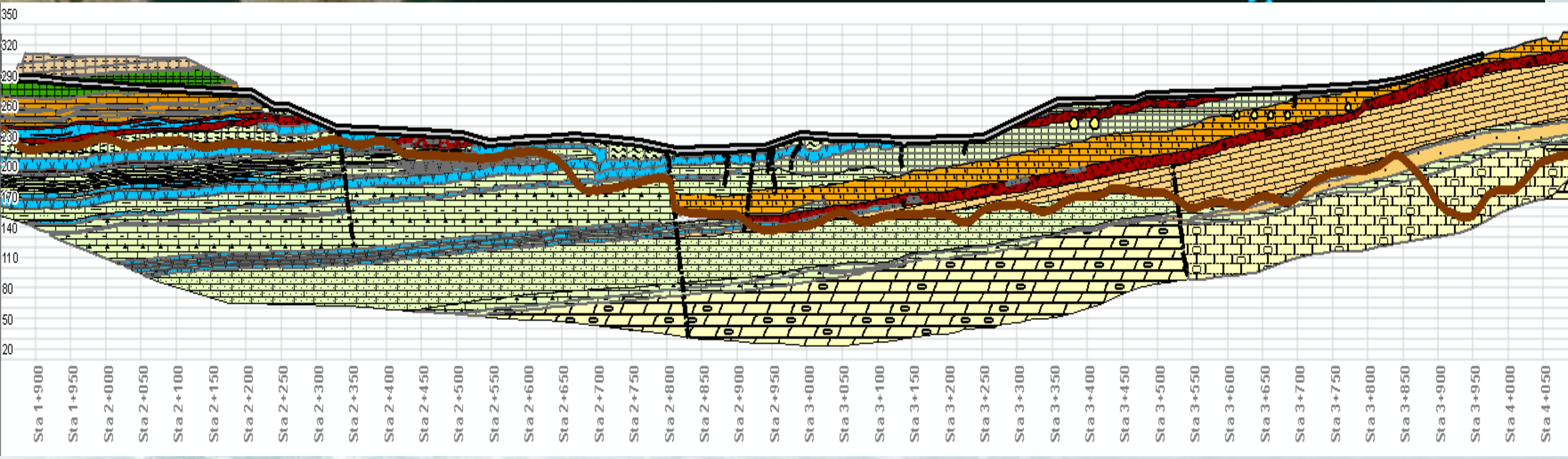
MoWR HISTORICAL GROUTING

- **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.**

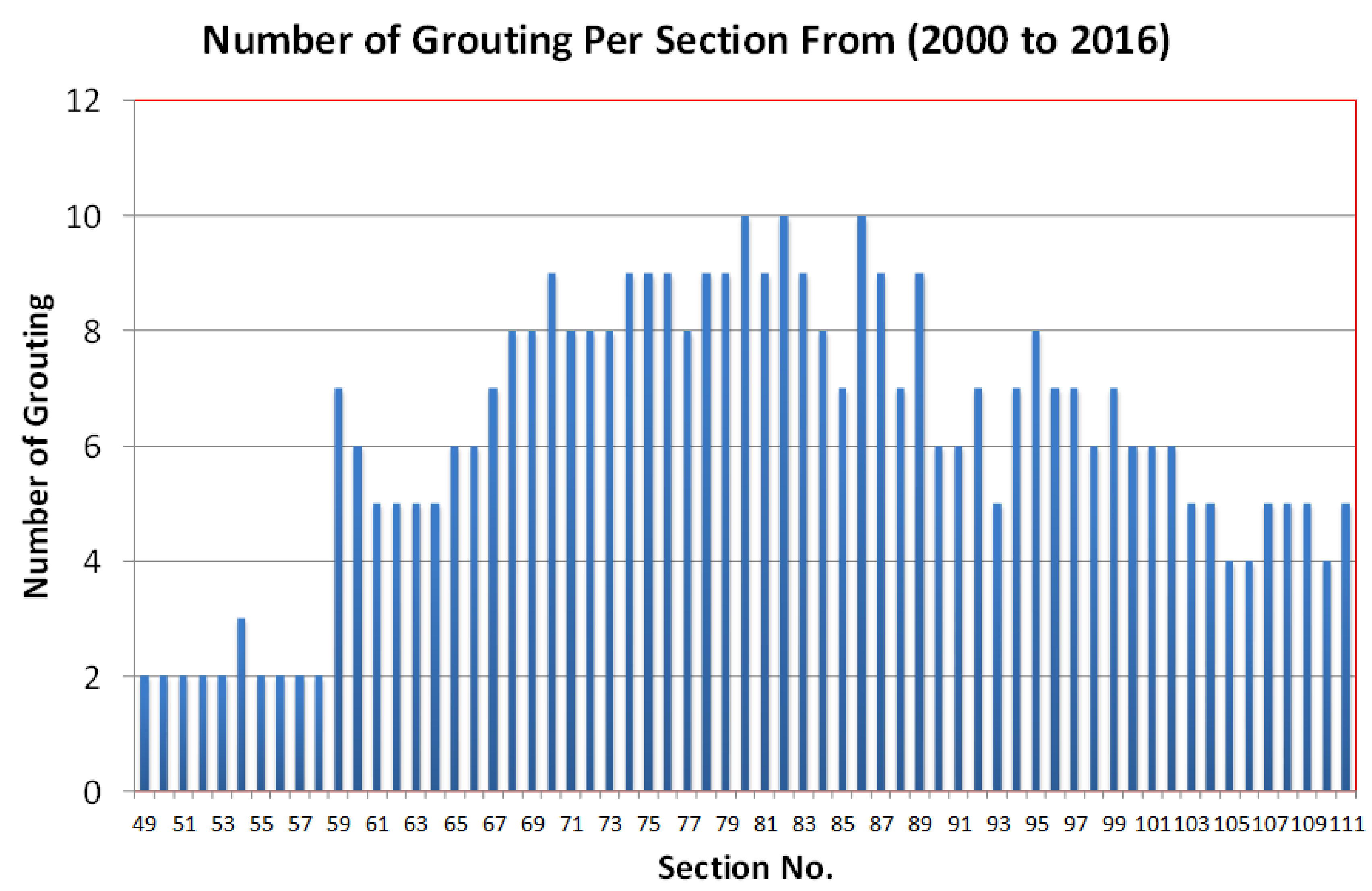
HISTORICAL GROUT LINES

GEOLOGY

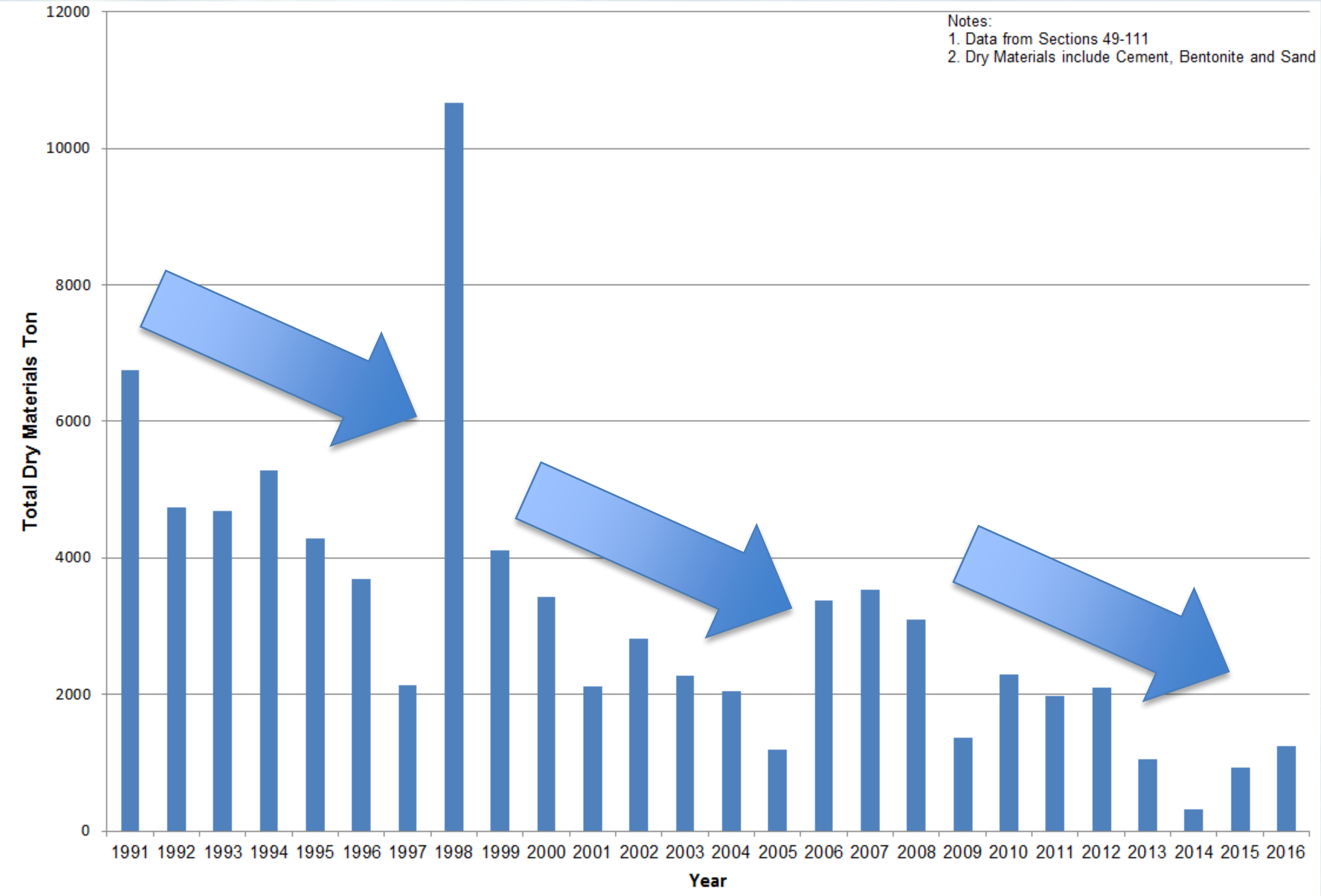
One Dam, Two Foundations



Historical Grouting INSTANCES



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

EMERGENCY GROUTING

MOSUL DAM

GROUTING GALLERY INFRASTRUCTURE

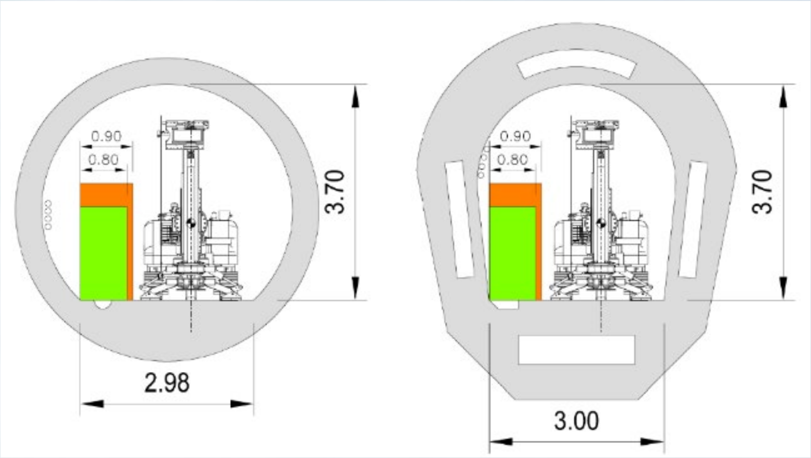
- **Removed**
  - **3,000 m electrical cable**
  - **2,000 m grout lines**
  - **2,000 m water lines**

- **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 AND GROUTING

- 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

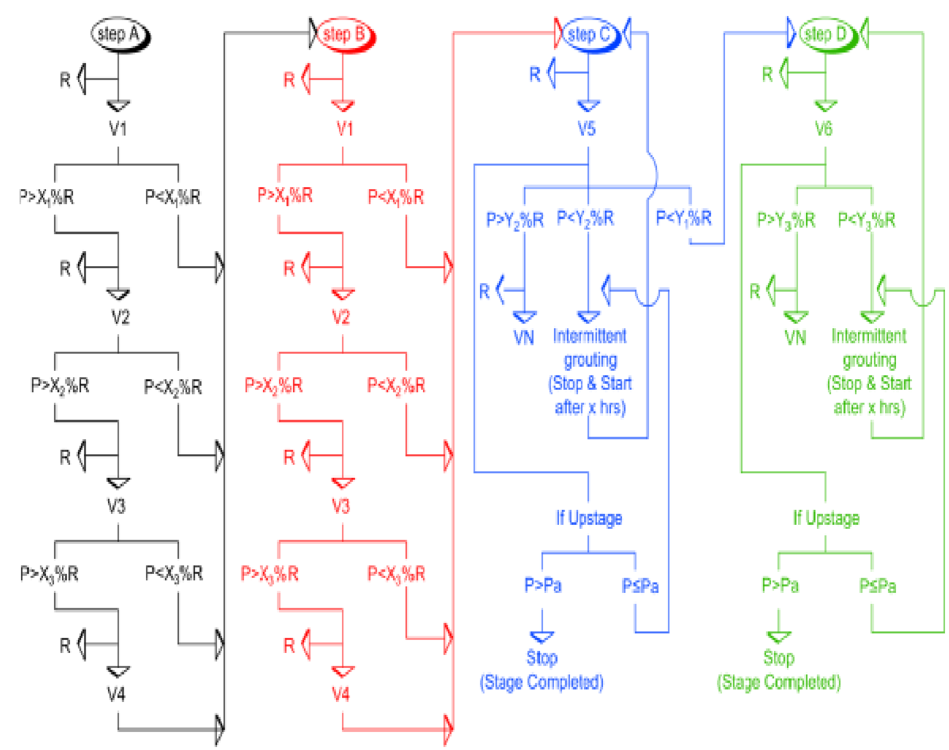
GROUT MIXES

	MIX A			Mix B			MIX C		
	MIX A03			Mix B04			MIX C01		
	kg	lit	kg/m3	kg	lit	kg/m3	kg	lit	kg/m3
W	1000	1000	900	1000	1000	850	1000	1000	753
C	300	97	270	500	161	425	1000	323	753
B	30	13.0	27.0	30	13.0	25.5	10	4.3	7.5
Additive	2.0	1.43	1.80	2.5	1.79	2.13	1.0	0.71	0.75
			density g/cm3			density g/cm3			density g/cm3
	1332	1111	1.199	1533	1176	1.303	2011	1328	1.515
B/W			3.0%			3.0%			1.0%
C/W			30.0%			50.0%			100.0%
Ad/W			0.20%			0.25%			0.10%
Ad/C			0.67%			0.50%			0.10%

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 immediatey 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 = 0.8 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 40,00 stages completed/5 meters stages
- 5,000 + grout holes
- 100-150 tons cement consumption daily

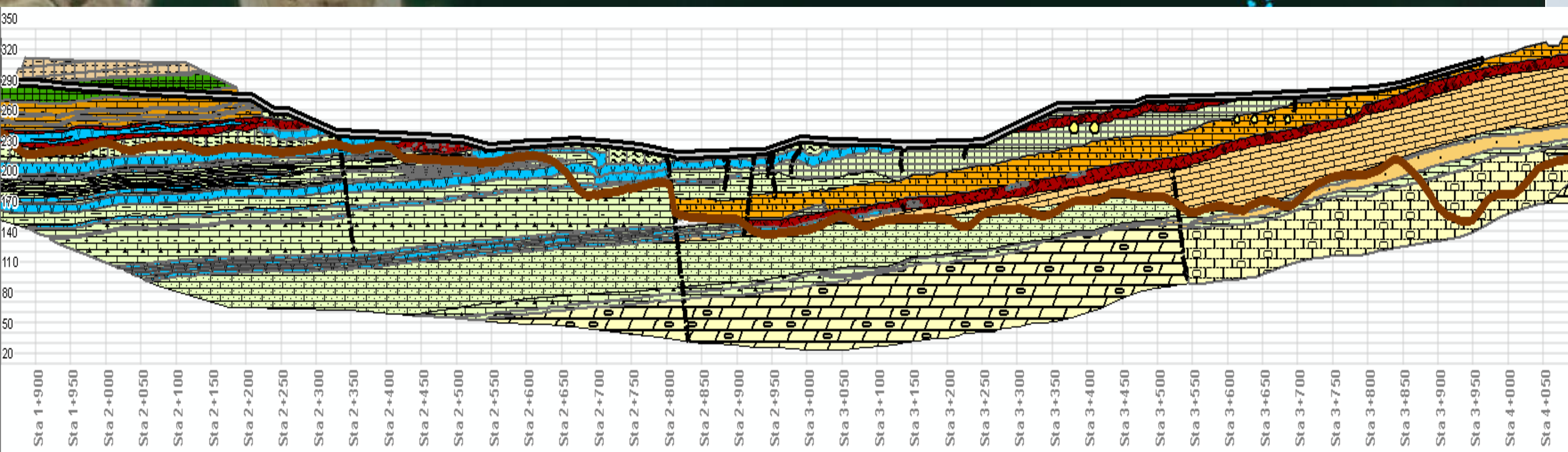
- **Equipment and Operations**
- T-Grout computer monitoring system/GIS system
- 3 Mixing Plants/20 drill rigs/20 BGU’s (secondary pumps)
- 24/6 operations

DRILLING & GROUTING SUMMARY

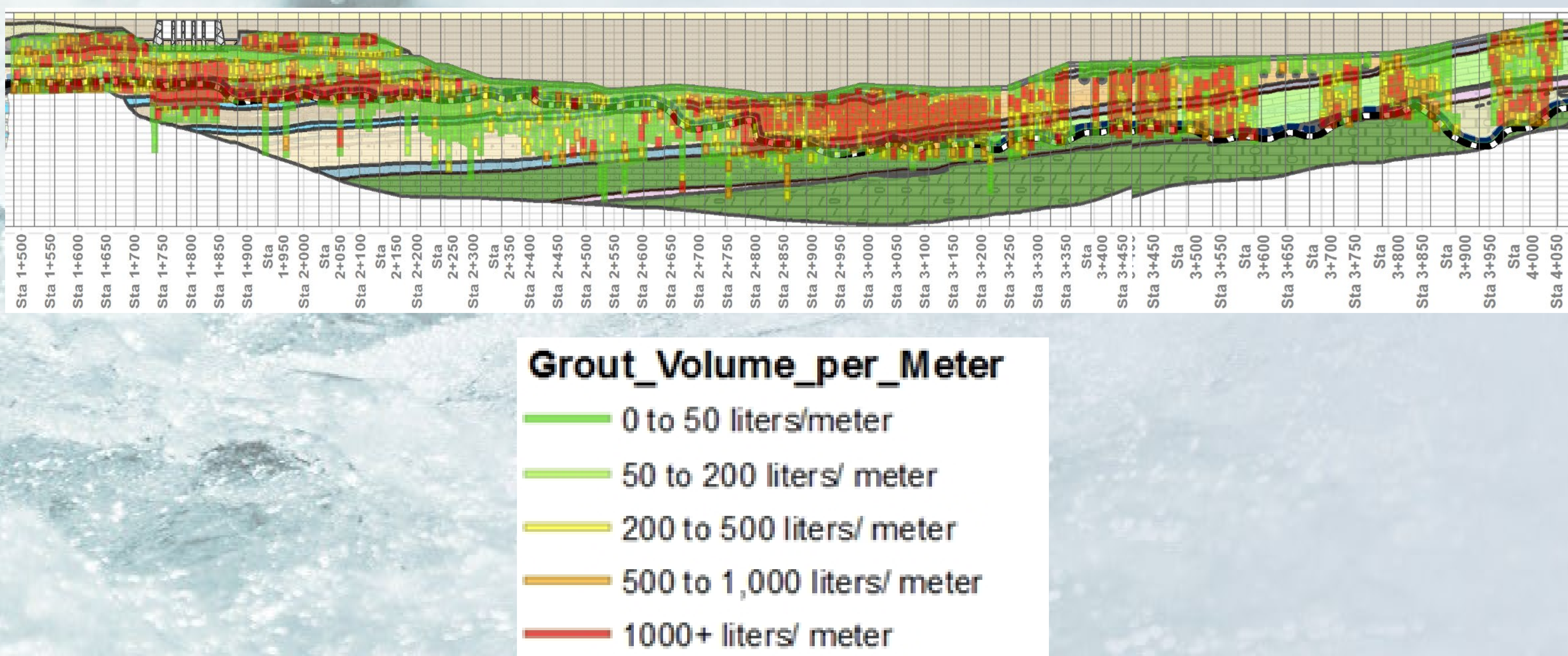
- ✓ 4,850 holes drilled & grouted
- ✓ 348,652 m length of drilling (216 miles)
- ✓ 39,227 m^3 of grout (22,177 tons of solids)
  - ✓ More than the last 13 years combined
  - ✓ **<u>(1.3 Washington Monuments)</u>**
  - ✓ 63000 m3 **previous 30 years**
  - ✓ **(2 Washington Monuments)**
- ✓ **Re-established 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

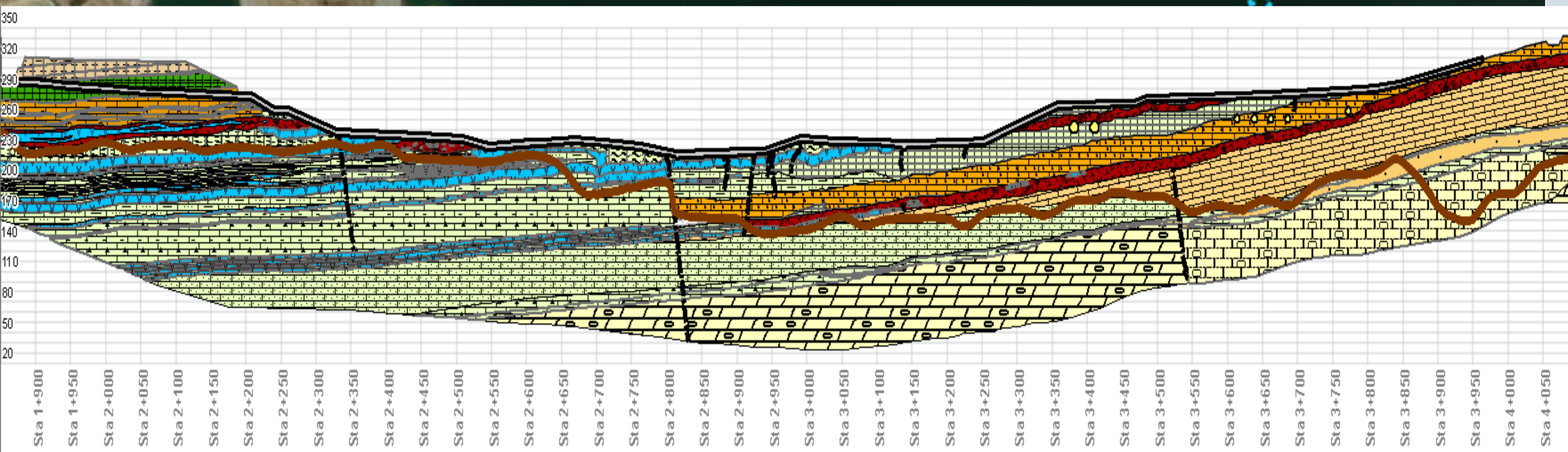


GROUTING RESULTS

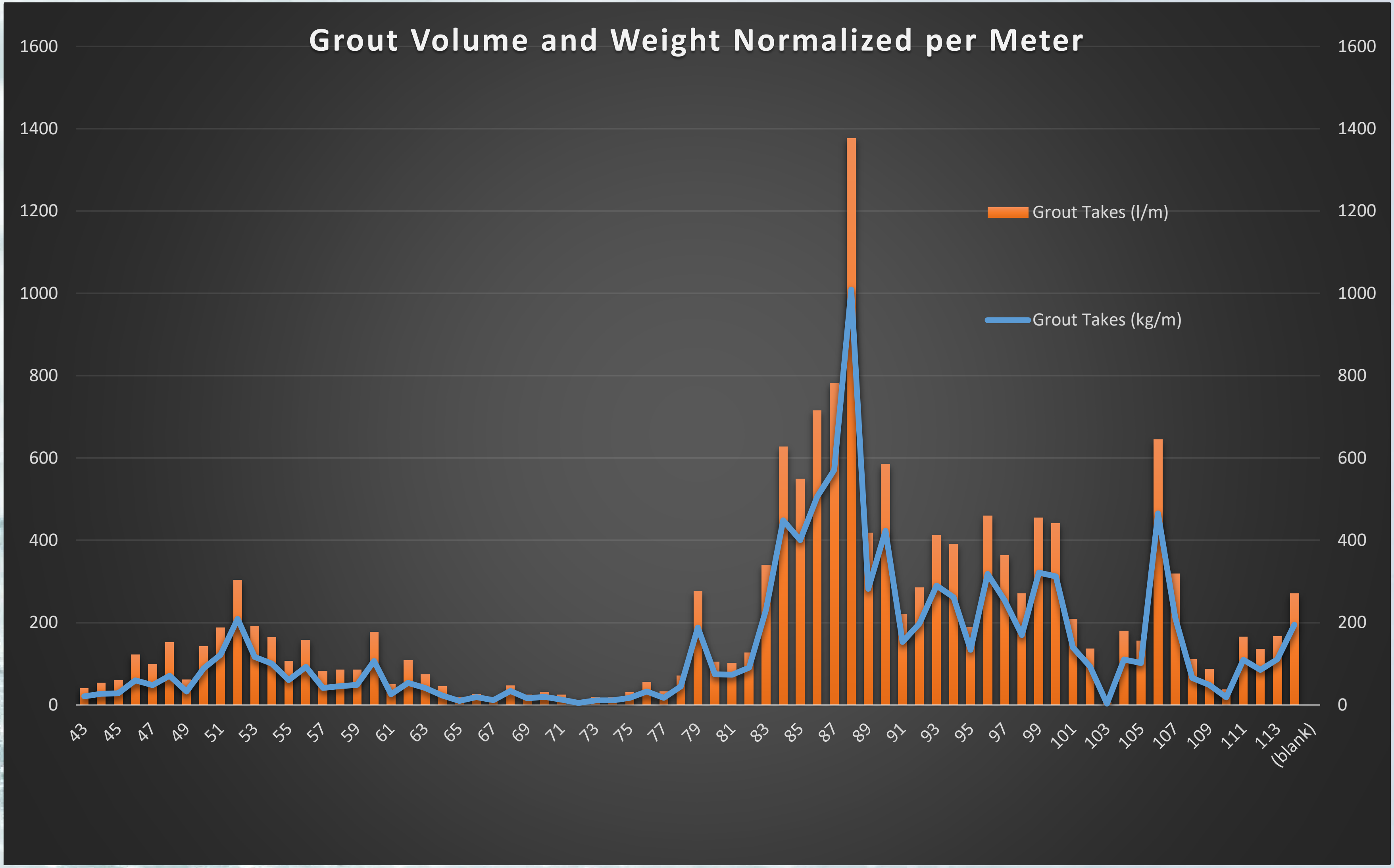


GEOLOGY

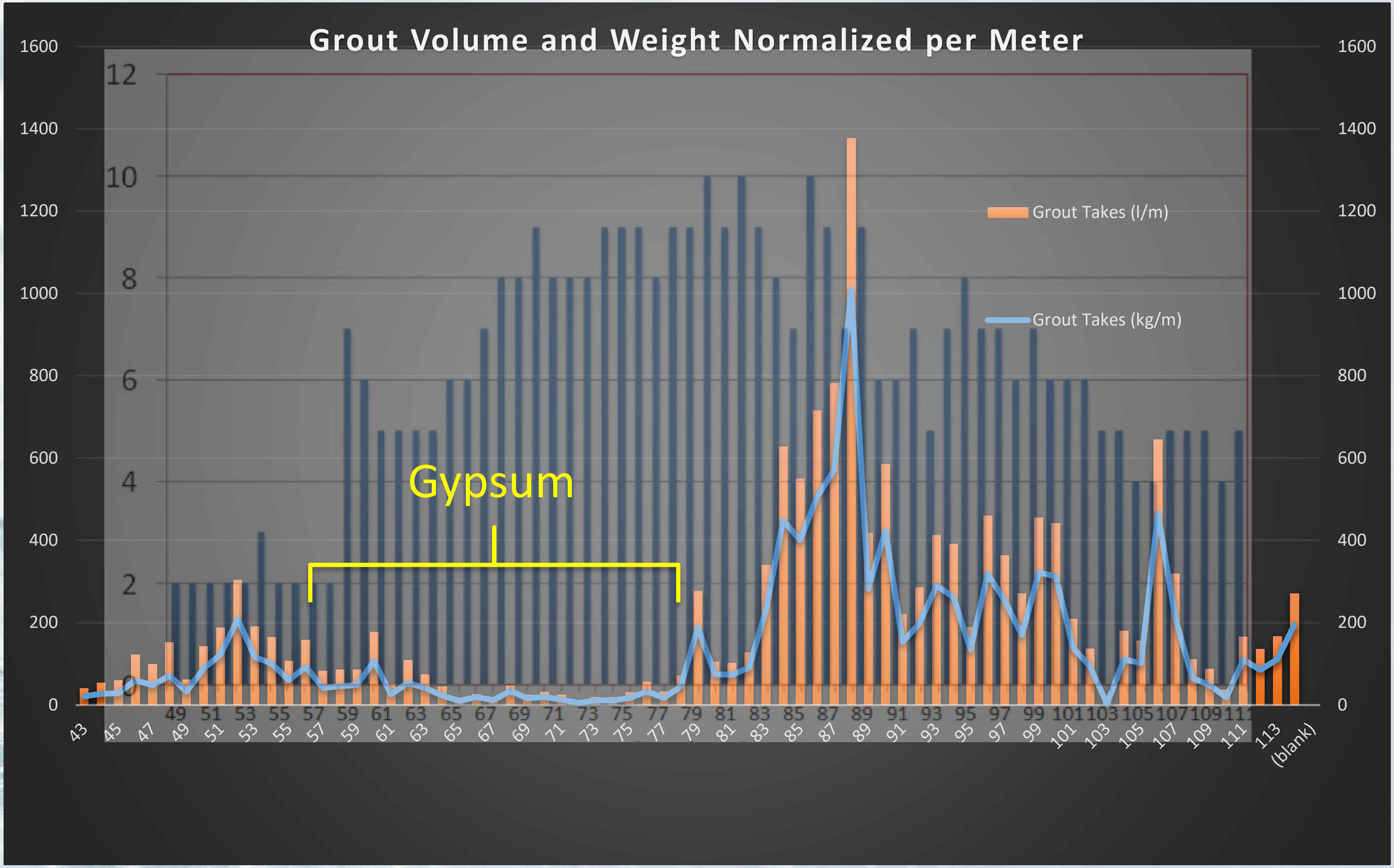
One Dam, Two Foundations



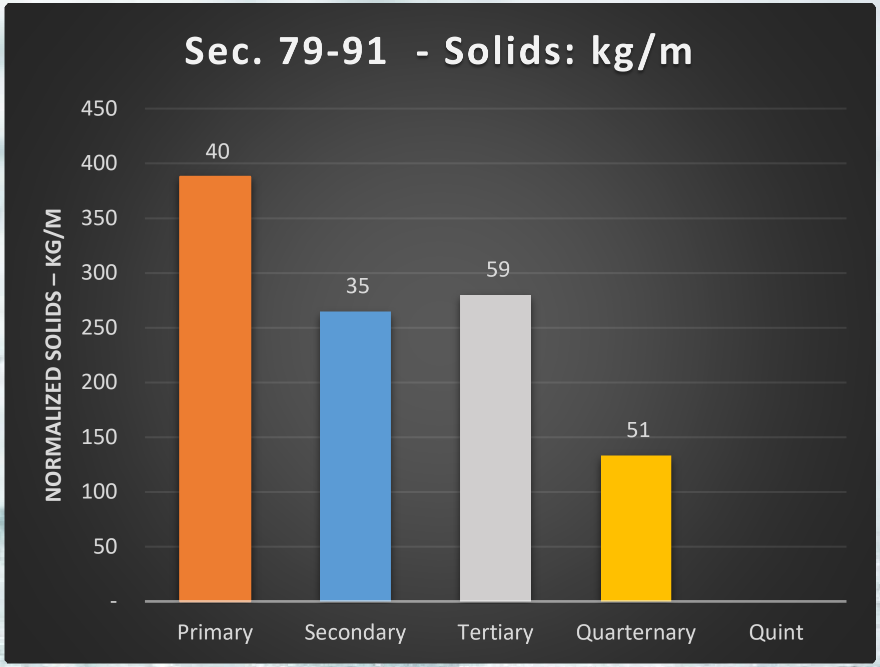
2017 Grout Takes By Section

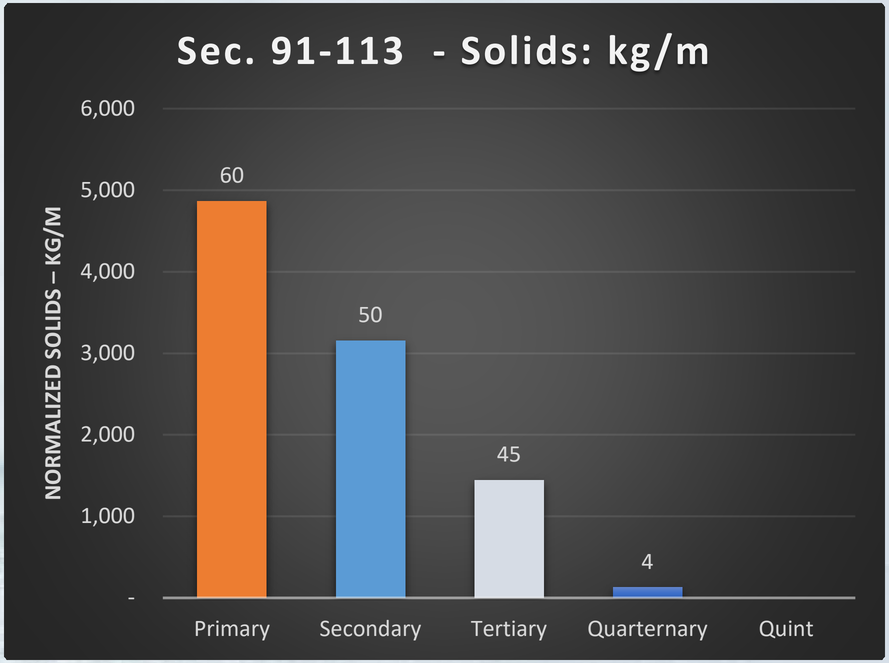


Historical Grouting Instances vs Recent Grout Takes



2017 PSTQ Analysis





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

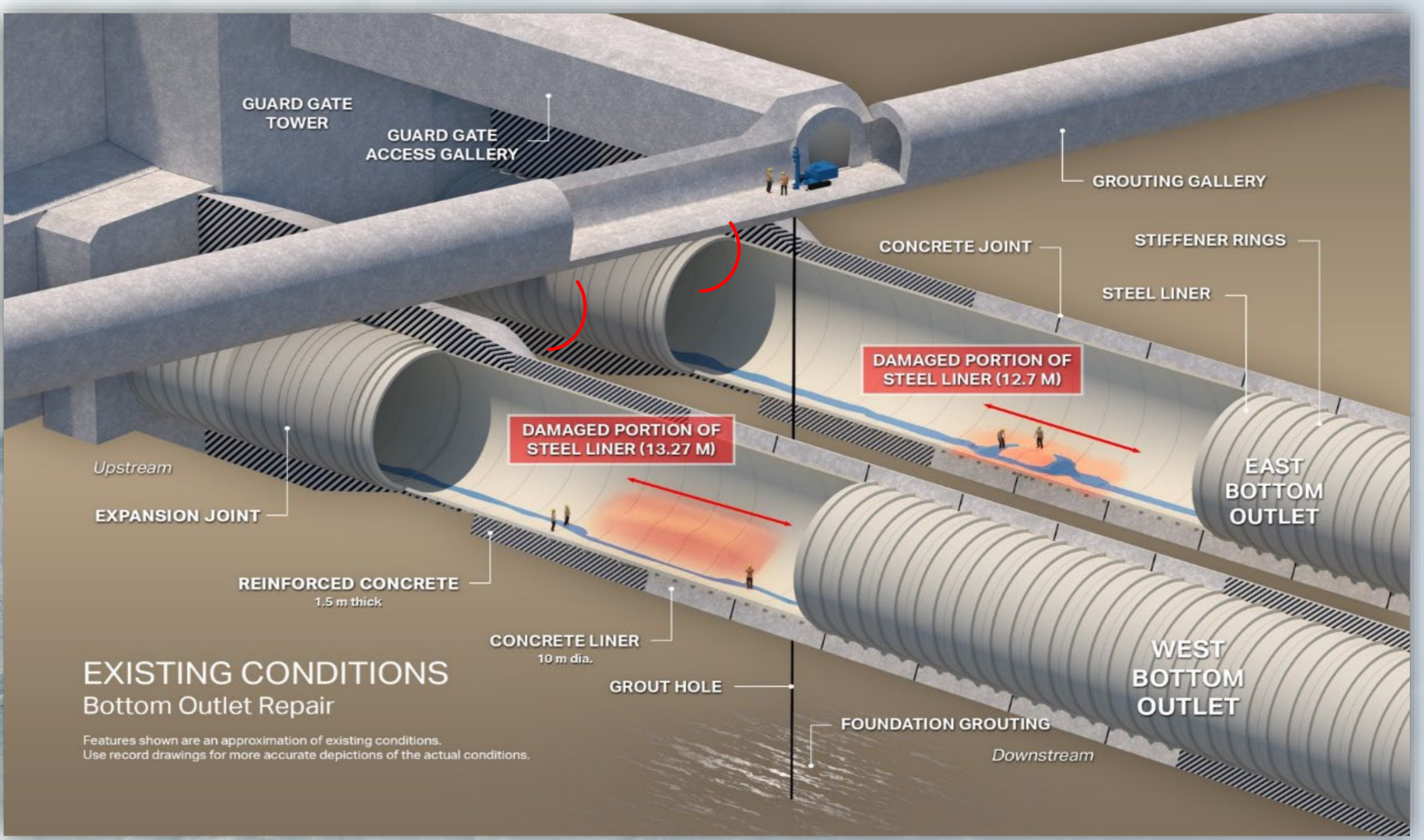
MOSUL DAM

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



RETURN TO NORMAL OPERATIONS
2019 15 YEAR RECORD POOL

Extremism Watch

Mosul Dam No Longer on Brink of Catastrophe

By Rikar Hussein
May 05, 2017 04:15 PM

FILE - Employees work at strengthening the Mosul Dam in northern Iraq, April 18, 2016.

RUDAW

KURDISTAN | MIDDLE EAST | OPINIONS | WORLD | BUSINESS | INTERVIEW | CULTURE | LOCAL | ANALYSIS | MULTIMEDIA

Engineer insists Mosul Dam not in danger despite heavy rain

Rudaw

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Tags: Iraq- Mosul- Mosul Dam- flooding- water crisis

RISK ASSESSMENT

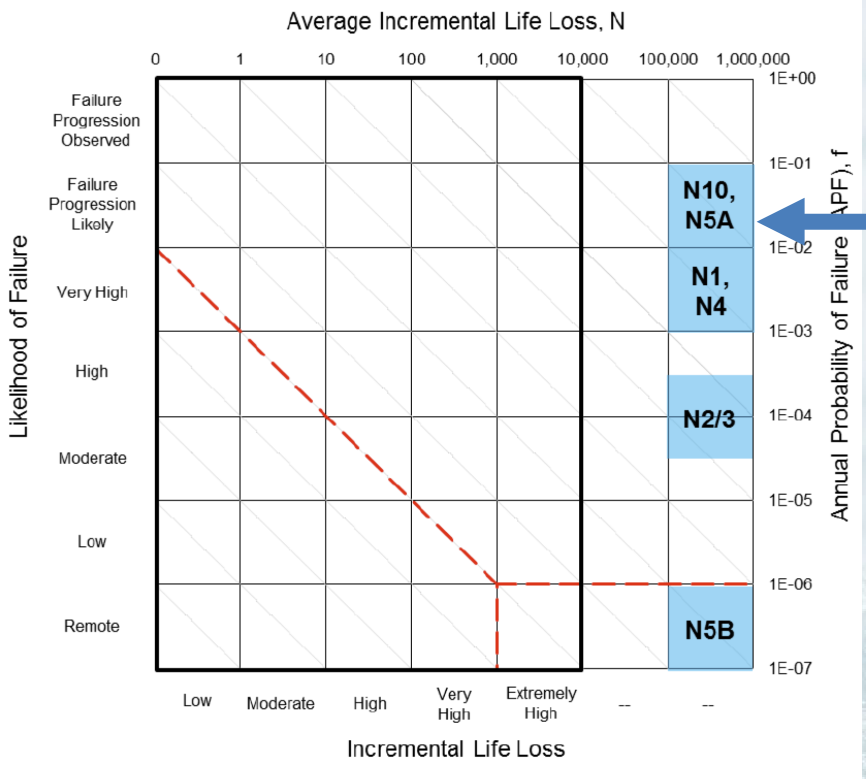
MOSUL DAM

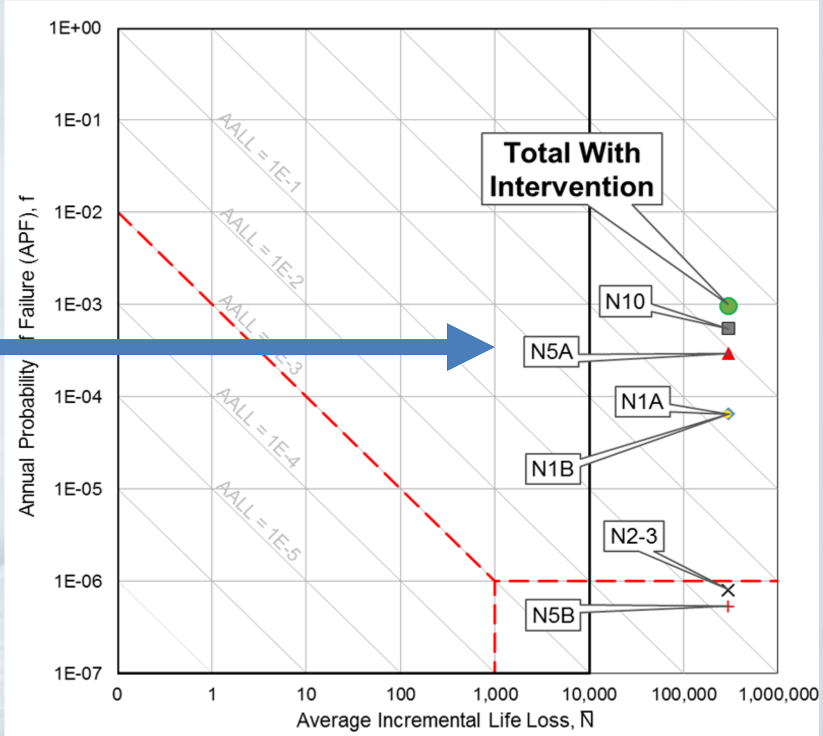
RISK ASSESSMENT RESULTS

Multiple 4 to 6 meter voids

RISK ASSESSMENT RESULTS

Normal Pool Elevation: 330; With Intervention





2016

2018

In general, risks fell 2 orders of magnitude.

Still very high risk due to downstream population

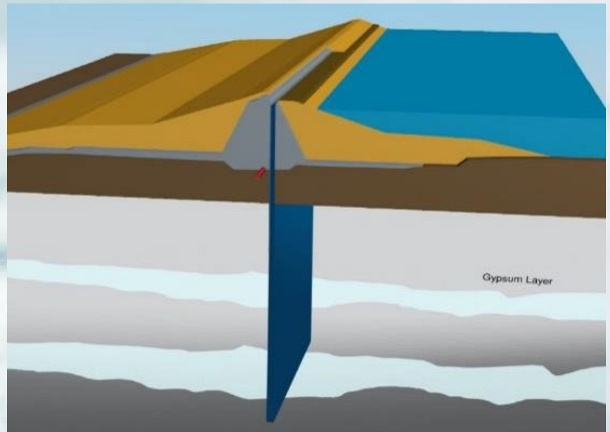
Why have the risks changed?

- 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

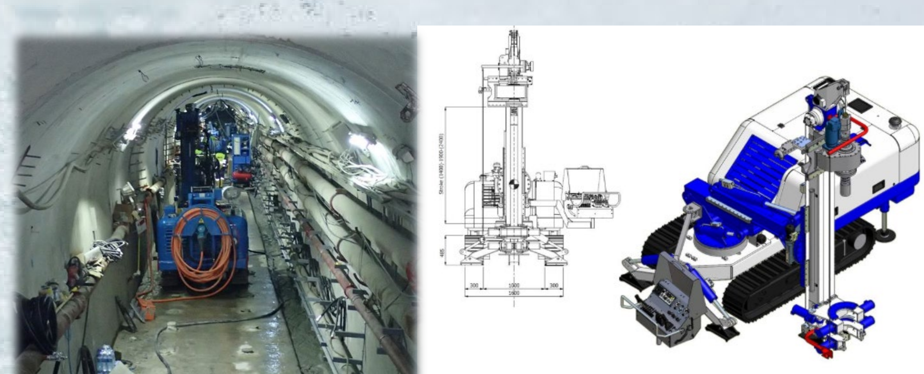


Cutoff Wall

DSMS Alternatives

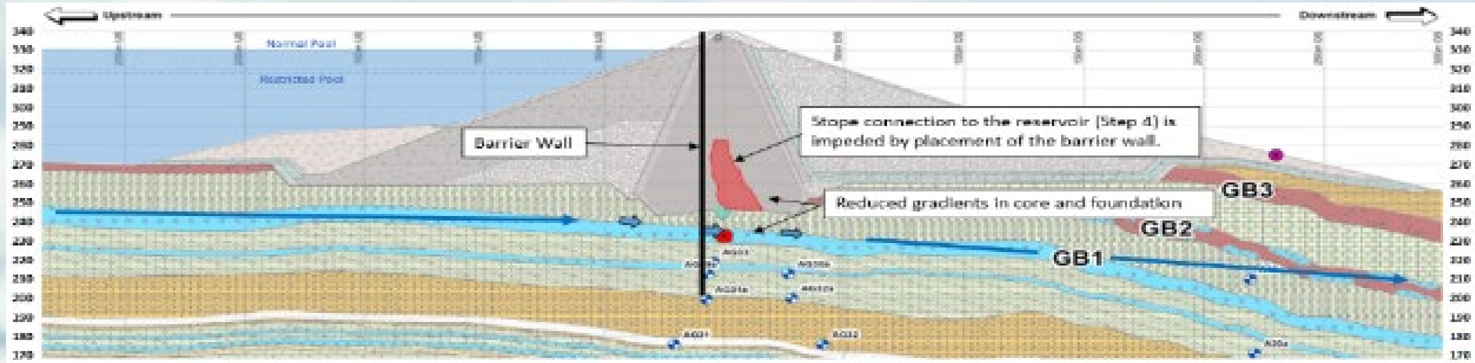
Pool Restriction

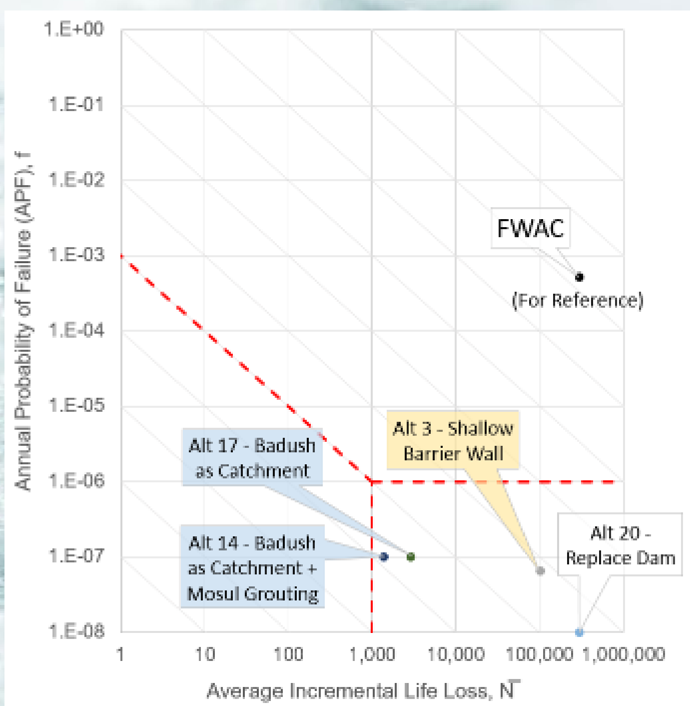
New Dam - Badush

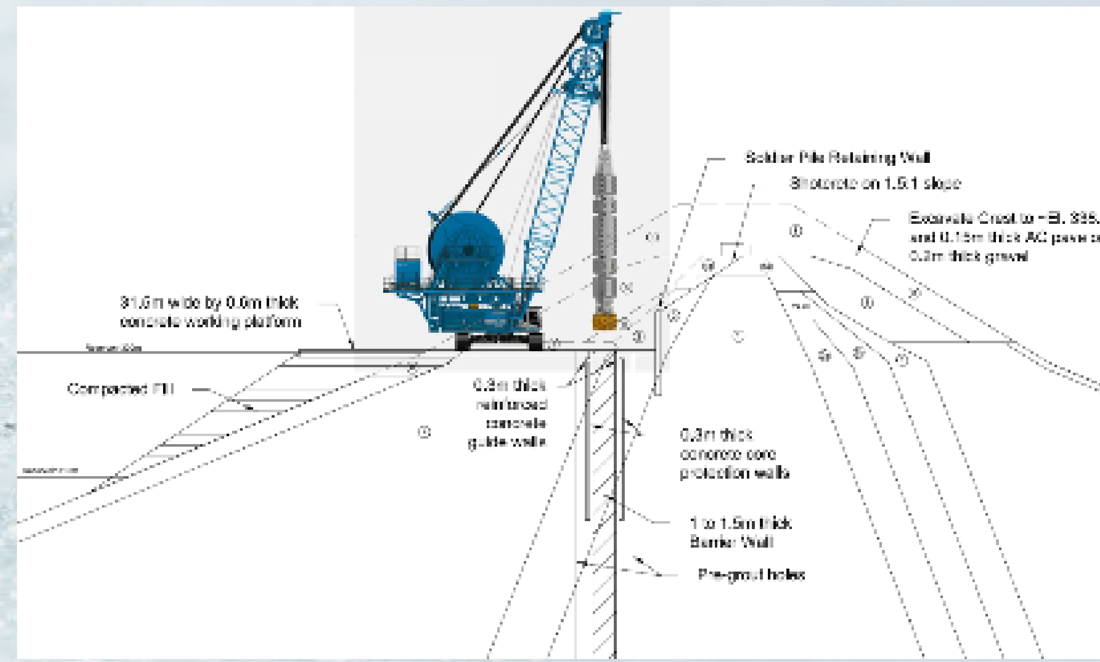


Grouting

GROUTING IS NOT A PERMANENT SOLUTION
BARRIER WALL $3-4.5 BILLION



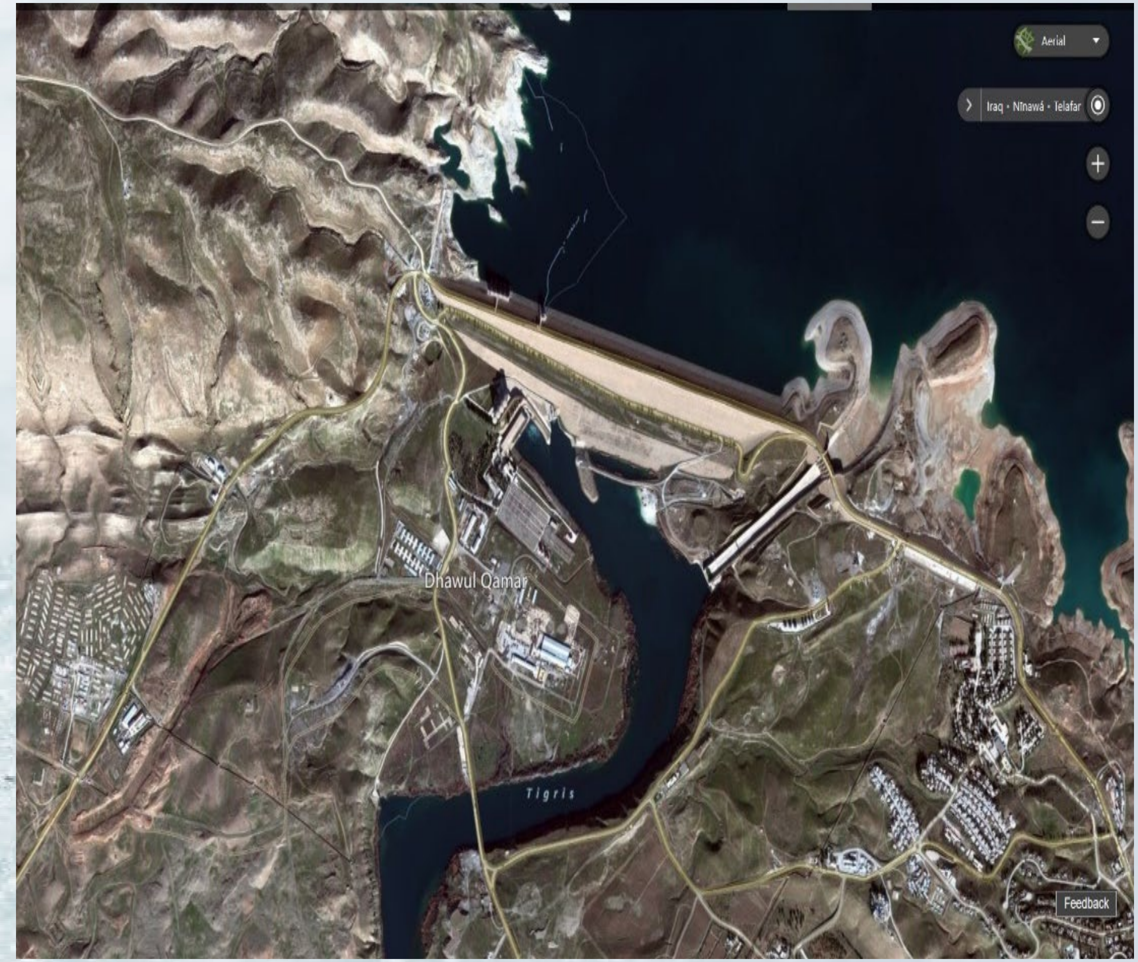




RELATIONSHIPS WERE KEY

Acknowledgements

- COL Michael Farrell, USACE, Commander, Mosul Dam Task Force
- Eric Halpin, USACE, Deputy Dam and Levee Safety Officer
- Bill Empson, USACE, Lead Engineer, MDTF
- Vanessa Bateman, USACE – Data Management
- USACE/AECOM Reachback Team
- Trevi Group
- AECOM




Thank You!

Discussion

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