

Navigating the Intersection of Mechanics and Engineering:

A Personal Odyssey Midst the Alphabet Soup of BoR, EPRI, NRC, ORNL, TEPCO, and Beyond

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Acknowledgments

Golsa Mahdavi

M. Amin Hariri

Jan Cervenka

Yann le Pape

Jerzy Salamon

Madhumita Sircar

C-10

Bureau of Reclamation

Electric Power Research Institute

Florida Power/PII

Nuclear Regulatory Commission

Oak Ridge National Laboratory

Tokyo Electric Power Company

Acknowledgment II

Heartfelt gratitude goes to two exceptional colleagues who, perhaps unbeknownst to them, have had a profound influence on me. Their remarkable personal character and outstanding professional achievements were a constant source of inspiration. **The rare combination of these qualities is regrettably uncommon in our profession.**



Kurt Gerstle



Kaspar Willam

Introduction

- There are times when Engineering problems are **too challenging for the Profession**.
- Time to call an **expert from Academia**.
- I have been involved in a few of them, where I had to combine my combined expertise in **fracture mechanics, AAR, probabilistic methods, nonlinear dynamic finite element analysis**. Skills acquired through my research over 30 years.
- When there is a **common denominator** to those problems, it is interesting to compare, contrast.
- I will address five projects, all but one shared a common underlying issue: Aggregate Reaction (AAR)

TEPCO
Crystal River

Tokyo Electric Power Company
Utility Company

R/C transmission tower
Delamination of a Nuclear Containment Building

ORNL

Oak Ridge National Laboratory

Nuclear Containment Building with AAR

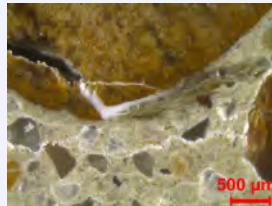
C-10/NRC
BoR

Nuclear Regulatory Commission
Bureau of Reclamation

Seabrook nuclear power plant
AAR in a arch-gravity dam

What is AAR

- AAR (Alkali Aggregate Reaction) is a lasting, irreversible reaction in concrete that leads to gel formation, concrete expansion, and degradation of mechanical properties over the long term.
- This phenomenon is intricate and multi-faceted, capturing the interest of various experts, including petrographers, cement chemists, material engineers, modelers, and civil engineers.
- Numerous experts specialize in various subfields.
- However, there are **very few individuals with comprehensive expertise covering theoretical modeling, laboratory and field testing, constitutive model development, finite element integration, and nonlinear seismic probabilistic analysis.**
- I am one of them 😊



Mathematics → Mechanics → Engineering → Codes

- **Mechanics** is the paradise of the mathematical sciences because by means of it one comes to the fruits of mathematics

Leonardo

- **Mechanics** is the grammar of **engineering**.

James Maxwell

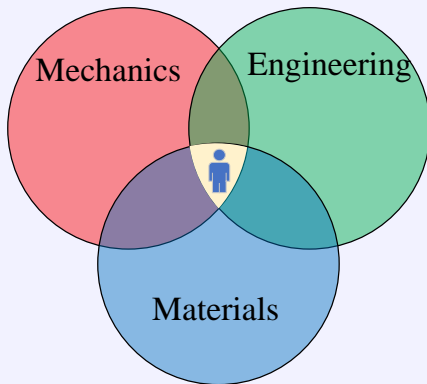
- Design code, is a simplified, no-brainer application of **engineering** practice

Victor Saouma

But what do you mean by Mechanics

- All solutions should **prioritize a foundation in mechanics** (i.e., no reliance on heuristics or code-based approaches).
- Mechanics is more than a concept; it's a **necessary mindset** for solving engineering problems
- In essence, a mechanics-based solution refers to one grounded in: 1) Reliable laboratory tests; 2) Semi-analytical constitutive models, and Proper mathematical and mechanics-rooted modeling.
- This is meant to be a **motivational** lecture to sesm students.



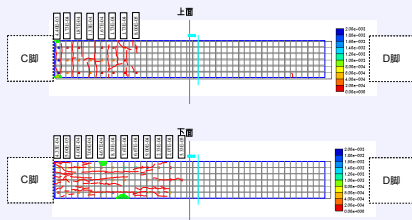
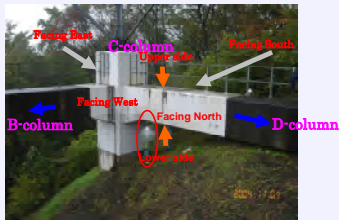


A profound comprehension of intricate materials, like concrete or soil, is indispensable in certain situations.

Engineering only; Exceptional people only

In specific instances, an **exceptionally thorough understanding** of structural principles by a **seasoned engineer** can suffice—examples include dam designers like Howard Boggs or building architects like Bill Baker.

TEPCO Massive R/C Frame



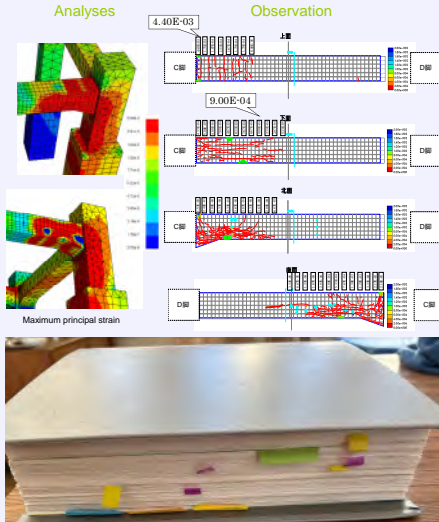
Memorable Quotes

- "Very cheap"
- "No AAR"
- "Perfection"

Observations

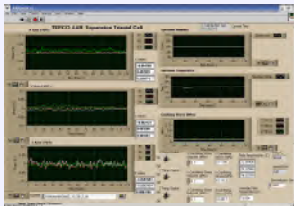
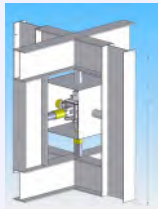
- Excellent field measurement
- Excellent analysis (Merlin)
- Excellent documentation,
- Transparent, published results

Analysis and Report



Japanese like big, thick reports!

TEPCO's Engineer Culture

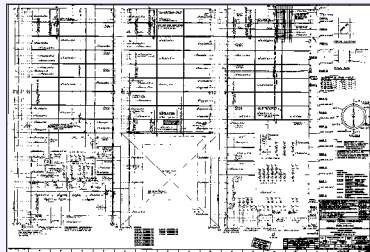
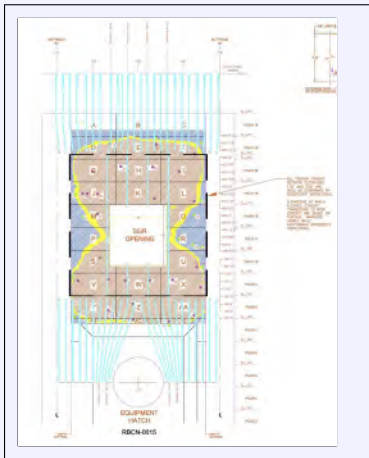


- Designed and built an innovative triaxial testing machine to monitor AAR expansion
- not quite working, sponsor could not understand difference between contract and research
- Afraid to report to the boss; asked to “pad” report with pages of confusing screen shots of the control panel

Crystal River/FP/PII

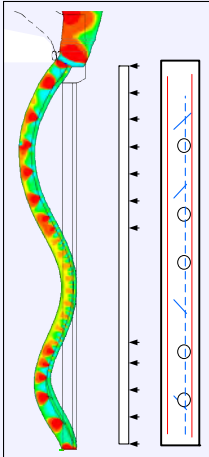


The Problem & the Solver(s)

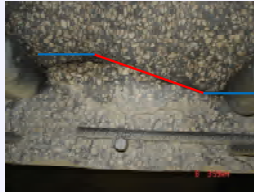


- Florida Power selected a “well connected” company PII.
- “Experts” in finite element modeling: Printers at HP.
- Had no idea what was creep
- Found me on the internet (\$\$\$ 😊)
- Exposure to the very well organized root cause investigation process
- Did not agree with their final report: pull out my name.

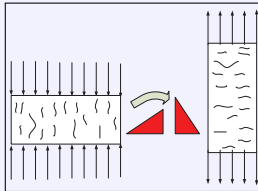
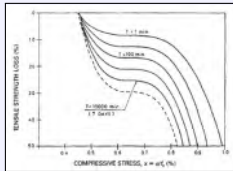
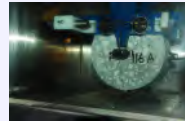
Back of the Envelope solution: Always first step



- Creep plus time: **inward radial displacement**.
- Release tendons: creep recovery, and segment of the wall unloaded, “bulge outward”, **skin reinforcement prevent cracks** on the exterior (none detected).
- Tendons right above and below cut not released, **sharp change in curvature**, large moment and shear.
- **No shear reinforcements**, shear cracks start inside, however sleeves of tendons “deviated” the cracks, ultimately causing **delamination**.

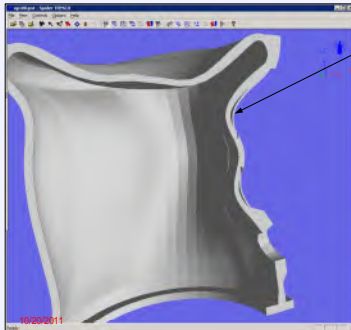
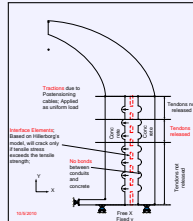
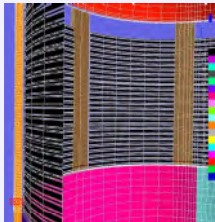
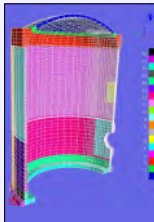


Some "Advanced" Testing



Drop in E and f_t . Careful, must investigate creep fracture.

Some "Advanced" Finite Element Analysis



Note delamination above and below SGR cut. This is increment 15 (concrete removal).



EPRI: Electric Power Research Institute

Structural Modeling of Nuclear Containment Structures

00-10006428

3rd Draft, Mar. 2017

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University of Colorado, Boulder

EPRI Project Manager
M. Guzman

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- One major project in the late 80's and this most recent one
- It is funded by utility companies, research must be “palpable” to engineers with a B.S/M.S at best.
- If your report is too detailed, they will ask you to cut it down and to “simplify” it.
- If they do not like your findings (which may not be what the industry would like to see), they will cut it out.
- Reasonably qualified program directors.
- Reports free to members, otherwise flat cost \$10k

AAR & Nuclear



Alkali-Silica Reaction (ASR) Where is ASR Confirmed to be Occurring at Seabrook?

- Affected Structures include:
 - B Electrical tunnel
 - Containment enclosure building
 - RHR vault
 - EDG building
 - EFW building

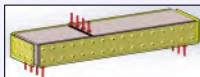
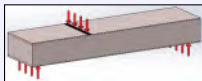
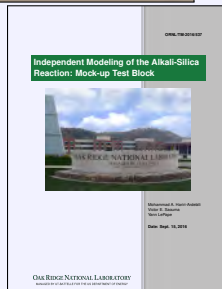
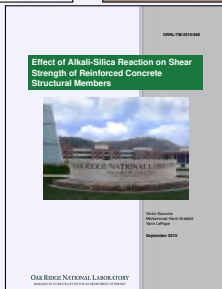
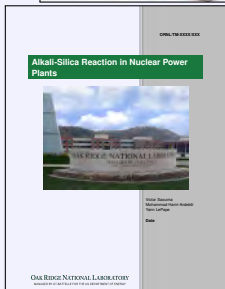


- For the first time, a nuclear reactor bldg, **Seabrook Station NPP Unit 1** was found to suffer from AAR. Panic!
- NRC caught **unprepared** for such a problem.
- Multiple “players”

NRC NextEra SGH U. TX

ORNL NIST CU C-10 **Saouma PhD-Curran Esq.**

- In 2010 NextEra submitted an application for renewal of the operating license for another 20 years beyond the current licensing date of 2030. **They had just learned that AAR existed but did not mention it!**



No bureaucracy, great
sponsor, **top notch**
engineers!

NRC's Approach

- No expertise,
- No external expert advisors.
- **Let NextEra come up with a plan**; will simply review/criticize/endorse
- All what NextEra has to do is to show that the **structures remain compliant with the ACI-318-71** code.
- Never mind all acquired knowledge since then.
- Funded some research. Internal feud as who is best. Finally settled for
 - ① Material: NIST (never had a scientist with a single peer-reviewed publication on AAR!), \$\$\$\$.
 - ② Structure: University of Colorado/Saouma \$
 - ③ No final independent peer-review; Very complacent toward Nuclear Industry.
- Extremely **transparent** through Agency wide Documents Access and Management System (ADAMS).

NRC Funded Research @ CU

Experimental and Numerical Investigation of Alkali Silica Reaction
in Nuclear Reactors

Grant No.: NRC-HQ-60-14-G-0010

Oct. 2014 - Dec. 2017
(\$703,197)

FINAL (PUBLIC) SUMMARY REPORT*
DECEMBER 2017

PRINCIPAL INVESTIGATOR
VICTOR E. SAGUMA
University of Colorado, Boulder

NRC TECHNICAL CONTACT
MAHUMITA SIRCAR

- ① 1-A: Design of an AAR-Prone Concrete Mix for Large-Scale Testing (93 pages).
- ② 1-B: AAR Expansion; Effect of Reinforcement, Specimen Type, and Temperature (123 pages).
- ③ 1-C: Effect of AAR on the Shear Strength of Panels (90 pages).
- ④ 2: Diagnosis & Prognosis of AAR in Existing Structures (191 pages).
- ⑤ 3-A: Risk-Based Assessment of the Effect of AAR on Shear Wall Strength (25 pages).
- ⑥ 3-B: Probabilistic-Based Nonlinear Seismic Analysis of Nuclear Containment Vessel Structures with AAR (216 pages).

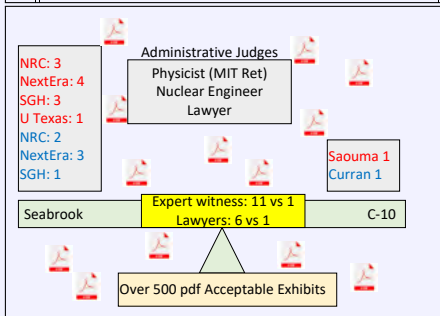
NRC Funded Research @ NIST

No identifiable (Google Scholar) prior research on AAR, but NIST is NIST

- Large scale testing of a huge beam with various reinforcement to assess internal expansion, and shear strength from cut block
- Finite element modeling with LS-Dyna (freshly minted PhD), using the Saouma-Perotti model 😊

C-10/Saouma vs. NRC (& NextEra & SGH & U Texas) Let the Game Begin!

5	+	+	+	+	+
6	HEARING				
7	-----x				
8	In the Matter of:			Docket No.	
9	NEXTERA ENERGY SEABROOK, LLC	:	50-443-LA-2		
10	(Seabrook Station, Unit 1)	:	ASLBP No.		
11				17-953-02-LA-BD01	
12	-----x				
13	Tuesday, September 24, 2019				



Main Safety Concern (Saouma)

- No shear reinforcement.
- Ability to resist seismic load.
- “Hidden” internal crack/delamination

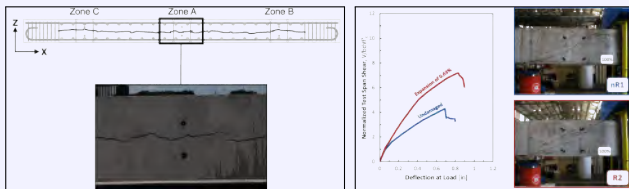
Licensee's Responsibility

The burden on the licensee is that the structures are required to remain operable. And they are required to **continue to stay within their design and licensing bases**. And so what the licensee opted to do to **demonstrate that the design codes and licensing basis remains intact** was the charge of the staff to review. So **looking beyond the codes is outside of the scope of the requirement for the structures to remain operable and to stay within the bounds of their licensing basis.**

NextEra's Approach

- Assigned SGH for various tasks, including field crack measurements, large-scale tests in Texas, finite element analysis, and the **adaptation of ACI-318-74 code to accommodate AAR as a supplementary "load."**
- (SGH) Great company, **operated in a completely different realm compared to academia—a purely simplified engineering approach**, without any endeavor to incorporate advanced mechanics or AAR knowledge, such as understanding the role of internal micro-cracks and moisture distribution.
- There is a substantial dependence on observed cracks to assess deterioration.
- **A license amendment request** has been submitted based on the proposed monitoring approach.
- Worth noting the **absence of any external peer review** by an AAR expert, which may be indicative of an attitude of arrogance rooted in narrow-minded engineering perspectives.

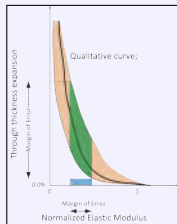
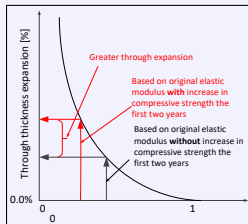
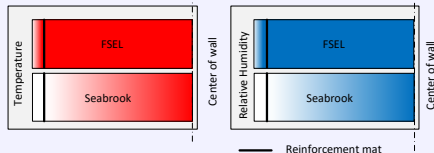
Texas



- Large scale testing (TX size).
- (Unanticipated) Structural crack (of course!), yet shear results used for validation
- One of many! many other baffling findings
- Very large AAR expansion

Crack Measurements

Misleading surface (or near surface) crack measurements



If surface and through thickness (near surface) expansions reach a threshold,

- 1 Measure local elastic modulus E_c
- 2 Retrieve neighboring stored cores
- 3 Measure its f_{c0}
- 4 Determine $E_{c0} = 57,000 \sqrt{f'_{c0}}$

5 Compute $E_n = E_{c0}/E_c$

6 From laboratory calibration curve determine corresponding $\Delta \epsilon^{AAR}$

Very flawed; DANGEROUS

Summary of Board Holdings and License Conditions

The Board finds that the following conditions are necessary ...

- ① NextEra shall undertake the monitoring for control extensometers every six months, rather than in 2025 and every ten years thereafter.
- ② If stress analyses ... NextEra must develop a monitoring program sufficient to ensure that rebar failure or yielding does not occur, or is detected if it has already occurred, in the areas at-risk of rebar failure or yielding.
- ③ If the ASR expansion rate in any area of a Seabrook... significantly exceeds 0.2 mm/m (0.02%) through-thickness expansion per year, NextEra's ... will perform an engineering evaluation focused on the continued suitability of the six-month monitoring interval for Tier 3 areas....
- ④ Each core extracted from Seabrook Unit 1 will be subjected to a petrographic analysis to detect internal microcracking and delamination.

Thanks from the city of Newburyport

for protecting the public health and the natural environment of Newburyport and beyond.

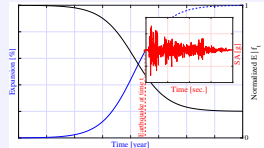
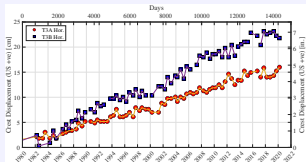


Bureau of Reclamation

- A Nameless dam, operated by Reclamation was found to suffer from AAR
- Prior in house studies, plus another one by a major consulting firm were not found to be satisfactory and **more in depth knowledge was needed.**
- **Contracted with CU to work on a Collaborative agreement** to shed some light on the issue of AAR in dams.
- Essentially, three major tasks:
 - ① **Literature Survey**
 - ② **Road Map for the Structural Assessment** of Concrete Dams Suffering from AAR with Specific Application to XXXX Dam
 - ③ **Long Term Assessment of “the” Dam** Suffering from Alkali Aggregate Reaction; Analyses Results

The issues

- The dam is 90 m high arch gravity dam.
- Q1: What is the expected extent of damage due to AAR?
- Q2: How resilient is the dam against an earthquake?
- Perform sufficient analyses to facilitate decision making about the long term health of the dam.



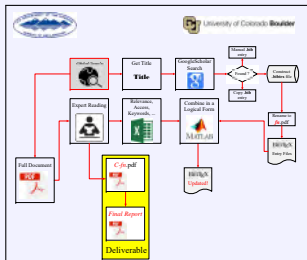
Literature Survey

Long Term Assessment of Dams Suffering from Alkali Aggregate Reaction; State of the Art Review

COOPERATIVE AGREEMENT No. R18AC00055

JULY 29, 2020

MOHAMMAD AMIN HARIRI-ARDEBILI
VICTOR E. SAOUMA
University of Colorado, Boulder



Road Map

Road Map for the Structural Assessment of Concrete Dams Suffering from AAR with Specific Application to [REDACTED] Dam

COOPERATIVE AGREEMENT NO. R18AC00055

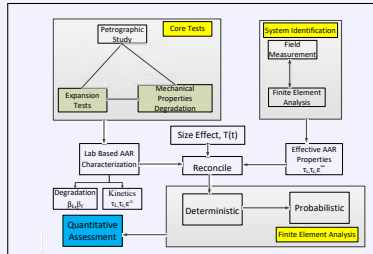
MARCH 14, 2023

VICTOR E. SAUMA
MOHAMMAD AMIN HARIRI-ARDEBILI

University of Colorado, Boulder

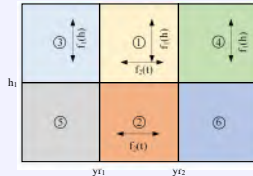
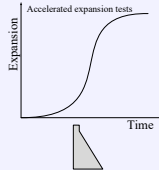
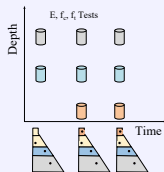
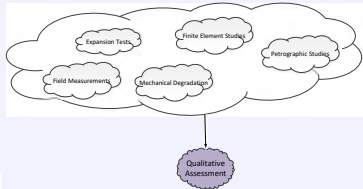
109 page report covering

- Review of existing documents
- Site investigation
- Concrete AAR & Fracture
- Laboratory investigation
- Analysis procedure



Current Practice

- Many (good) players, but little (bad) symbiosis
- Partition (arbitrarily) dam into zones and perform “tests”.
- Spatial and temporal interpolations.



Different Galaxies

"State of the Practice"

of Analyses Multiple, one for each year we are interested in

Parameters Topological distribution of damaged concrete properties over the dam at the time of analysis
How do we obtain them **Partition** the dam in multiple regions; Extract sufficient representative cores from each one of them; perform tests (E and f_c primarily)

Advantage **Easier** to perform the analysis

Dis-advantage **Approximate** does not capture: 1) interaction of temperature with AAR expansion; 2) effect of confinement on the anisotropic expansion;

Displacements/stresses **Analysis Output** **Yes, a snapshot at time t** (of analysis), i.e. one single scalar quantity at time t

Concrete deterioration **No**, that was part of the input

Possible Based on the **time dependent concrete deterioration**

Reliability **Low** would rely on the extrapolation of concrete damage measured in the laboratory and inputted in the mesh

State of the Art (e.g. Merlin)

Single analysis that starts at time 0 (dam construction) up till desired year

Characteristics of the concrete expansion to capture its kinetics (3 parameters)
 Accelerated expansion tests or preferably **parameter identification**

Single analysis that capture the entire response. Parameter identification is an automated lengthy procedure.
 Some numerical instability may occur in a non-linear time history analysis

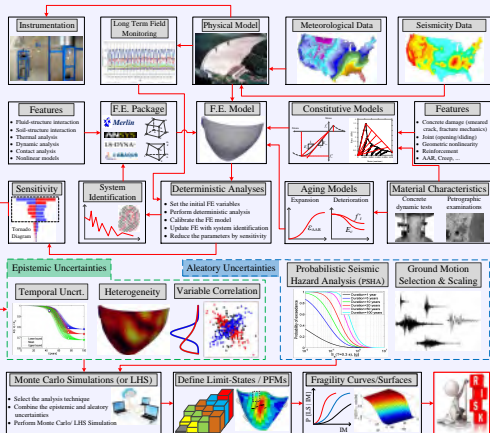
Yes, a "movie" that captures the **evolution** of the dam response, i.e. a vector for each response in terms of time)
Yes as computed by the AAR model

Yes By just letting the analysis go beyond present date.

High, embedded in the analysis are the expansion characteristics

The CU Way

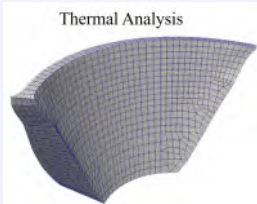
- Instrumentation
- FE model
- Nonlinear material
- AAR model
- Hazard analysis
- Sensitivity analysis
- Model calibration
- Uncertainty sources
- Probabilistic simulation
- Damage index
- Capacity models
- Fragility functions
- Risk assessment
- Decision making



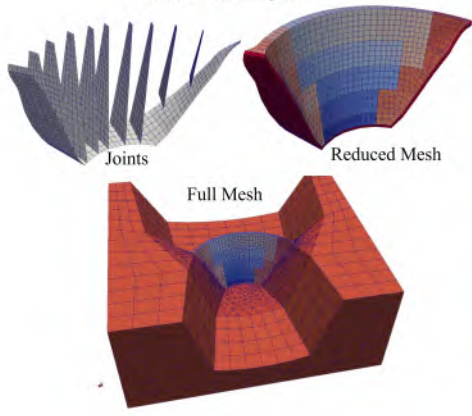
FEA Meshes

- Finite element mesh generated for Thermal and Static analyses

Thermal Analysis



Static AAR Analysis



Long Term Assessment of a Dam Suffering from Alkali Aggregate Reaction; Analyses Results

Long Term Assessment of Dams Suffering from Alkali
Aggregate Reaction;

Analyses Results
Final Report

COOPERATIVE AGREEMENT NO. R18AC00055

MARCH 11, 2023

GOLSA MAHDAVI
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UNIVERSITY OF COLORADO, BOULDER

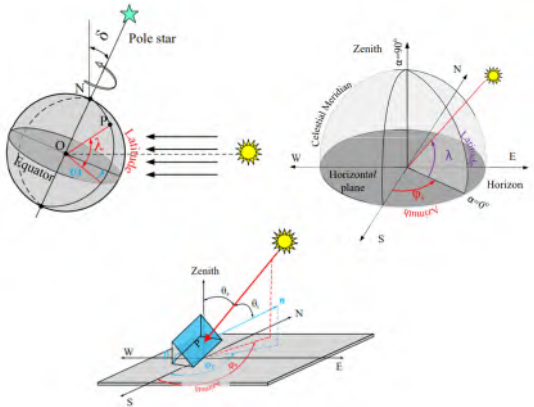
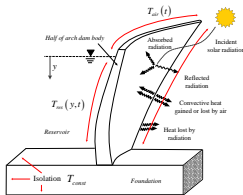
CU

Most comprehensive study,
thermal, probabilistic,
Matched perfectly well
the kinetic of the crest
horizontal and vertical
displacements.

Did not match downstream
cracks allegedly caused by
AAR (yet never measured,
and may be caused by
shrinkage and other rea-
sons). Strong disagreement
with sponsor

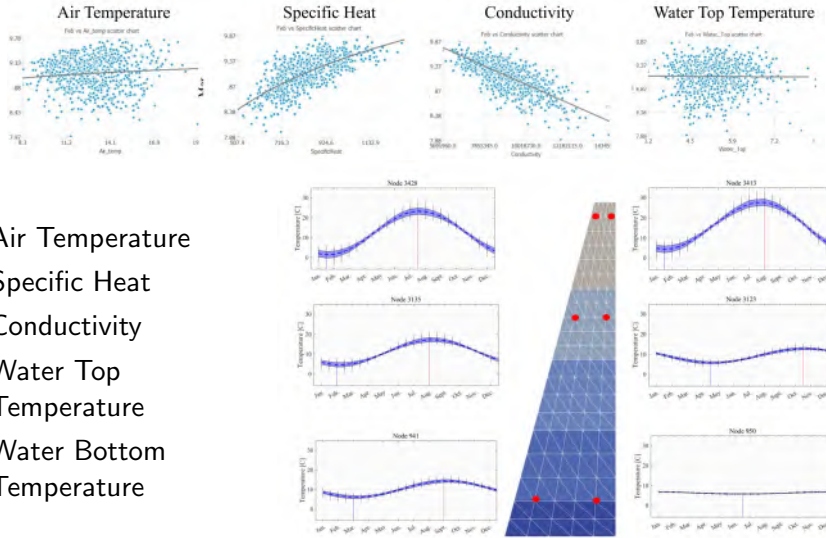
Thermal transient analysis is a pre-requisite for any AAR assessment. Thermal loads affect the structural behavior of **(thin) arch dams**.

- 0.6 Air temperature
- Solar radiation
- 0.6 Water temperature
- 0.6 Pool elevation

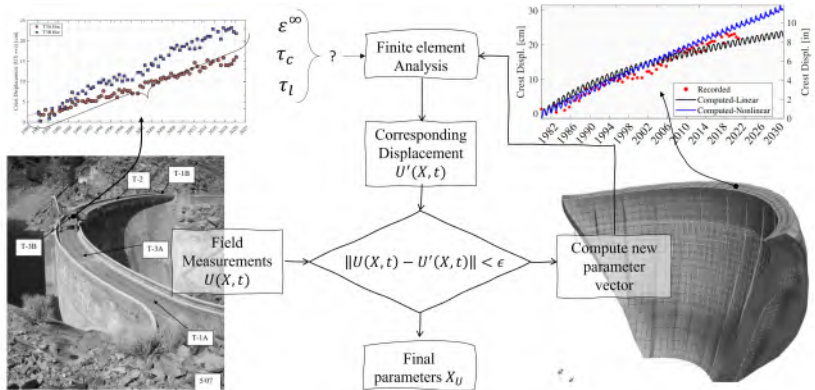


The sources of uncertainty in the thermal analysis were identified as follows:

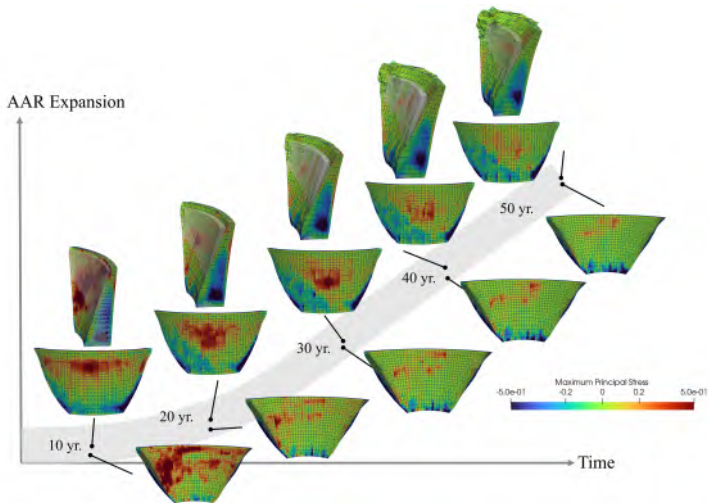
- Air Temperature
- Specific Heat
- Conductivity
- Water Top Temperature
- Water Bottom Temperature



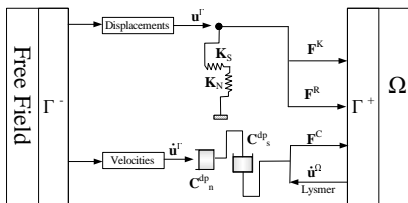
In order to determine the AAR model parameters a parameter identification process (Based on nonlinear least square problem solving) is utilized.



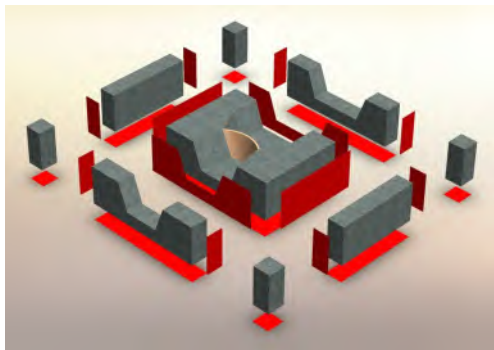
- Evolution of maximum principal stress using nonlinear concrete model + nonlinear joint



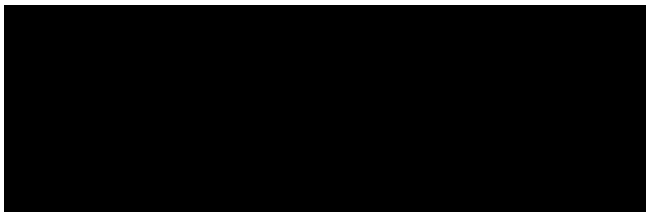
The interaction between the free field and the foundation is examined first (Saouma-Miura model)



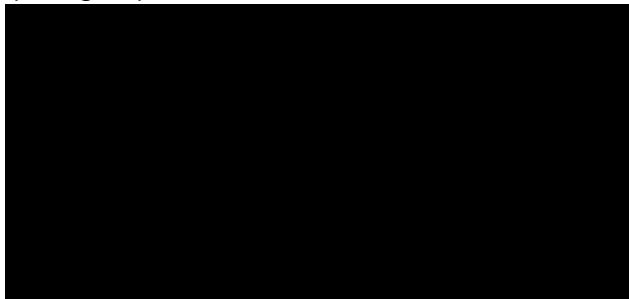
- Finite element mesh generated for Dynamic analyses consists of 9 separate meshes; 4 corner, 4 side and 1 main mesh
- One should start with analyzing corners first applying their effect on sides and only after transferring the side response the main mesh will be analyzed
- Matlab code written can be easily adapted to any FE code.



- Horizontal crest displacements for the AAR affected and sound dam

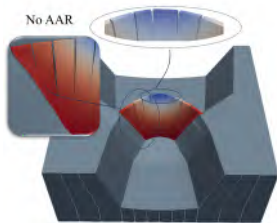


- Joint Opening displacements at the dam toe and heel



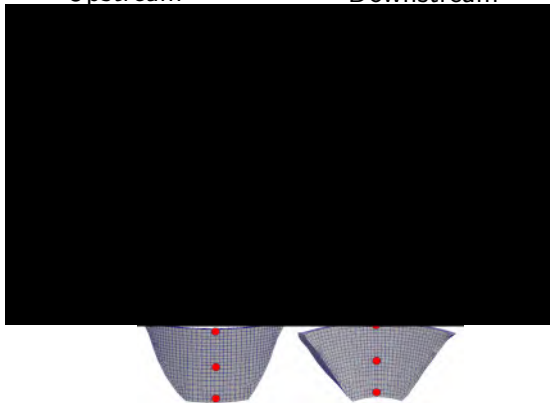
The stress plots suggest that:

- In general the crest stresses are higher on the DS face compared to upstream
- At the higher intensity levels the AAR-affected dam shows lower stresses than the sound dam



Upstream

Downstream



- A comparison study has been conducted to investigate the effect of SSI
- The study shows that failing to properly account for the effect of dam-foundation interaction results in underestimating the stresses on the crest

Dispute

BoR

...the outcome of the investigations **does not match the field monitoring data** (for cracks downstream no mention of crest displacements) and poses a programmatic concern for the project that is under an ongoing issue evaluation by Reclamation. Overall, the **concern is not about reporting that XXX Dam is suffering from AAR**, ... but publishing detailed project data in a Reclamation sponsored report **that raises security, potential public relation concerns, and conflicts** with confirmed field observations of the dam.

Conclusions

Unsubstantiated remark. In denial! (possible internal issue)

BoR 2023 (Karl close your ears ☺)

- **Glorious past** (Peck, Terzaghi, Westergaard, Abdunnur); Great engineer (refer to Billington's book), great Laboratory.
- **No new dam** design/construction
- Technical staff and laboratory is a **mere shadow of its glorious past**, yet seems to have a hard time accepting it.
- Some **well intention-ed and good** engineers in charge.
- Unfortunately, the **bureaucracy made it rigid and practically dysfunctional**; obsession with secrecy.
- **No centralized database** (like ADAMS for the NRC).
- Numerous field tests, but **not always coherent with the needs**.
- My **first and last project at CU have been with BoR** thanks to two persons of believed in me (Boggs and **Salamon**), and to them **I am grateful despite countless arguments with both of them^a**.

^aHoward once told me, if you are dealing with a big structure such as dams, you better have a strong personality and be sure of yourself. **I listened!**

Final Remarks

- In an academic setting for SESM:
 - We acquire, share, and advocate advanced technical skills.
 - There is a common (though mistaken) assumption that these skills are nearly self-evident and would be embraced.
- However, in the "real world" context of federal agencies and industry:
 - Unlike in the EU and Japan, when industry faces a problem, they typically do not turn to local universities, except for prestigious institutions like MIT and Berkeley.
 - Academic research is often perceived as overly academic.
 - There is more trust placed in well-known companies (even with limited expertise, such as SGH/WJE) or certain national laboratories like NIST, despite potential deficiencies in in-house expertise.
- There is a **need for us to do a better job in getting the broader community to embrace our research.**

Final Remarks

- had great joy in the work at CU, had a lot of fun.
- Particularly relished challenges demanding a **diverse set of expertise**.
- Strived (not always successfully) to **stay closely aligned with first principles**.
- Always preferred **working independently**, without co-authors or co-PIs, relying solely on self-developed software, steering clear of commercial codes. (OK, **I am not an easy person to work with!**)
- Unfortunately, the current **mindset and values** no longer align with mine; right time to move out.
- **hanks, CU!**

Future Work

Prof. Victor E. Saouma (Ret.)

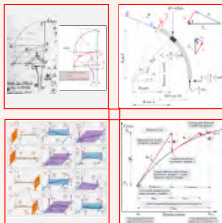
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January 1, 2024

The Four Books of Structural Analysis

Victor E. Saouma

University of Colorado, Boulder



Ver 1
November 10, 2023

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Draft

- A never ending pet project (so far over 1,400 pages, and 40 chapters).
- Enjoy particularly Book I
- Spiced with occasional consulting

Thank You



Thank You!

Questions?