Navigating the Intersection of Mechanics and Engineering: A Personal Odyssey Midst the Alphabet Soup of BoR, EPRI, NRC, ORNL, TEPCO, and Beyond

Prof. Victor E. Saouma (CEAE)

Department of Civil, Environmental and Architectural Engineering

December 8, 2023

▲□▶ ▲□▶ ▲□▶ ▲□▶ ■ ●の00

#### 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

▲□▶ ▲□▶ ▲□▶ ▲□▶ □ のQで

#### 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



#### 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	Tokyo Electric Power Company	R/C transmission tower
Crystal River	Utility Company	Delamination of a Nuclear Con-
		tainment Building
ORNL	Oak Ridge National Laboratory	Nuclear Containment Building
		with AAR
C-10/NRC	Nuclear Regulatory Commission	Seabrook nuclear power plant
BoR	Bureau of Reclamation	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 🙂



#### $\mathsf{Mathematics} \to \mathsf{Mechanics} \to \mathsf{Engineering} \to \mathsf{Codes}$

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

Victor Saouma

James Maxwell

#### 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.



#### Mech-Eng-Mat



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 (\$\$\$ <sup>(()</sup>)
- 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



#### EPRI: Electric Power Research Institute

Structural Modeling of Nuclear Containment Structures		
00-10006428		
3 <sup>rd</sup> Draft; Mar. 2017		
Victor E. Saouma University of Colorado, Bo	lder	
EPRI Project Manager M. Guimaraes		
300 Hilbine Avecus, Palo At 801 1	ELECTRIC POWER RESEAR , California 94306-1138 PO E 1.1774 683.855.2121 adequil	OH INSTITUTE as 2012, Pale Alto, California (H20) - rpl com seve spil com

- 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

▲□▶ ▲□▶ ▲□▶ ▲□▶ □ のQで

#### AAR & Nuclear



- 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!

## ORNL





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
  - Material: NIST (never had a scientist with a single peer-reviewed publication on AAR!), \$\$\$\$.
  - Structure: University of Colorado/Saouma \$
  - 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



- 1-A: Design of an AAR-Prone Concrete Mix for Large-Scale Testing (93 pages).
- 1-B: AAR Expansion; Effect of Reinforcement, Specimen Type, and Temperature (123 pages).

▲ロ ▶ ▲周 ▶ ▲ 国 ▶ ▲ 国 ▶ ● の Q @

- **1**-C: Effect of AAR on the Shear Strength of Panels (90 pages).
- 2: Diagnosis & Prognosis of AAR in Existing Structures (191 pages).
- 3-A: Risk-Based Assessment of the Effect of AAR on Shear Wall Strength (25 pages).
- 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

▲□▶ ▲□▶ ▲□▶ ▲□▶ □ のQで

- 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 ③

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



#### Main Safety Concern (Saouma)

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

#### Licensee's Responsability

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.

▲□▶ ▲□▶ ▲□▶ ▲□▶ □ のQで

#### Texas



- Large scale testing (TX size).
- (Unanticipated) Structural crack (of course!), yet shear results used for validation

▲□▶ ▲□▶ ▲三▶ ▲三▶ 三三 のへの

- 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,

- Measure local elastic modulus E<sub>c</sub>
- Retrieve neighboring stored cores
- Measure its f<sub>c0</sub>
  - Determine  $E_{c0} = 57,000\sqrt{f_{c0}'}$

**(5)** Compute  $E_n = E_{c0}/E_c$ 

**(** From laboratory calibration curve determine corresponding  $\Delta \varepsilon^{AAR}$ 

#### Very flawed; DANGEROUS

#### Summary of Board Holdings and License Conditions

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

- NextEra shall undertake the monitoring .... for control extensioneters every six months, rather than in 2025 and every ten years thereafter.
- 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.
- 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....
- Each core extracted from Seabrook Unit 1 will be subjected to a petrographic analysis to detect internal microcracking and delamination.

▲□▶ ▲□▶ ▲ 三▶ ▲ 三▶ ▲ 三 ● ● ●

## Thanks from the city of Newburyport

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

]	<b>PROCLAMATION</b>
WHEREAS,	Dr. Saouma, a Professor of civil and structural engineering at the University of Colorado, Boolder, and internationally-acchime- ceptor is serving as C-10°s expert miness in the case regarding Seabrook's concrete. One of the world's leading experts on allali like reaction (ASR). Saouma has attacid is effects on nuclear neateness, in particular how the containment structure could be weatened should an earthquake occur, and
WHEREAS,	The City of Newburyport wishes to acknowledge Dr. Victor Sauuma for his work in calling for more rigorous monitoring and analysis of the degraded concrete at the Seabrool Station nuclear power plant, located approximately seven milet from the City's center; and
WHEREAS,	Dr. Stoums has spent countless pro bono hours representing the C 10 Research and Education Foundation in the group's lega challenge to Seabrook's concrete aging management protocols, in a case before the US Nuclear Regulatory Commission's Atomis Safety and Licensing Board; and
WHEREAS,	Newburyport's City officials recognizes the critical service Dr Saouma gave to our community with his participation in a week long hearing at Newburyport City Hall in September 2019.
THEREFOR deepest gratitude the natural enviro	E, be it proclaimed that the City of Newburyport hereby extends it to Dr. Victor Saouma for his efforts on protecting public health and nment in Newburyport and beyond.
and the second sec	Gyrer under ny hand aud sied his toerestiek dag o Bornester Houssand auf Mereck Donna 2. Juliaday, Nagar

#### 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:
  - Literature Survey
  - Provide the Structural Assessment of Concrete Dams Suffering from AAR with Specific Application to XXXX Dam
  - 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





SEN4AAR	
Sign In Username	
username	
Password	
Sign In	

## Road Map

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

COOPERATIVE AGREEMENT NO. R18AC00055

March 14, 2023

Victor E. Saouma 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



▲□▶▲□▶▲≡▶▲≡▶ ≡ めぬる

## **Current Practice**

- Many (good) players, but little (bad) symbiosis
- Partition (arbitrarily) dam into zones and perform "tests".

E, f,, f, Tests

٥

٥

Time

• Spatial and temporal interpolations.

Depth

٥

0 0 0



## Different Galaxies

	"State of the Practice"	State of the Art (e.g. Merlin)		
# of Ana- lyses	Multiple, one for each year we are interested in	Single analysis that starts at time 0 (dam con- struction) up till desired year		
	What do we need for inp	out data		
Parameters	Topological distribution of damaged concrete properties over the dam at the time of analysis	Characteristics of the concrete expansion to capture its kinetics (3 parameters)		
How do	Partition the dam in multiple regions; Extract	Accelerated expansion tests or preferably pa-		
we obtain them	sufficient representative cores from each one of them; perform tests ( $E$ and $f_c$ primarily)	rameter identification		
	Analysis			
Advantage	Easier to perform the analysis	Single analysis that capture the entire re- sponse. Parameter identification is an auto- mated lengthy procedure.		
Dis-	Approximate does not capture: 1) interaction	Some numerical instability may occur in a non-		
advantage	of temperature with AAR expansion; 2) effect of confinement on the anisotropic expansion; Analysis Output	linear time history analysis		
Displacements	/Yes, a snapshot at time t (of analysis), i.e. one	Yes, a "movie" that captures the evolution of		
stresses	single scalar quantity at time $t$	the dam response, i.e. a vector for each re- sponse in terms of time)		
Concrete deteriora- tion	No, that was part of the input	Yes as computed by the AAR model		
Future Prediction				
Possible	Based on the time dependent concrete deteri- oration	Yes By just letting the analysis go beyond present date.		
Reliability	Low would rely on the extrapolation of con- crete damage measured in the laboratory and inputted in the mesh	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



◆□▶ ◆□▶ ◆目▶ ◆目▶ ▲□ ◆ ��や

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

CU

Long Term Assessment of Dams Suffering from Alkali Aggregate Reaction;

Analyses Results

Final Report

Cooperative Agreement No. R18AC00055

March 11, 2023

Golsa Mahdavi Victor E. Saouma University of Colorado, Boulder

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 reasons). 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.

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





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





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



◆□▶ ◆□▶ ◆三▶ ◆三▶ 三三 のへぐ

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



▲□▶ ▲□▶ ▲ 三▶ ▲ 三▶ 三三 - のへぐ

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 transfering the side response the main mesh will be analyzed
- Matlab code written can be easily adapted to any FE code.



▲□▶ ▲圖▶ ▲国▶ ▲国▶

æ

Horizontal crest displacements for the AAR affected and sound dam



• Joint Opening displacements at the dam toe and heel



▲□▶ ▲□▶ ▲三▶ ▲三▶ 三三 のへで

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





▲□▶ ▲□▶ ▲□▶ ▲□▶ ■ ●の00

- 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 <sup>©</sup>)

- 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<sup>a</sup>.

<sup>a</sup>Howard 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!)

▲□▶ ▲□▶ ▲□▶ ▲□▶ □ のQで

- 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.)

880 Gapter Road, Boulder CO 80303

January 1, 2024



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

◆□ > ◆□ > ◆豆 > ◆豆 > ・豆

• Spiced with occasional consulting

## Thank You





## Questions?