DOE/NRC Natural Phenomena Hazards Meeting
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# Coupled Multiphysics Simulations of Seismic Response of Degraded Concrete Structures

Idaho National Laboratory

# Acknowledgement

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# Outline

- Concrete degradation induced by Alkali-Silica Reaction (ASR)
- Coupled framework for dynamic analysis of degraded concrete structures
- Demonstration problems
  - Case 1: Validation of ASR analysis benchmarking concrete dam structure
  - Case 2: Soil-structure interaction
  - Case 3: Source-to-site wave propagation generated from an earthquake fault rupture scenarios
- Concluding remarks

NEWS

## New radiation monitor installed near Seabrook nuke plant

**Max Sullivan**

Published 1:11 p.m. ET Oct. 1, 2020

https://www.seacoastonline.com/story/news/2020/10/01/new-radiation-monitor-installed-near-seabrook-nuke-plant/42712569/

EDITOR'S PICK

## Radiation monitor installed at Seabrook Beach

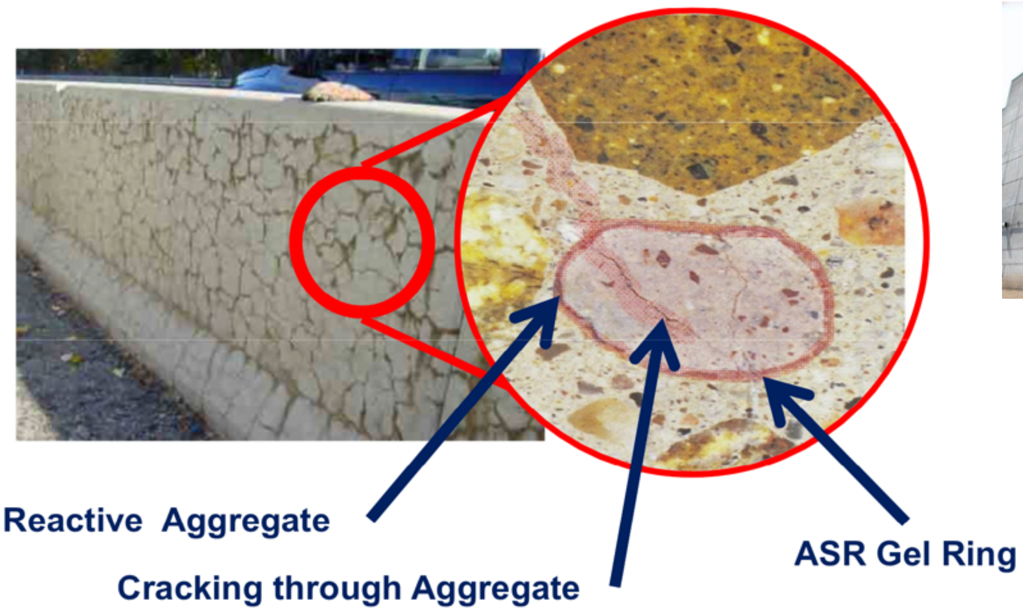
By Jack Shea Staff writer Oct 12, 2020

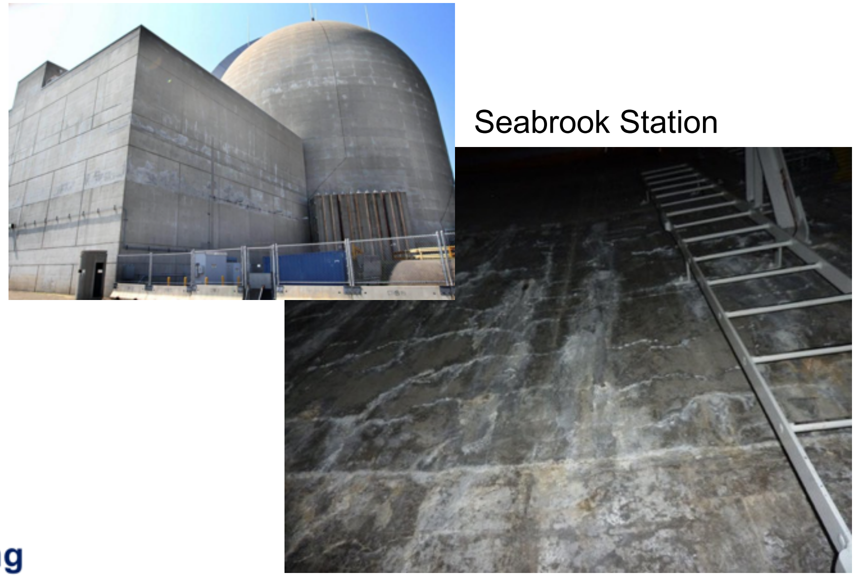
https://www.eagletribune.com/news/new_hampshire/radiation-monitor-installed-at-seabrook-beach/article_eb045dd0-e9f6-5b42-8782-03e7e11a80d0.html

# Alkali-Silica Reaction (ASR)

- ASR is a slow chemical reaction in concrete, which occurs in the presence of water, between the alkaline cement and reactive silica found in some aggregates
- ASR forms a gel that absorbs water and expands causing micro-cracks that affects concrete properties (stiffness, bond strength of concrete, and overall service life in power plants, dams, bridges, pavements, etc.)
- Current RC design procedure and practice do not account for effects of ASR

*Reference: "Seabrook station safety in light of the alkali-silica reaction occurring in plant structures", 2011 reactor oversight process Nuclear Regulatory Commission – Region I*



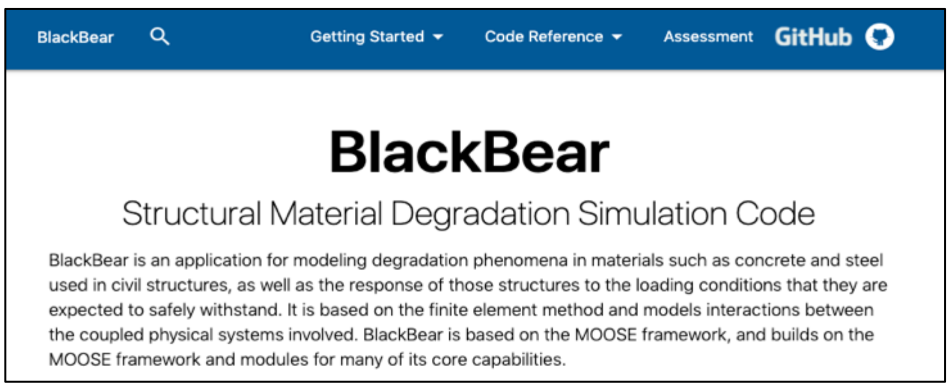
Seabrook Station

Photos from https://www.sgh.com/projects/seabrook-station-nuclear-power-plant#solution

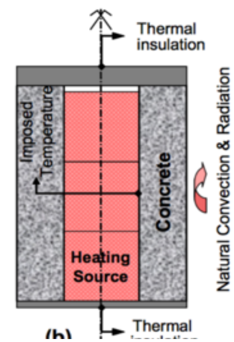
# BlackBear

## *INL Developing Structural Material Degradation Simulation Code*

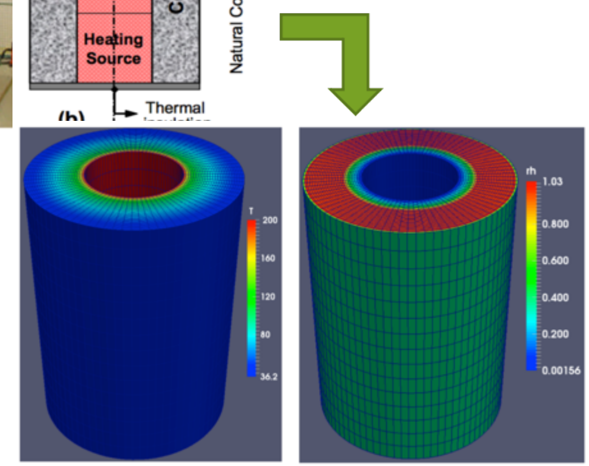
- Modeling of concrete degradation process using a fully coupled thermo-hydro-mechanical-chemical (THMC) concrete model
- Implementation of **ASR swelling model**, coupled with heat and moisture transport
- Ultimately, simulating and predicting the long-term performance of concrete structures, subjected to various aging mechanisms by interacting physical, chemical, and mechanical processes



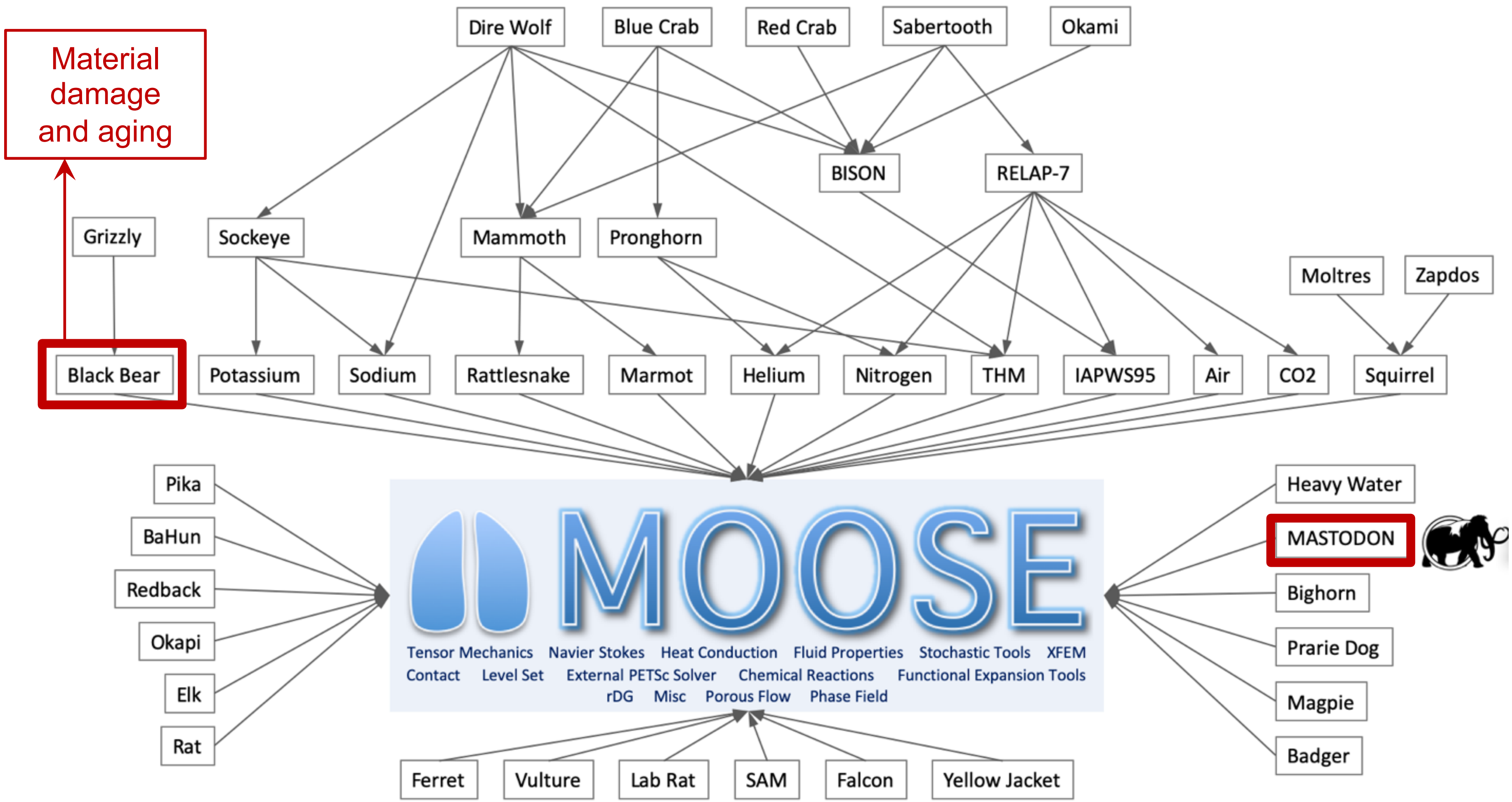

[https://mooseframework.inl.gov/blackbear/](https://mooseframework.inl.gov/blackbear/)




Coupled moisture/heat transfer model



# MOOSE Apps

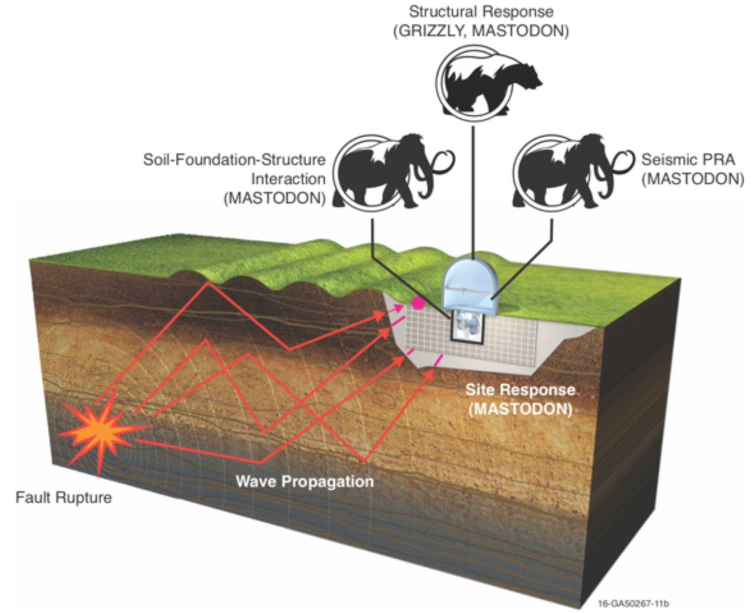


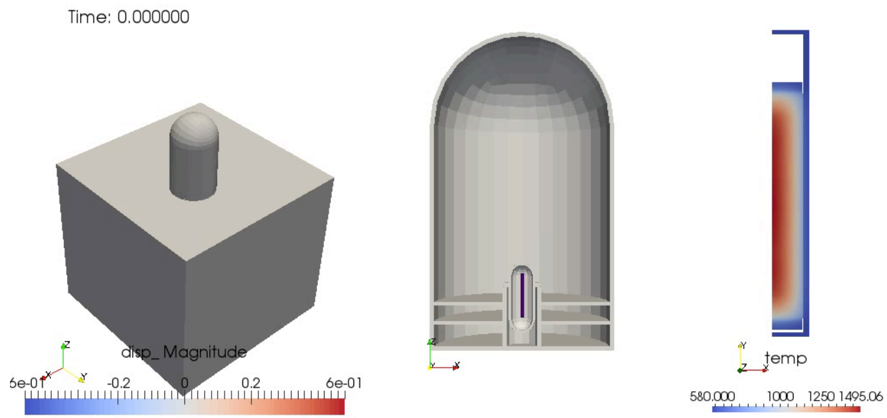

**MOOSE: M**ultiphysics **O**bject-**O**riented **S**imulation **E**nvironment

# MASTODON

***Multi-hazard Analysis for STOchastic time-DOmainN phenomena***

- Nonlinear site response and soil-structure interaction
- Source-to-site simulation
- Seismic probabilistic risk assessment
- Implicit and explicit integration
- Easy coupling with other physics
- Highly parallelizable – MOOSE tools routinely used on 1000s of processors
- Automated testing and documentation maintenance




MASTODON

# Modeling Approach

***Dynamic/Seismic Response of Degraded Concrete Structures***

**Concrete Material Degradation Analysis**

- Heat transfer and moisture diffusion
- Alkali-silica reaction (ASR) swelling model
  - ASR reaction kinetics
  - Anisotropic ASR strain distribution
  - Isotropic thermal expansion
- Damage material constitutive model

Required analysis time step = days

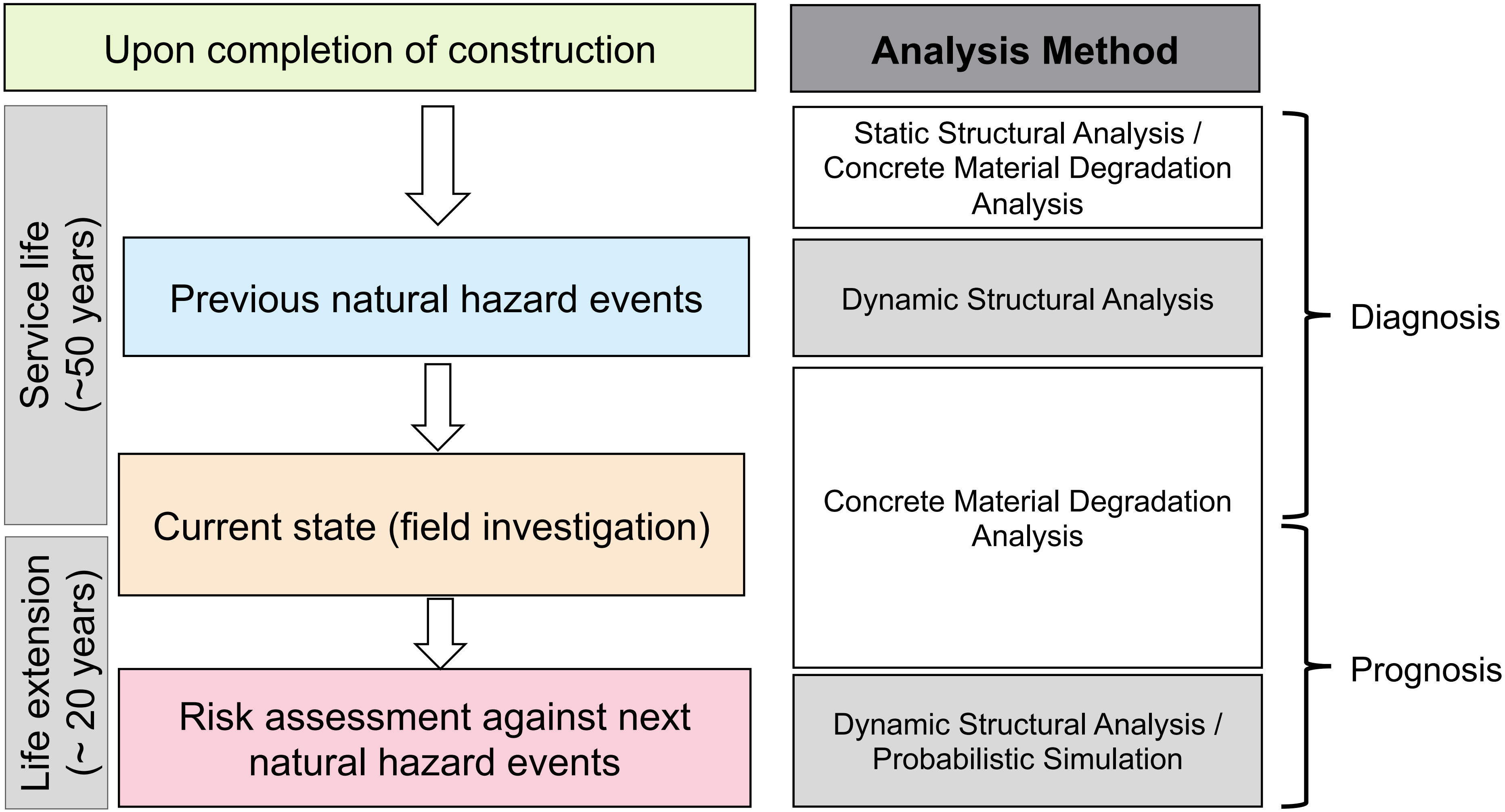
**Static/Dynamic Structural Analysis**

- System dentification (modal analysis)
- Seismic/Dynamic loading
- Soil-Structure Interaction
- Source-to-site wave propagation from earthquake fault rupture

Required analysis time step = seconds

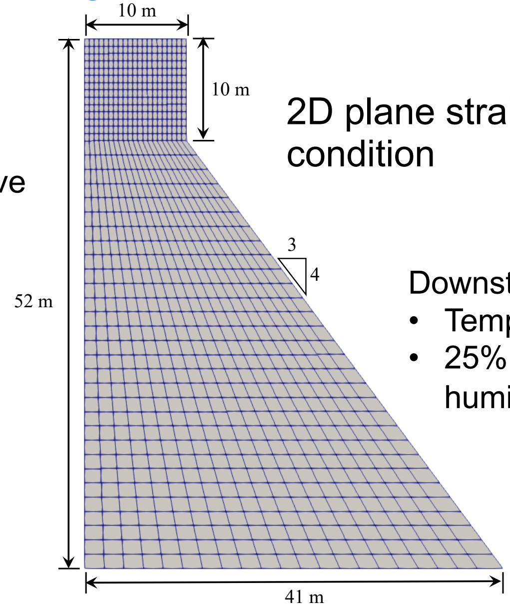
**BlackBear + MASTODON**

# Simulation Approach



# Case Study: Validation for ASR-induced Material Degradation

Upstream
- Temp. = 8°C
- 100% Relative humidity



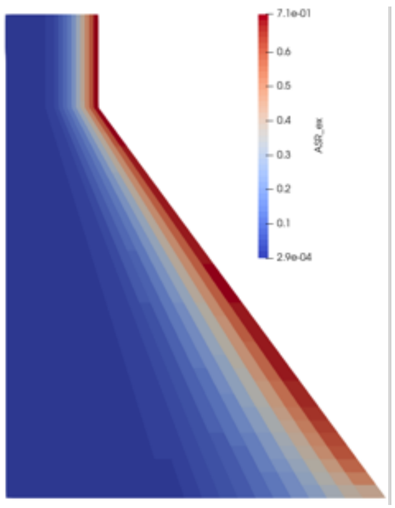

2D plane strain condition

Downstream
- Temp = 15°C
- 25% Relative humidity

- Input parameters are adopted from Ulm et al. (2000) and Huang and Spencer (2016)

| Material Parameter | Value |
|---|---|
| Young's modulus ($E$) | 22.0 GPa |
| Poisson's ratio ($v$) | 0.2 |
| Compression strength ($f_c$) | 25 MPa |
| Tensile strength ($f_t$) | 2 MPa |
| Mass density ($\rho$) | 2643 kg/m$^3$ |
| Thermal expansion coefficient | 1 x 10$^{-5}$ /°C |
| Characteristic time, ($\tau_c$, $T_o$ = 311 K) | 50 days |
| Latency time, ($\tau_l$, $T_o$ = 311 K) | 200 days |
| Chemical expansion coefficient ($\beta = \varepsilon(\infty)$) | 0.3% |
| Thermal activation constant ($U_C$) | 5,400 K |
| Thermal activation constant ($U_L$) | 9,700 K |

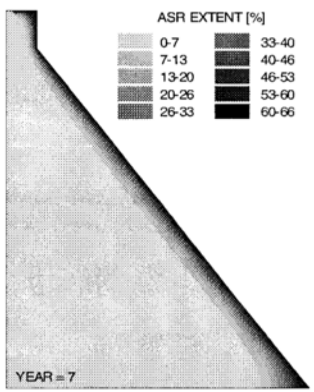
- Results from thermal conduction and moisture diffusion at 7 years



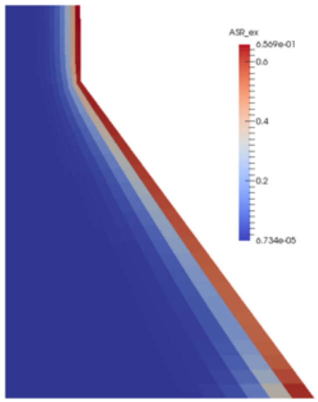

(c) ASR extent

Shows almost identical results, compared to the earlier studies

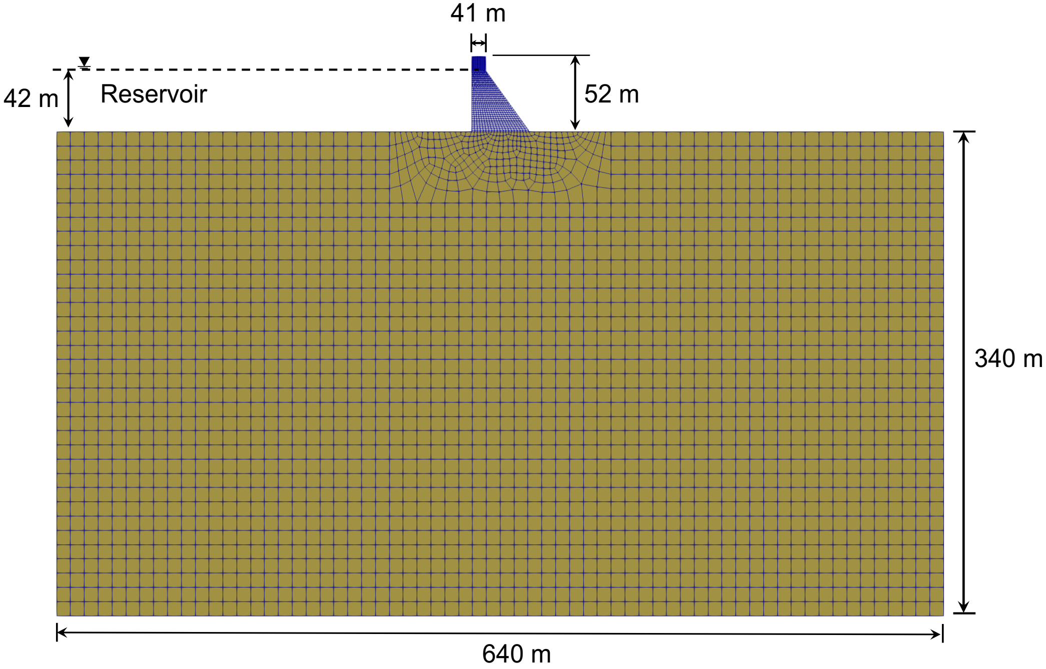
Ulm et al. (2000)



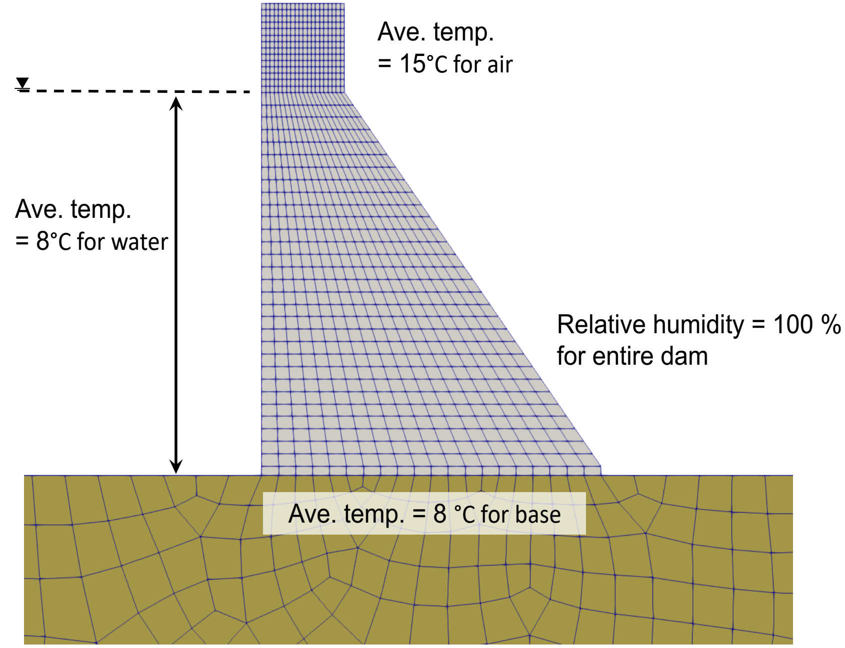

Huang and Spencer (2016)



# Case Study: Soil-Structure Interaction Model




- Initial conditions of temperature and relative humidity / hydrostatic pressure from reservoir

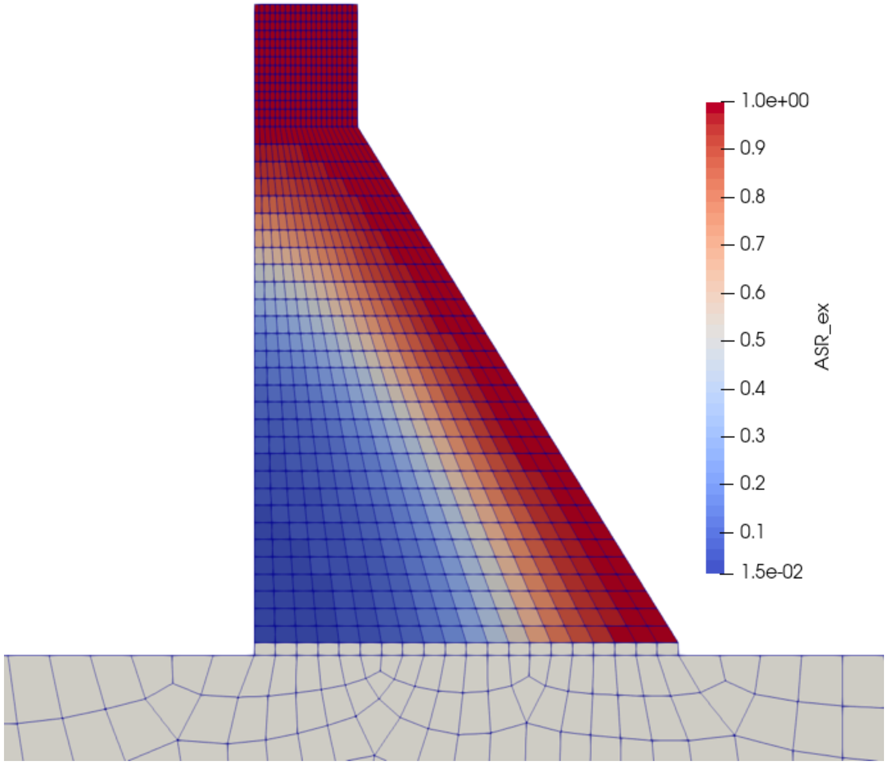


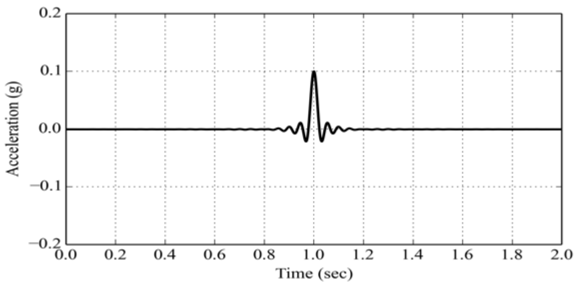

- Linear soil material properties
- No slip/separation at soil-structure interface
- Fixed base condition
- Shear beam lateral boundary condition

| Soil Material Property | Value |
|---|---|
| Shear wave velocity | 1000 m/s |
| Shear modulus | 1.7 GPa |
| Poisson's ratio | 0.3 |
| Mass density | 1700 kg/m$^3$ |

# Case Study: Soil-Structure Interaction Model

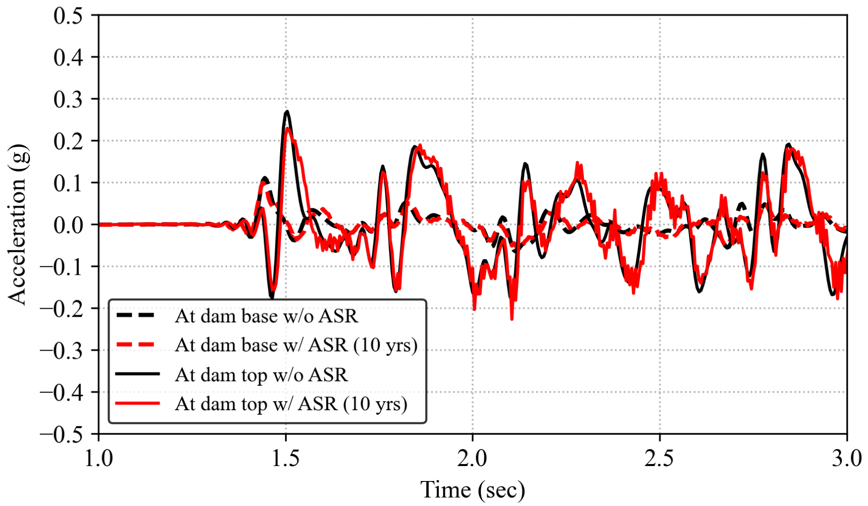
- ASR extent at 10 years

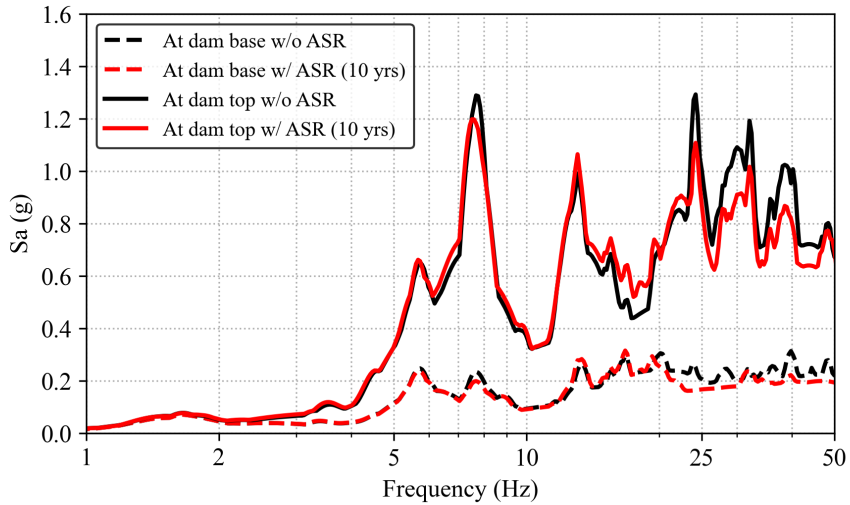



**Ormsby wavelet input motion after 10-year ASR analysis**

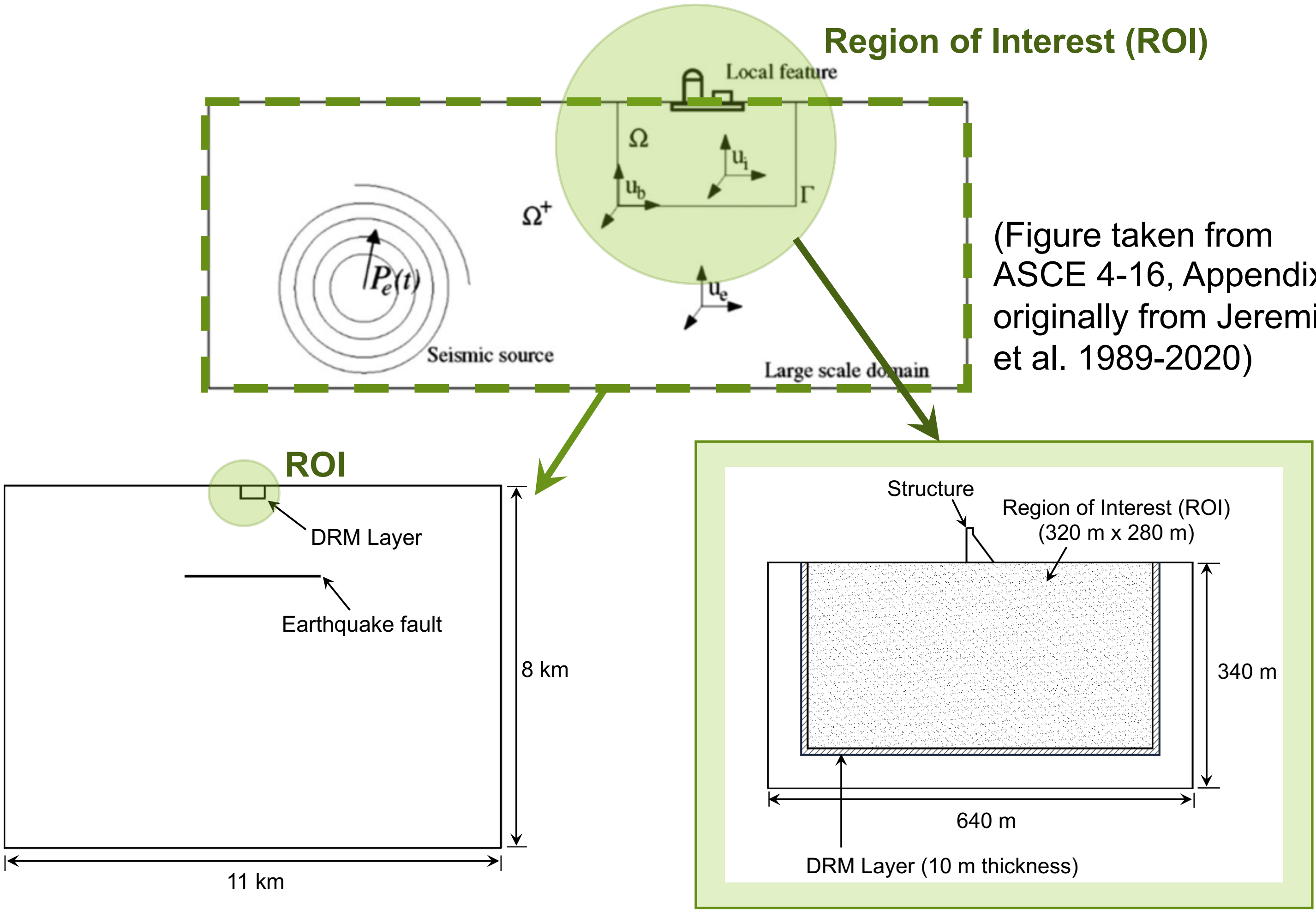
- Acceleration at top and base of the dam



# Case Study: Source-to-Site Wave Propagation Model

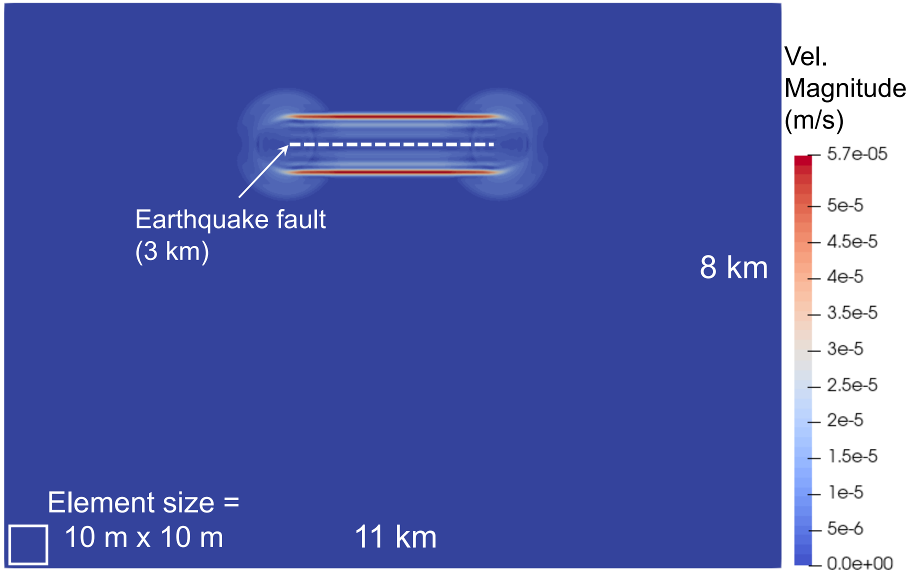
- ASCE 4-16, Appendix B: Nonlinear Time-domain Soil-Structure Interaction (Nonmandatory)
- B.3 Ground motion Input using Domain Reduction Method, DRM (Bielak et al. 2003)

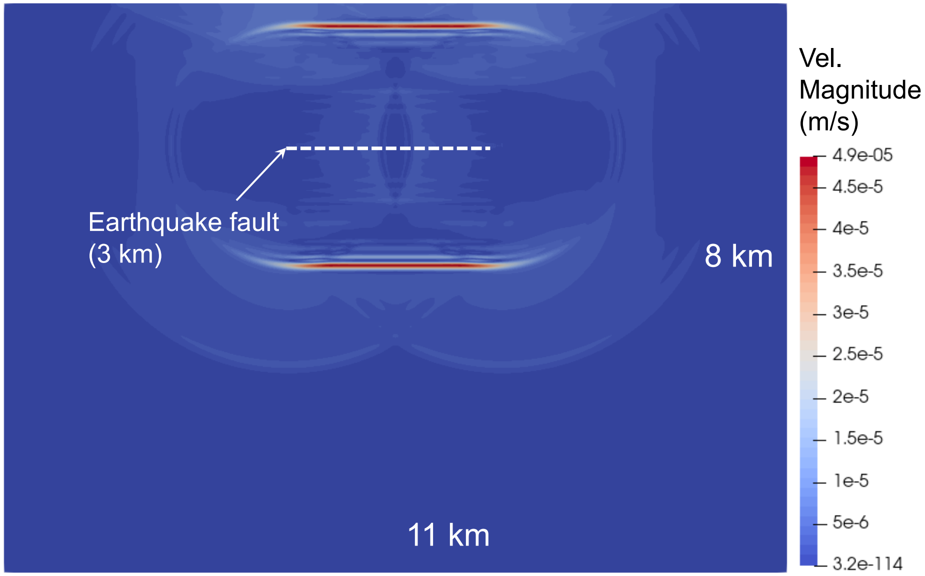



(Figure taken from ASCE 4-16, Appendix B; originally from Jeremic et al. 1989-2020)

# Case Study: Source-to-Site Wave Propagation Model

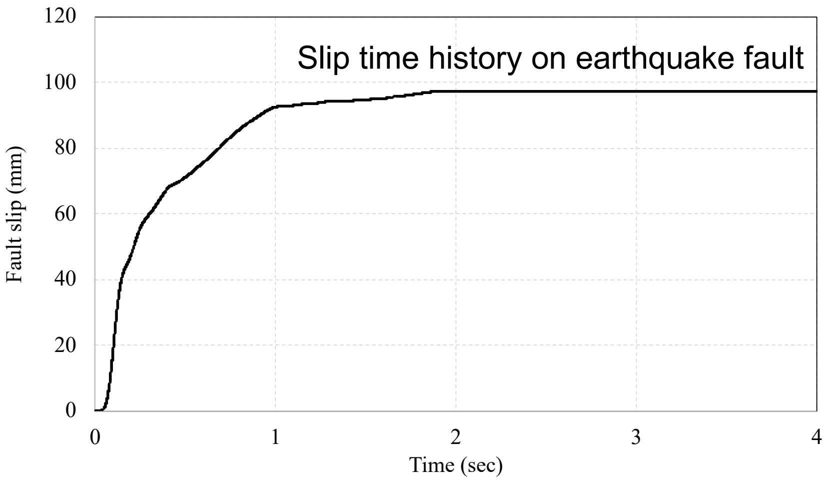
- Free-field earthquake simulation in 1st step using DRM (2D plane strain condition)



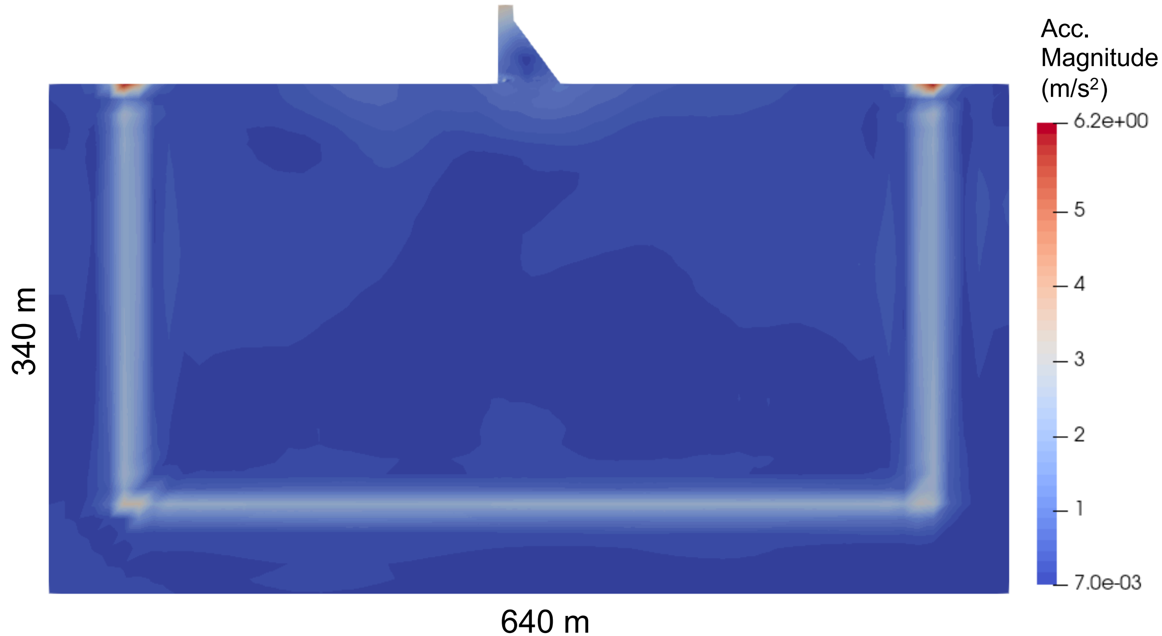



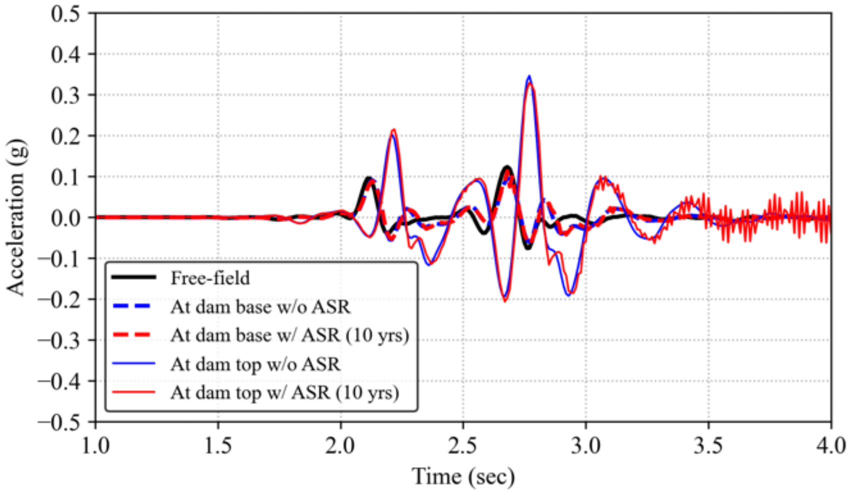

Earthquake fault rupture scenario (Veeraraghavan et al. 2017)

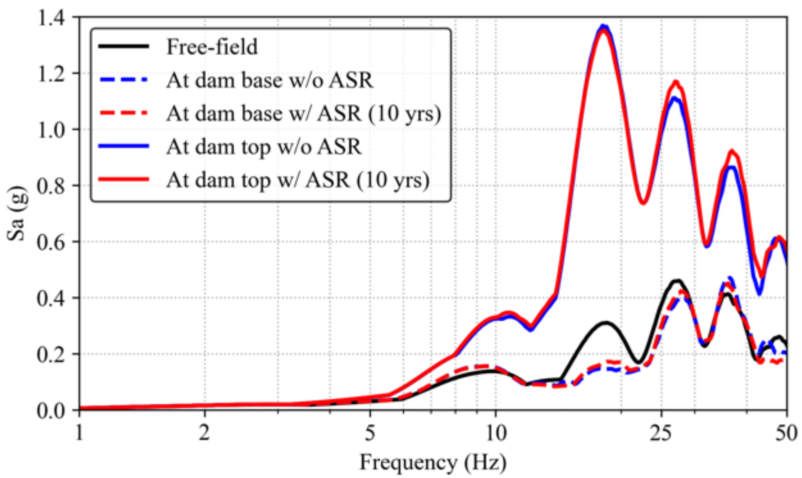
| Parameter | Values |
|---|---|
| Shear wave velocity | 1000 m/s |
| P-wave velocity | 1870.8 m/s |
| Poisson's ratio | 0.3 |
| Density | 1700 kg/m3 |
| Fault length | 3 km |
| Dip angle | 0 deg. |
| Strike angle | 0 deg. |
| Rake angle | 90 deg. |



# Case Study: Source-to-Site Wave Propagation Model

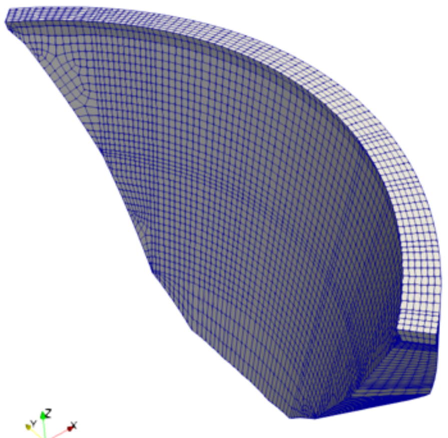


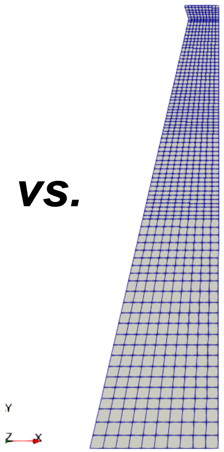
# Further Validation for Long-Term ASR Response

- Seminoe Dam is a concrete thick-arch dam on the North Platte River in the U.S State of Wyoming, owned and operated by the U.S. Bureau of Reclamation.
- The 295-foot (90m) dam was constructed in 1939. This was at a time before the discovery that low alkali cement, air entraining admixtures, and other beneficial modifications to concrete could ameliorate deleterious chemical and physical deterioration.
- The dam is exposed to severe winter conditions, fairly rapid and extreme temperature changes, and frequent freeze-thaw cycles.
- A few years after construction some cracking, and deterioration of the concrete was observed.



3D model

*vs.*



2D Axisymmetric

Photo from https://en.wikipedia.org/wiki/Seminoe_Dam#/media/File:SeminoeDam.jpg

Photo from https://www.wyohistory.org/encyclopedia/history-seminoe-and-kortes-dams

# Concluding Remarks

- The performed demonstrations show that the combined code can be successfully used for a full coupling of ASR-degradation and seismic analysis including a fault-rupture-to-site simulation.
- Within the scope of this research, the short-term effect of the ASR-induced material degradation is not significant on the seismic behavior of the benchmarked structure.
- Further long-term validation effort is underway using the seminoe dam, which will be a more representative scenario for nuclear-related structures suffered from ASR-induced damages.
- These applications can be applied to seismic and other external hazard analyses of aging concrete structures designed for long life spans: nuclear power plants and other critical facilities owned by the Department of Energy (DOE), National Nuclear Safety Administration (NNSA), Department of Defense (DOD), and the Department of Homeland Security (DHS).

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- https://www.sgh.com/projects/seabrook-station-nuclear-power-plant#solution

# Thank You