Large Power Transformer Seismic Response: Predictions and Experimental Validation

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Northwest Energy Systems Symposium

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WEGAI RESEARCH

Agenda

- Problem Statement – Large Power Transformer Seismic Vulnerability
- Broader Grid Impacts
- Transformer Seismic Failure Modes
  - Primary failure mode – Bushings
  - Additional failure modes
- Mitigation – Two Approaches
  - Bushing-specific
  - Full transformer or targeted structural protection
- Shake Table Testing of a 230kV Transformer

Transformer Protection Work Supported By:

- Idaho National Laboratory
- US Department Of Energy
  - Office of Electricity - Transformer Resilience and Advanced Components (DOE-OE-TRAC) Program
  - Office of Cybersecurity, Energy Security, and Emergency Response (DOE-CESER) Program
  - Natural Hazards Program
- WEGAI Research

Industry Partners:

SDGE™

PG&E

EPS Earthquake Protection Systems

SIEMENS energy

Hitachi Energy

SOUTHERN CALIFORNIA EDISON®

Bonneville POWER ADMINISTRATION

Seattle City Light

GE VERNOVA

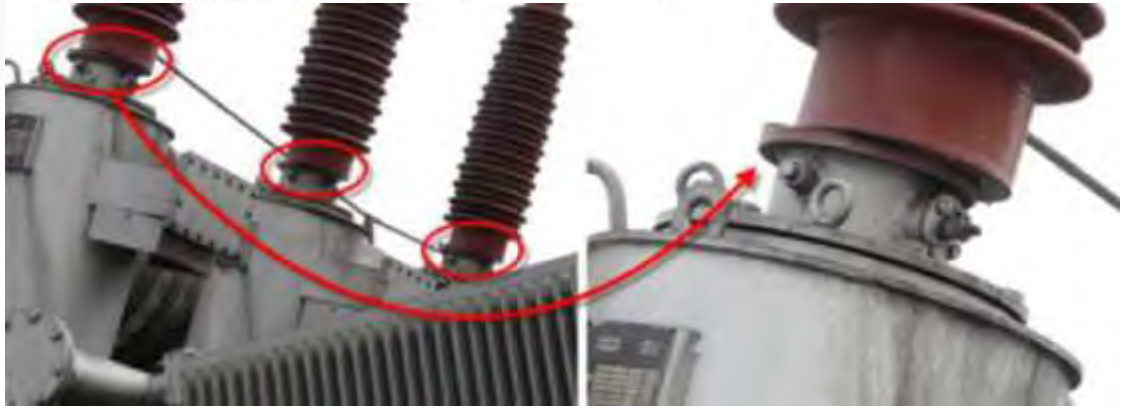
Power Transformer Seismic Failures

Izmit earthquake, 1999

Wenchuan earthquake, 2008

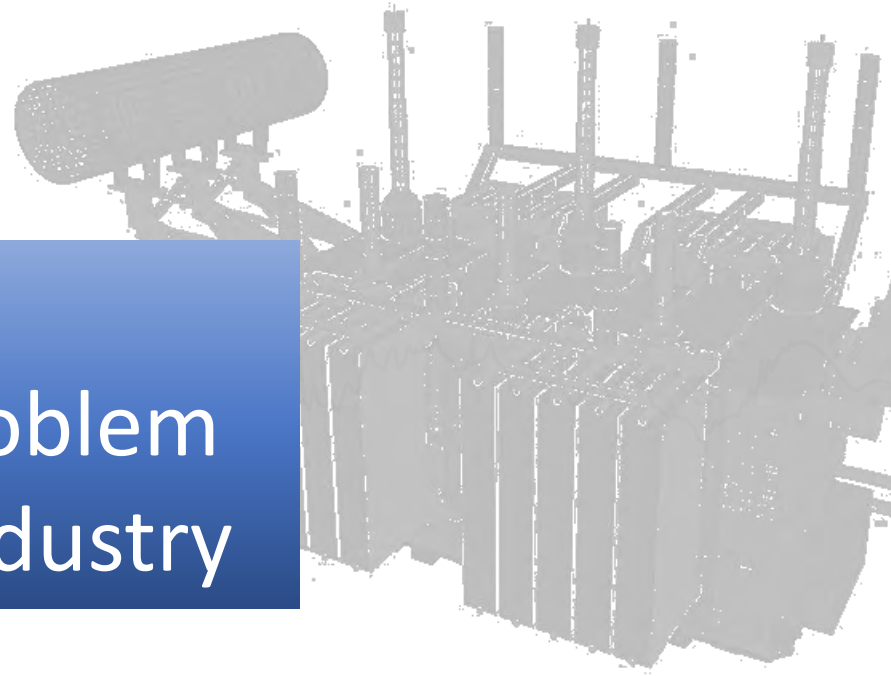
El Mayor earthquake, 2010

Northridge earthquake, 1994



Wenchuan earthquake, 2008

Reliability at a Reasonable Cost



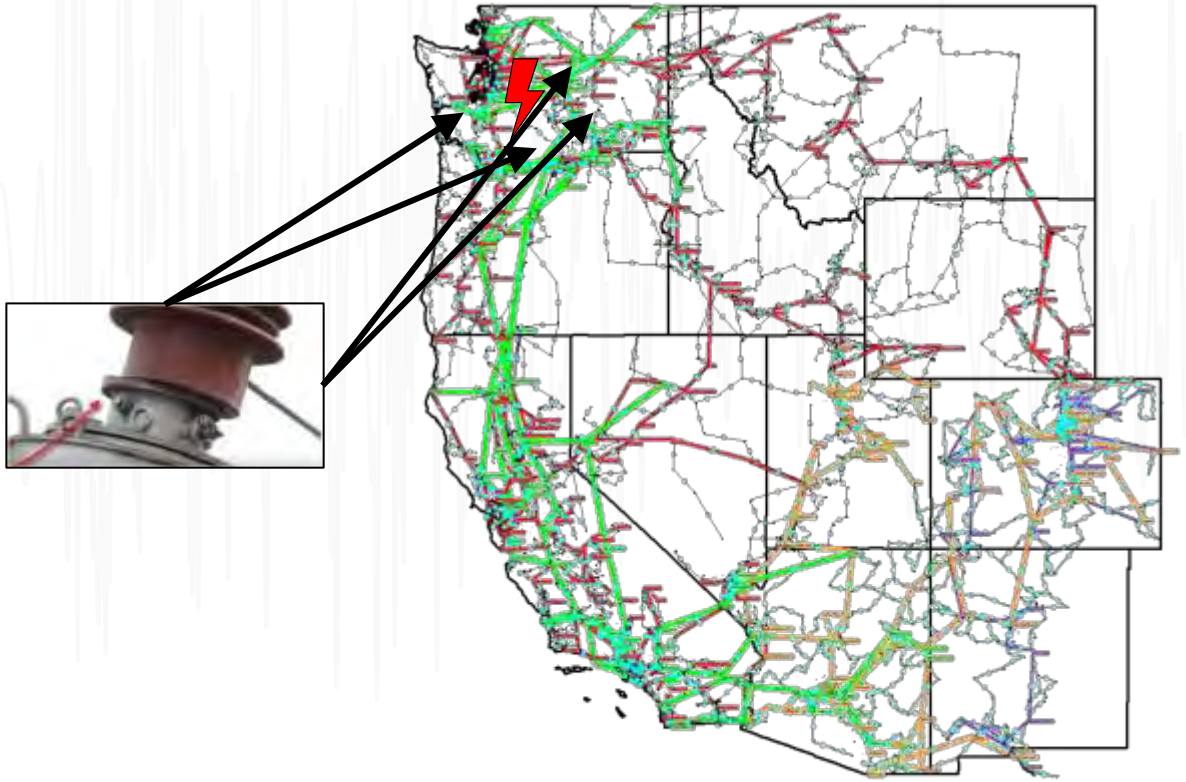
Mandate:
Solve a known seismic problem with minimal impact to industry

Broader Grid Impacts

What happens to the electric grid when a power transformer fails?

Grid Impact - Seismic Resilience

Targeting Questions:

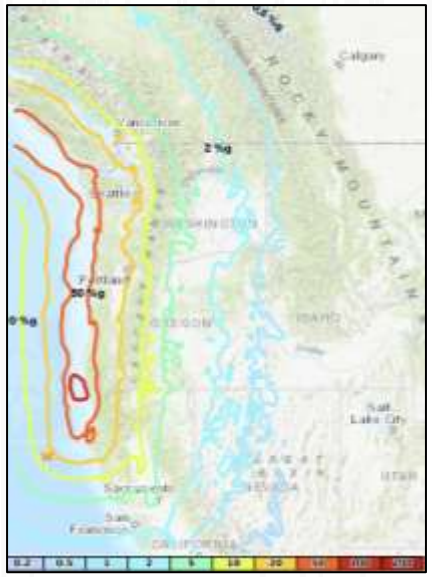


Transformers are a known seismic vulnerability

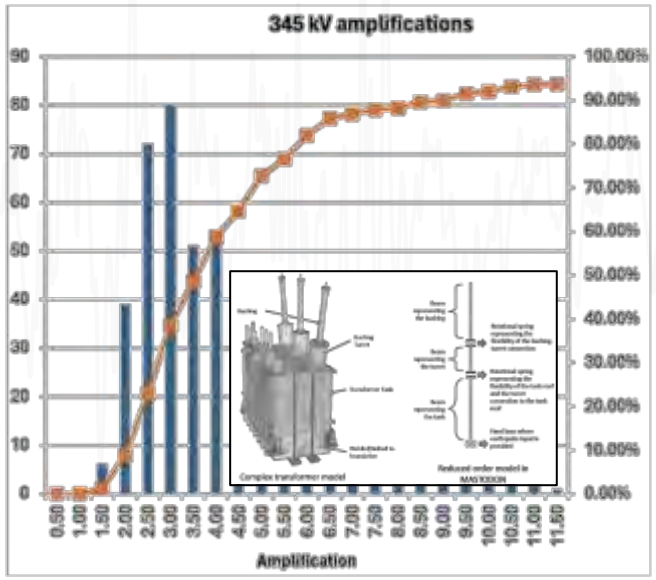
What is the large-scale risk?

Grid Impact – Methodology

- First-of-a-Kind Integration of Transformer Structural Dynamics Modeling and Grid Modeling



Select earthquake scenario, Calculate PGAs



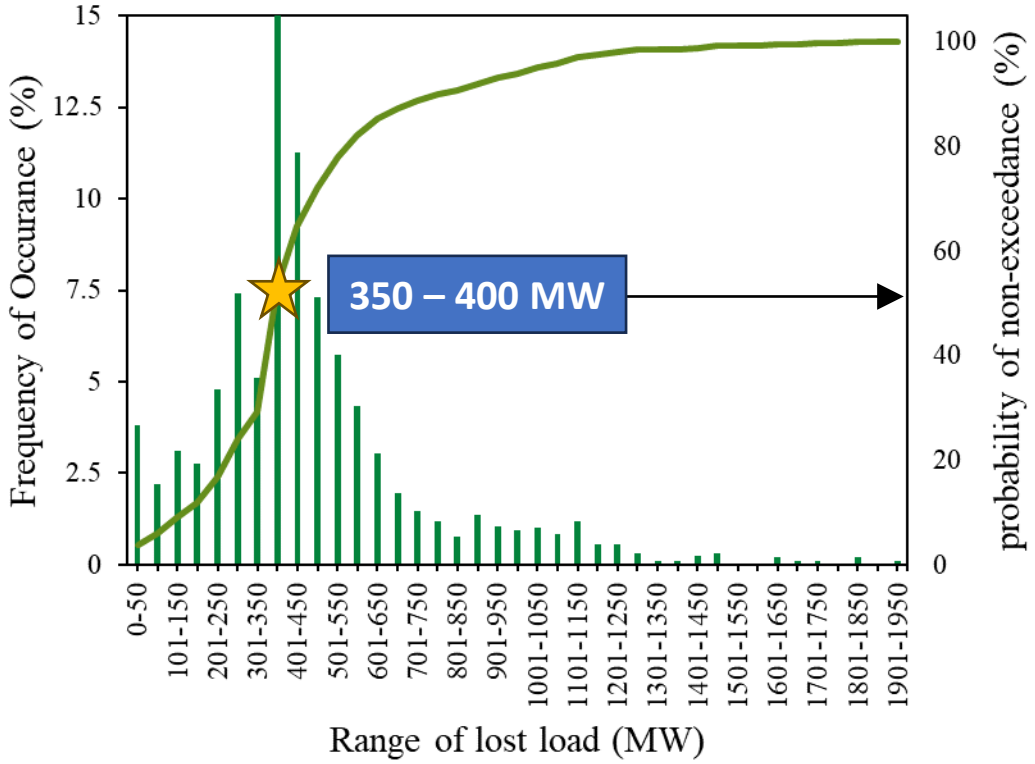
Calculate bushing demands, Identify transformers ”at risk”

Evaluate grid impact, Calculate potential load lost

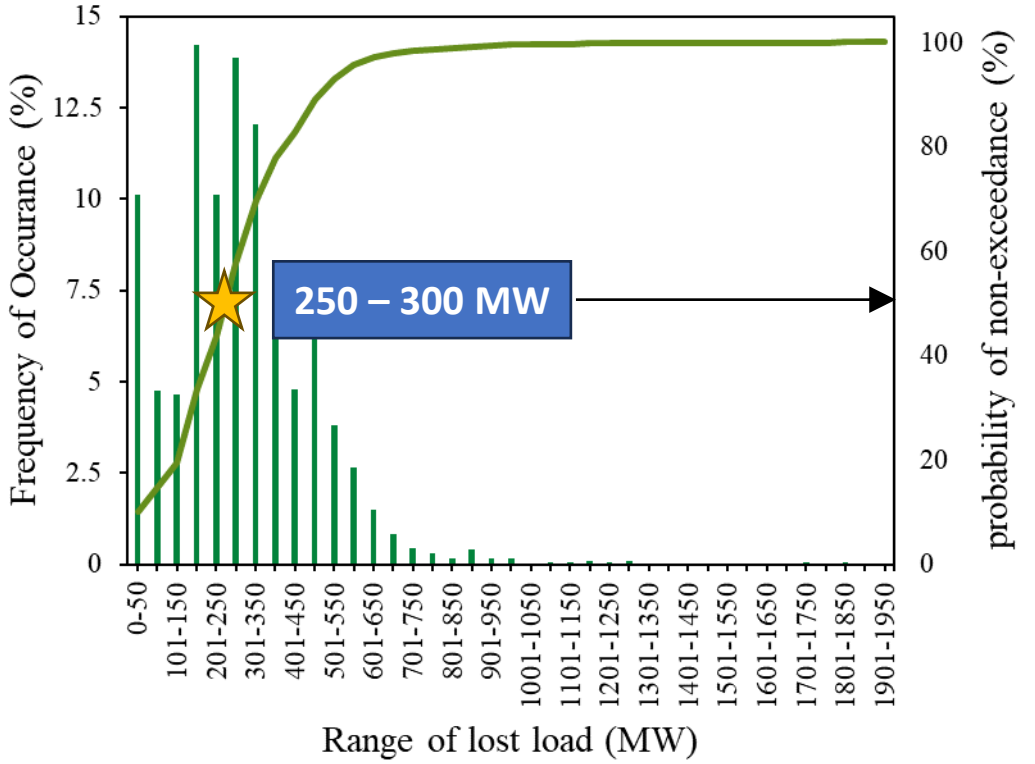
Grid Impact – M7.2 Seattle Middle Fault

- Results

Trip at 125% capacity

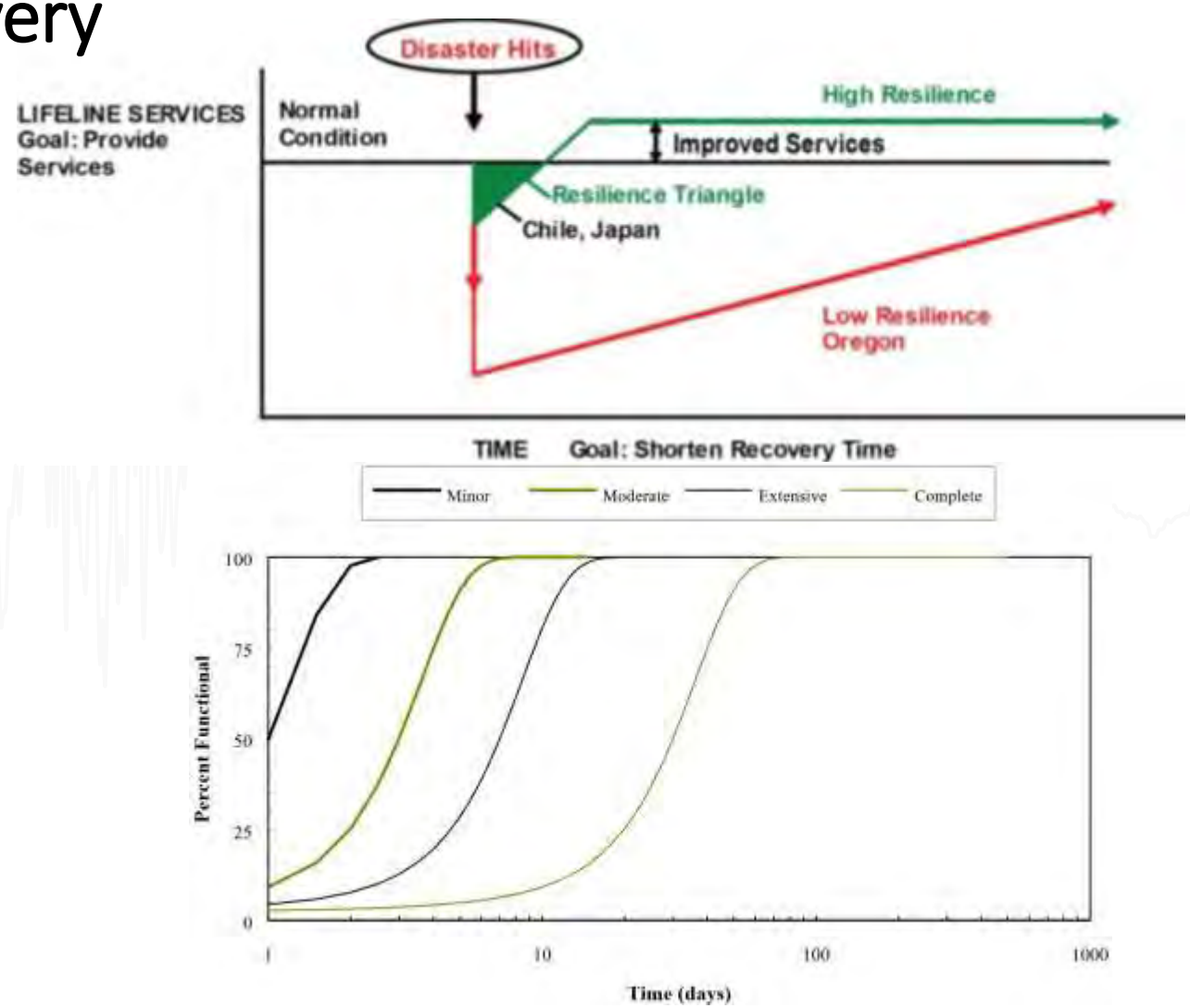


Trip at 150% capacity



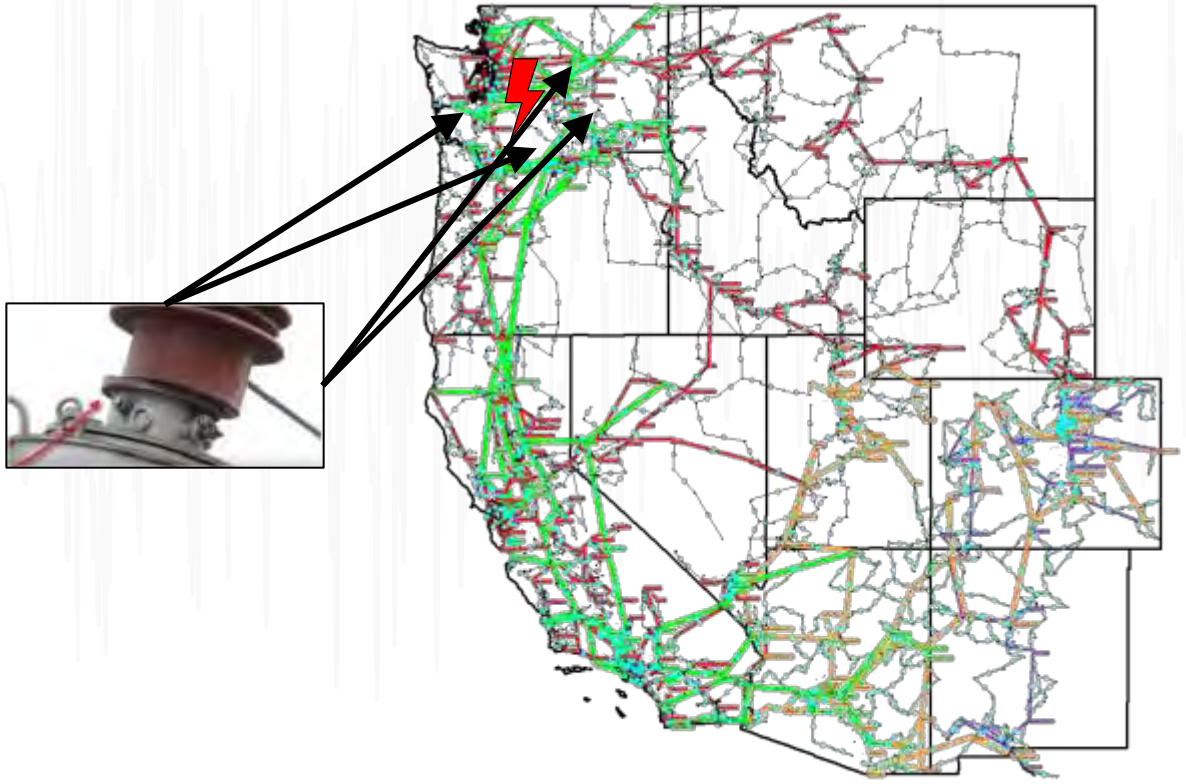
Grid Impact – Time to Recovery

- Time to recovery & service restoration
  - Takes time to restore lifelines following an earthquake
  - In some cases, this can be on the order of weeks to months for extensive damage



Grid Impact - Seismic Resilience

Targeting Questions:



Transformers are a known seismic vulnerability

What is the large-scale risk?

What measures can be taken to protect this equipment and the grid?

Seismic Vulnerability

How do we harden the electrical grid against seismic events?

What are the most common substation seismic failure mode(s)?

CIGRE Survey

- 99 respondents
- 19 different countries

cigre

SURVEY REPORT ON EARTHQUAKE DAMAGE AND SEISMIC DESIGN OF SUBSTATIONS

CIGRE WG B3.64 "Guidelines on Optimising Seismic Design of Substations for Power Resiliency"

AUGUST 2024

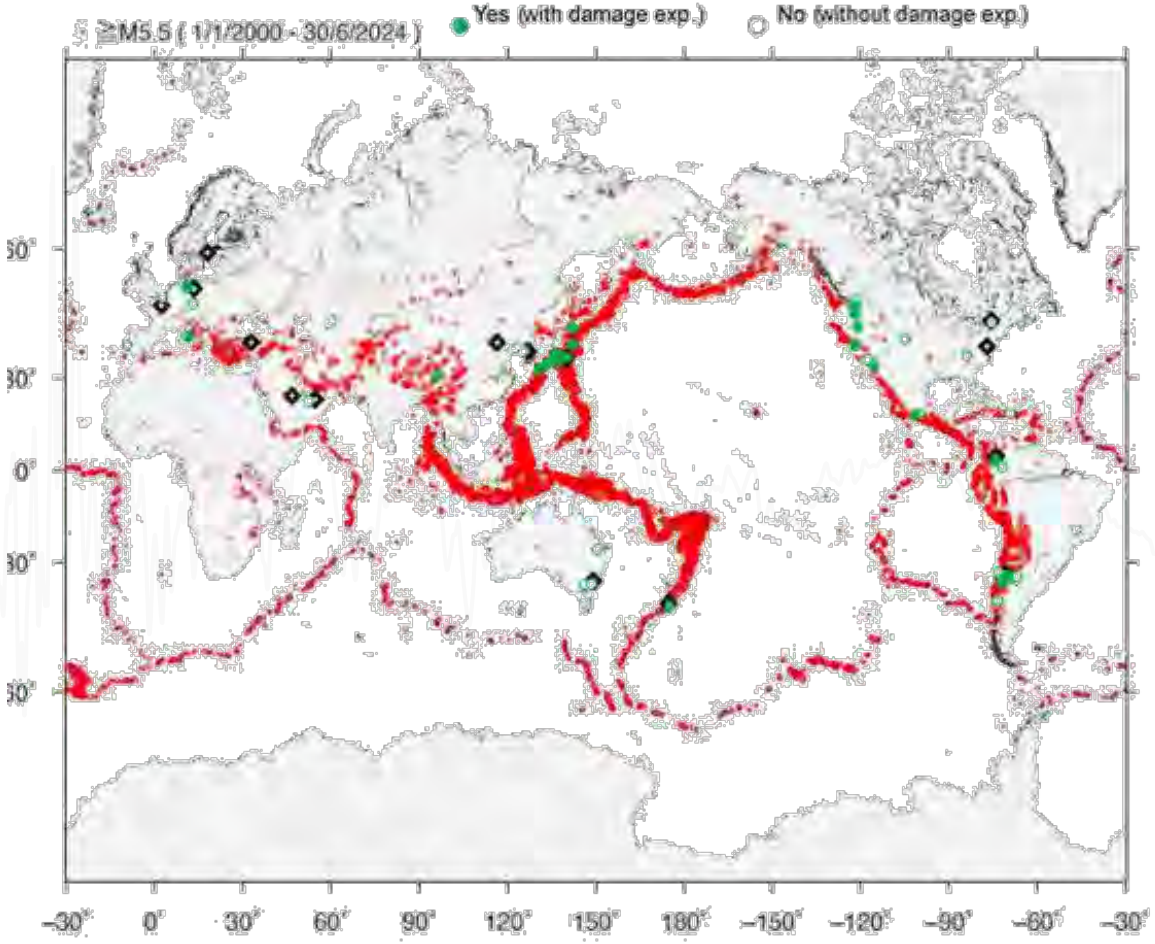


Figure 4: Distribution of respondents' experience of earthquake damage (Q3 responses)

CIGRE Survey

- *Which main circuit equipment types were damaged due to earthquakes at your substation?*

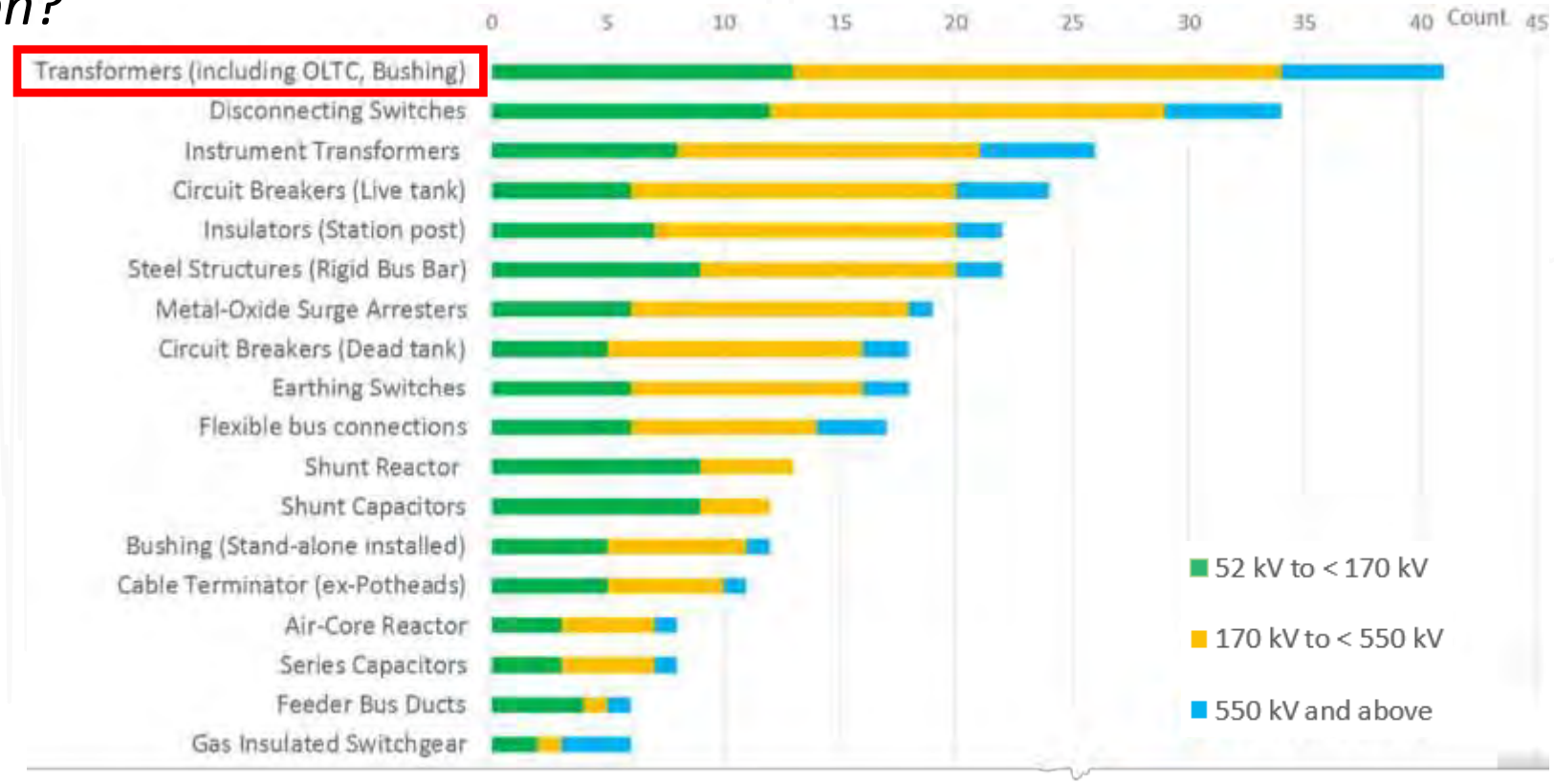
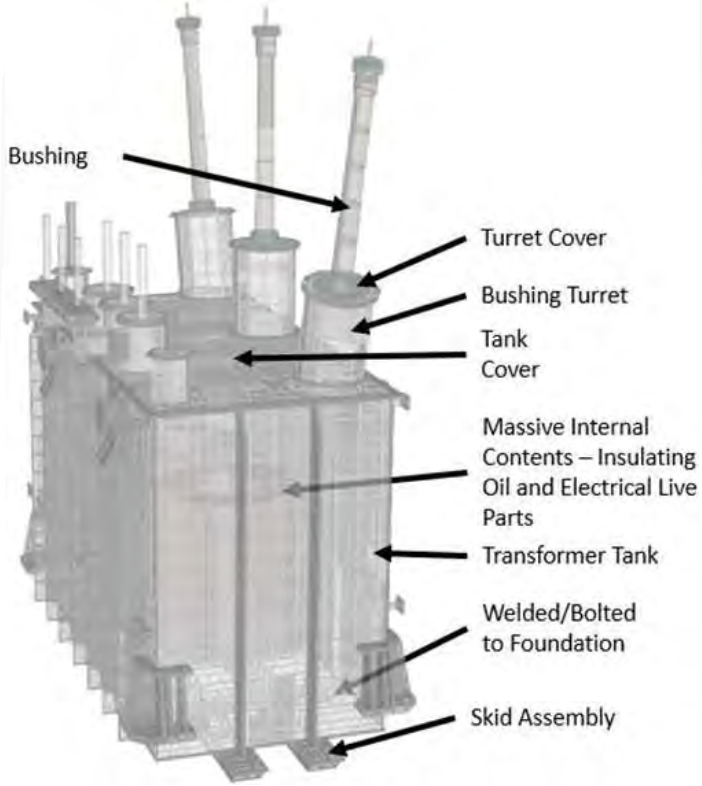
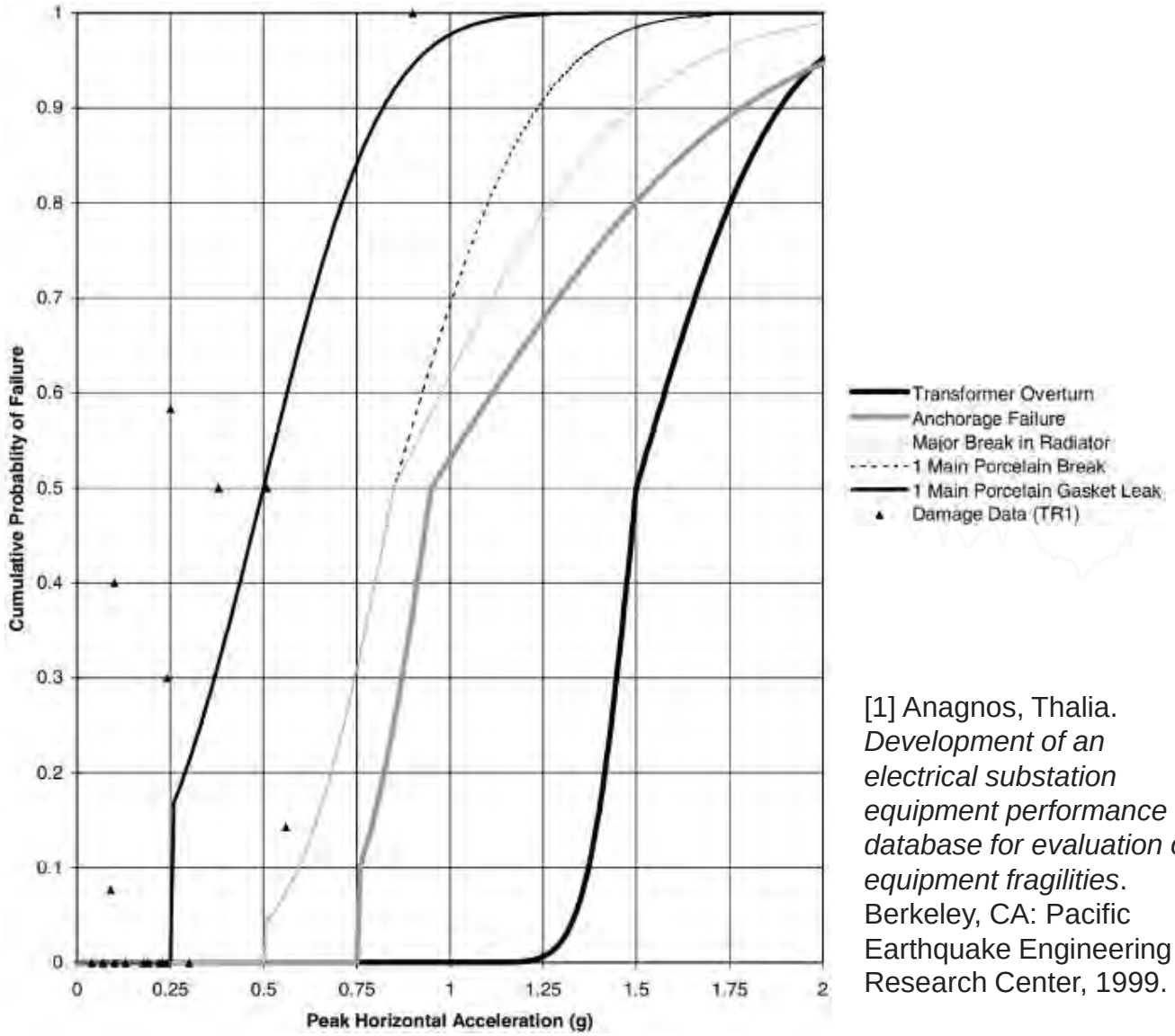


Figure 9: Frequency of earthquake damage experience by equipment type (Q5 responses)

Risk for Transformers

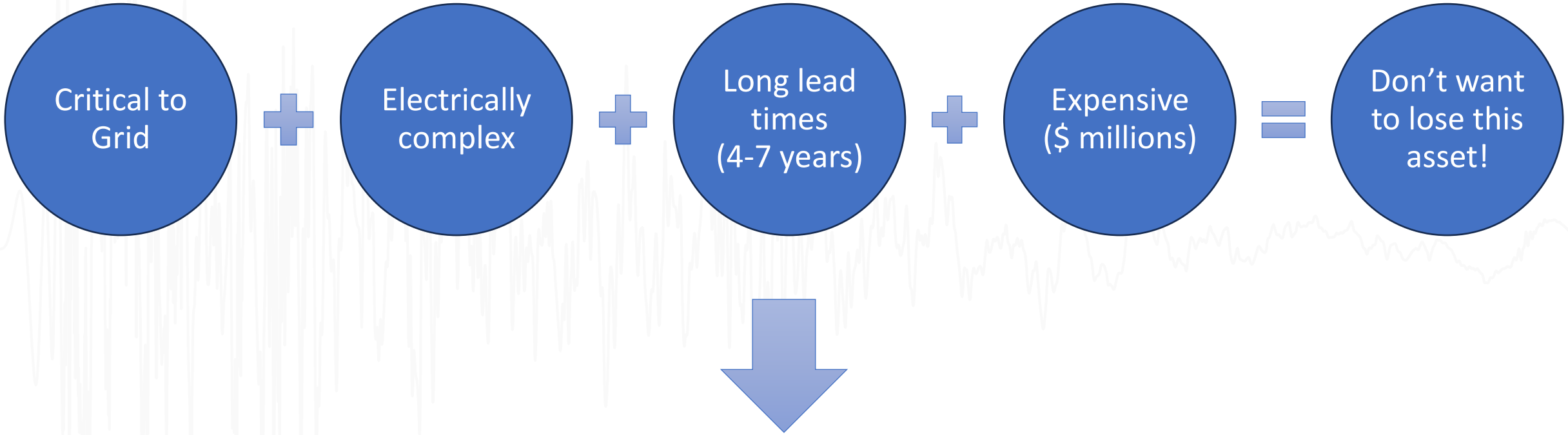
- Fragility curves for a single-phase 230kV transformers





[1] Anagnos, Thalia. *Development of an electrical substation equipment performance database for evaluation of equipment fragilities*. Berkeley, CA: Pacific Earthquake Engineering Research Center, 1999.

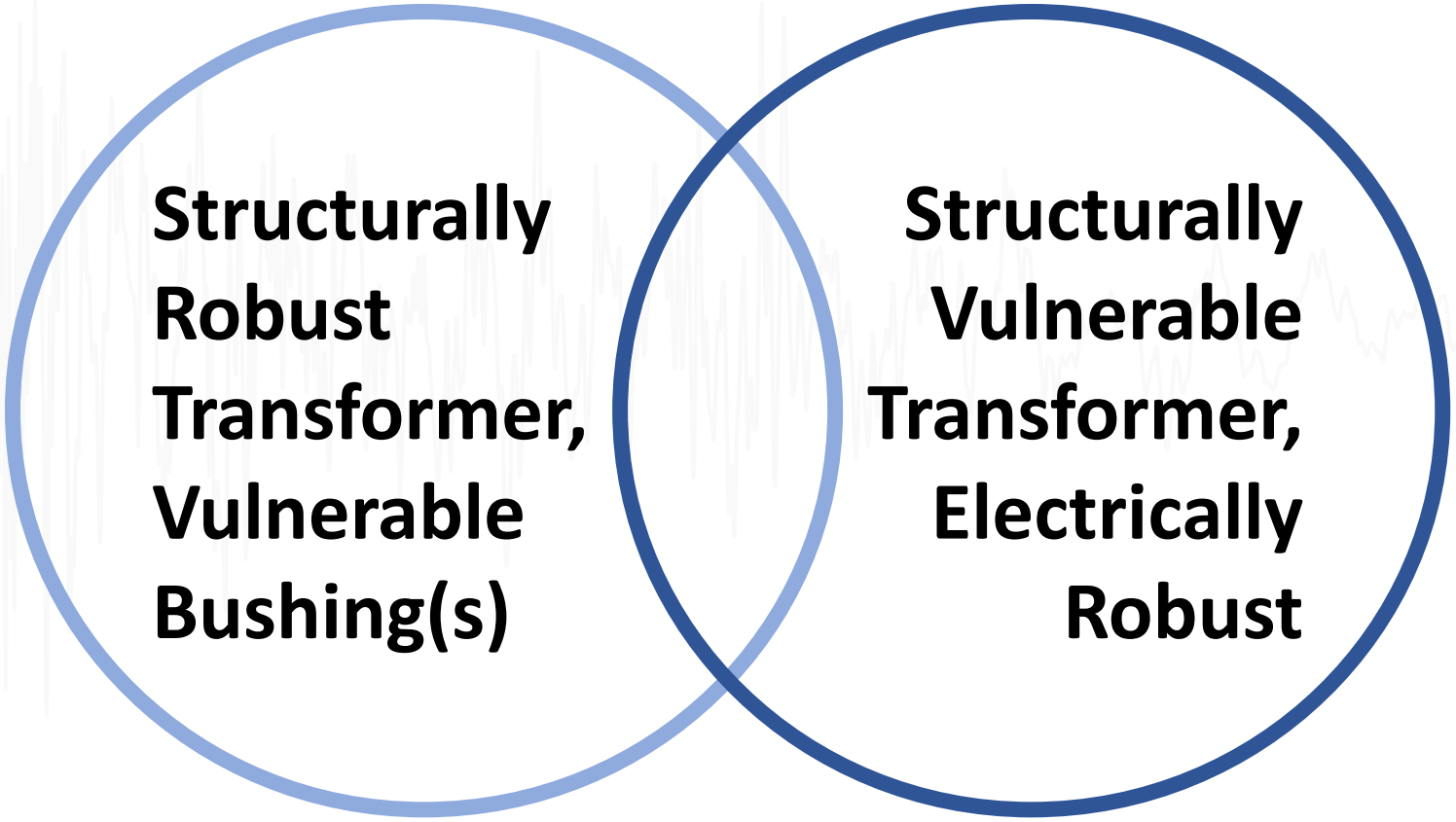
High Voltage Power Transformers



What can we do about this?

Transformer-Bushing System Vulnerability

Two Vulnerability Cases:



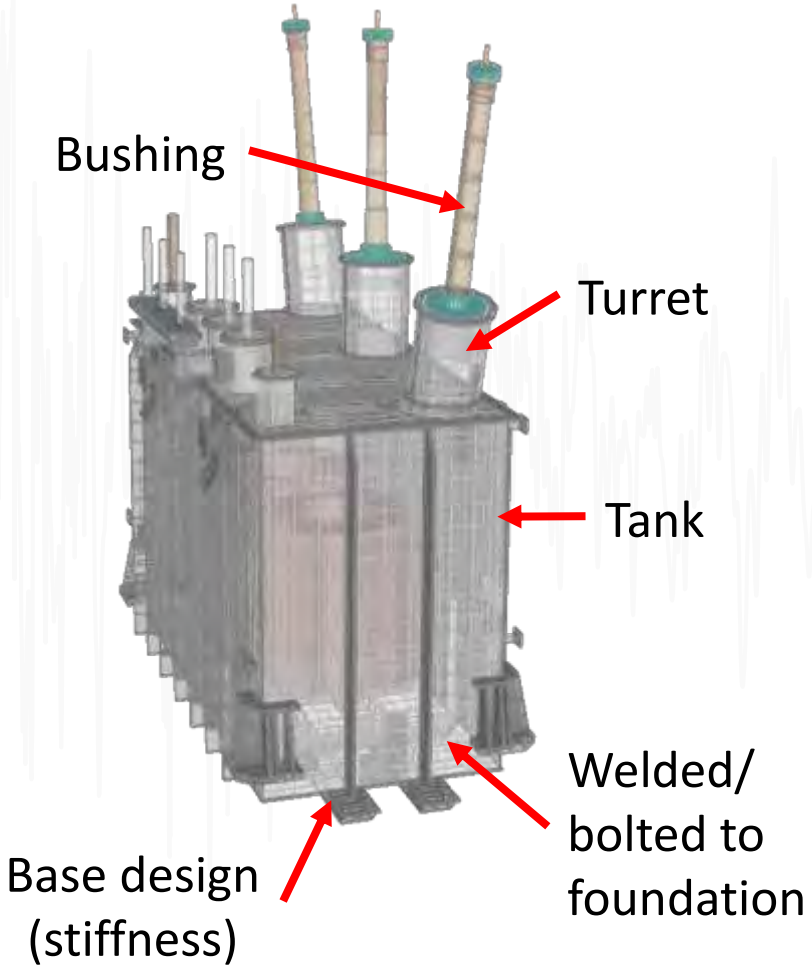
Case 1

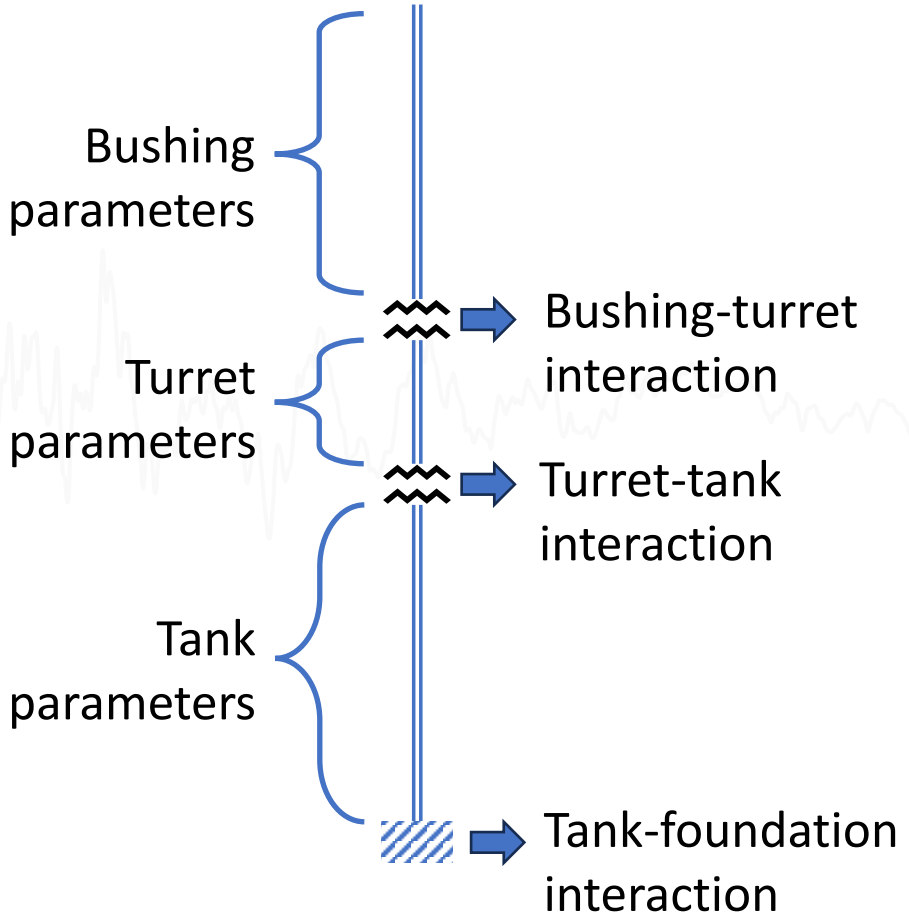
Case 2

Bushings – Vulnerabilities and Solutions

How do we protect transformers from the most common seismic failure mode?

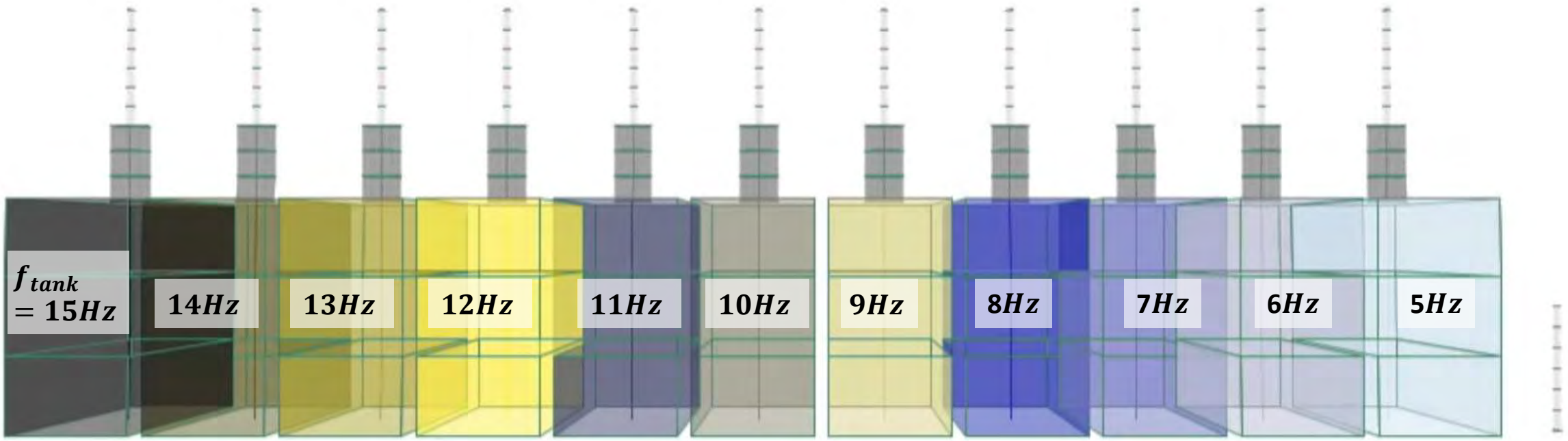
Critical Load Path Elements





Dynamic Amplification

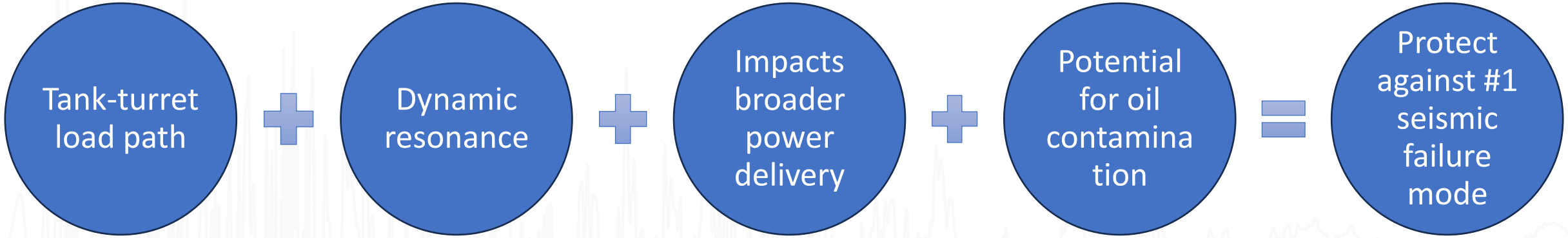
$f_{bushing} = \sim 7Hz$ *(Mounted – All Configurations)*



Different Transformer Designs – Varied Tank Frequencies

Same Bushing on All Transformers – Same Bushing Frequency

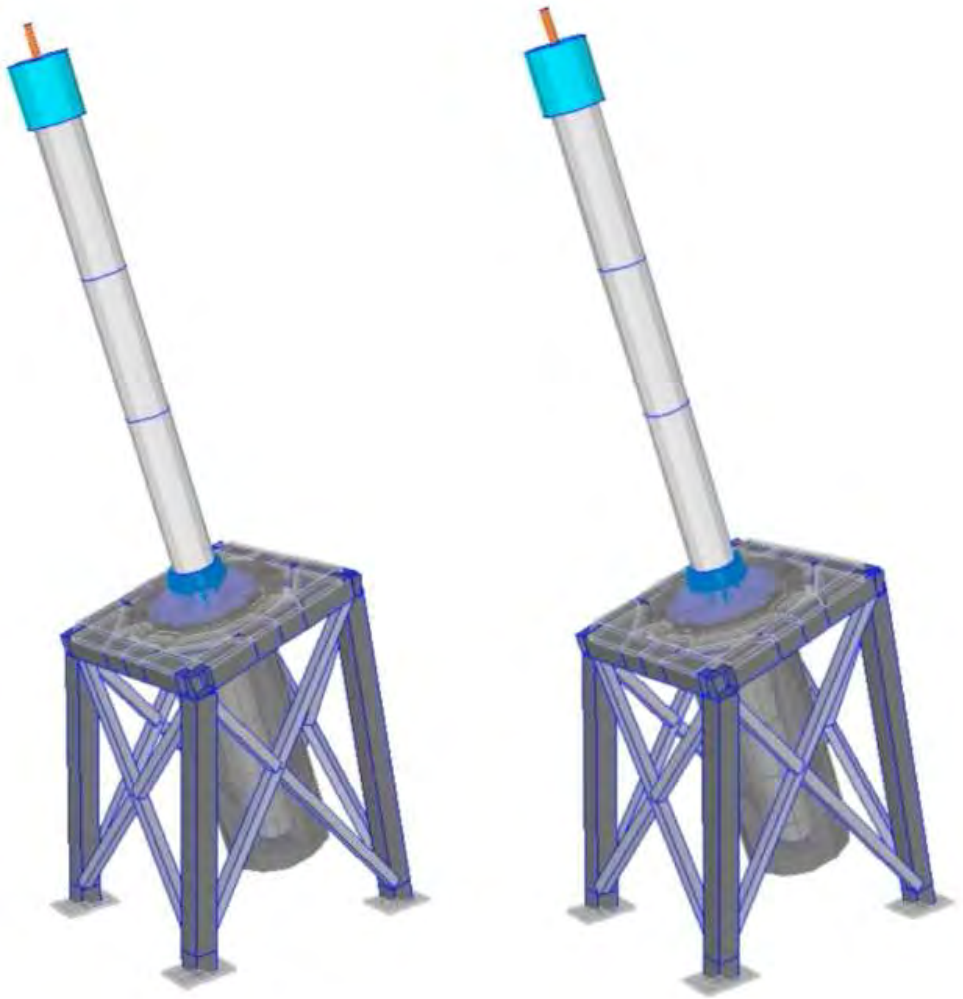
Bushing Vulnerabilities



What can we do about this?

Protecting Bushings

- Bushing Decoupler System
  - Low cost
  - Retrofittable
  - Easy installation
  - Design independent

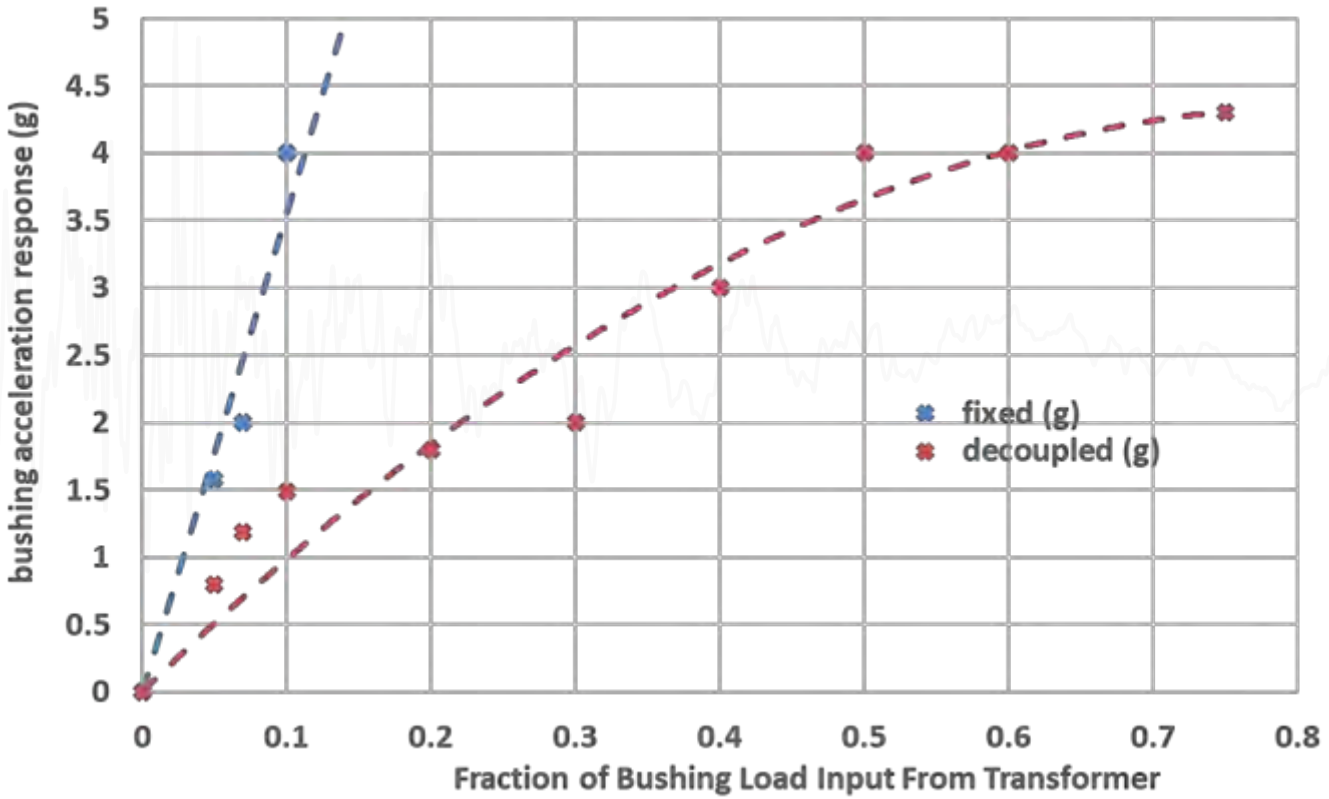


Fixed Bushing

Bushing w/ Decoupler

Protecting Bushings

- Bushing Decoupler System
  - Low cost
  - Retrofittable
  - Easy installation
  - Design independent
  - 62-86% load reduction

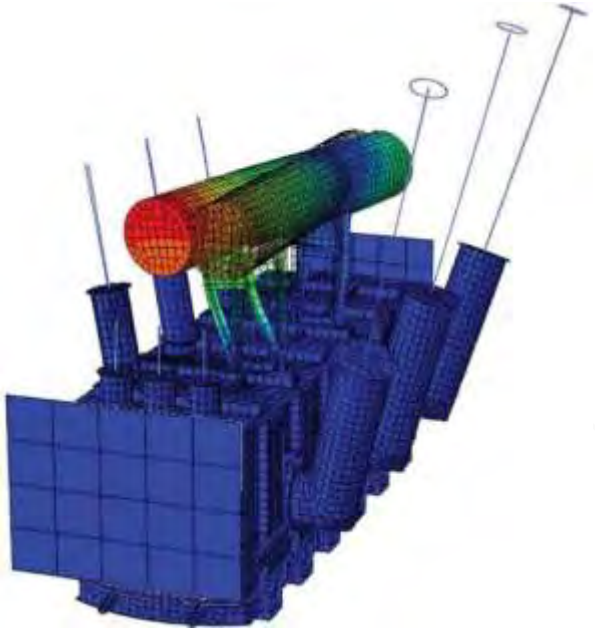


More Seismic Failure Modes & Solutions

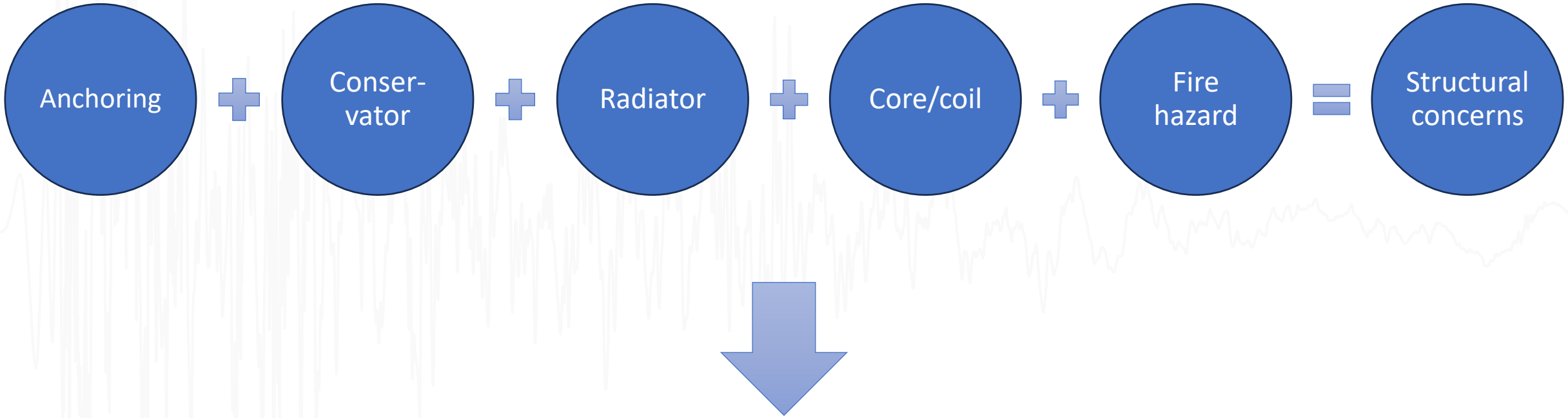
How do we protect transformers from other seismic failure modes?

Additional Transformer Seismic Failure Modes

- Anchorage Failures
- Unanchored / foundation
- Conservator supports
- Radiator valves
- Core/Coil damage
- Fire hazard from oil leakage



Structural Vulnerabilities



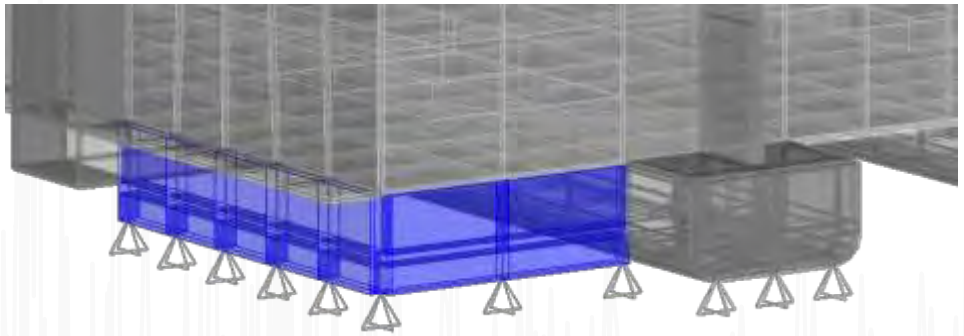
What can we do about this?

Structural Mitigations

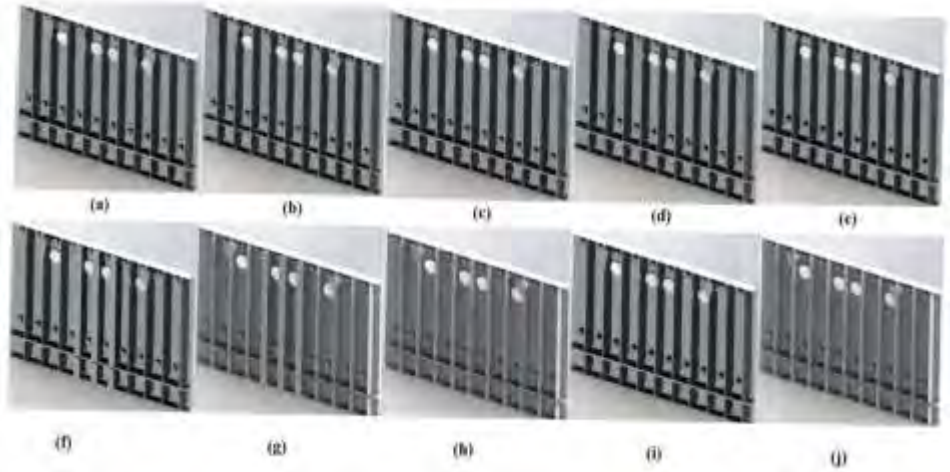
- Improve tank base foundation & load path(s)
- Increase stiffener quantity and strategic placement
- Improve bracing for under-supported components
- Base isolation

Note: not all of these are equal, and in some cases, a broadly-helpful solution may exacerbate other seismic vulnerabilities

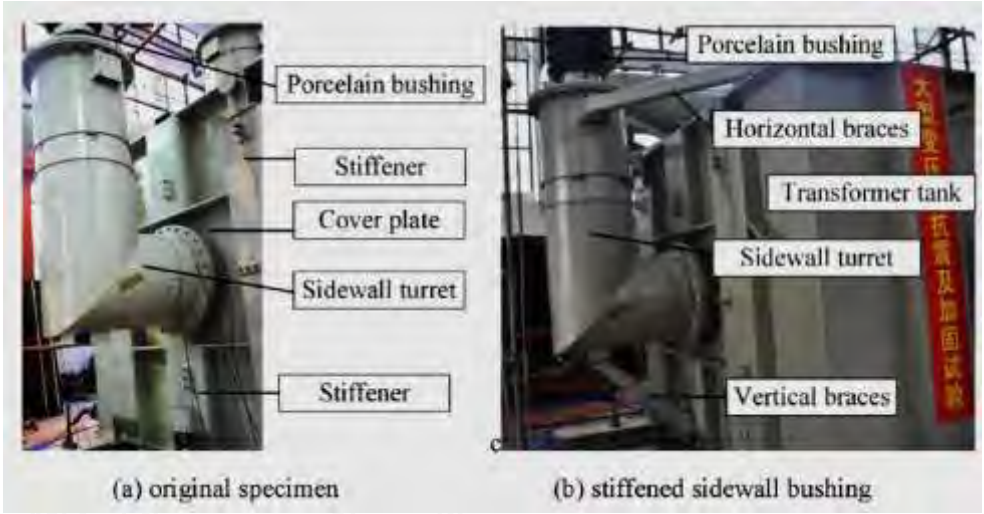
Structural Mitigations



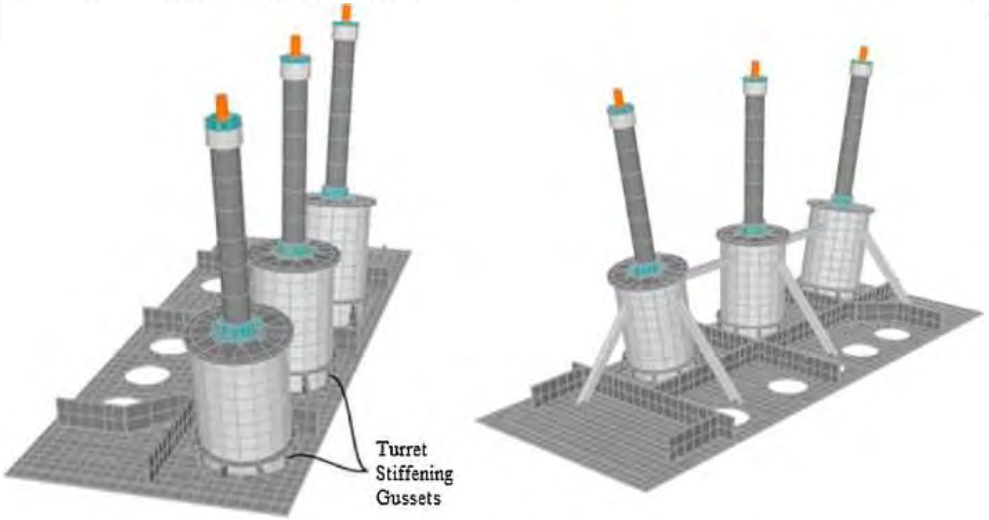
Improve tank base foundation



Increase stiffeners quantity and strategic placement



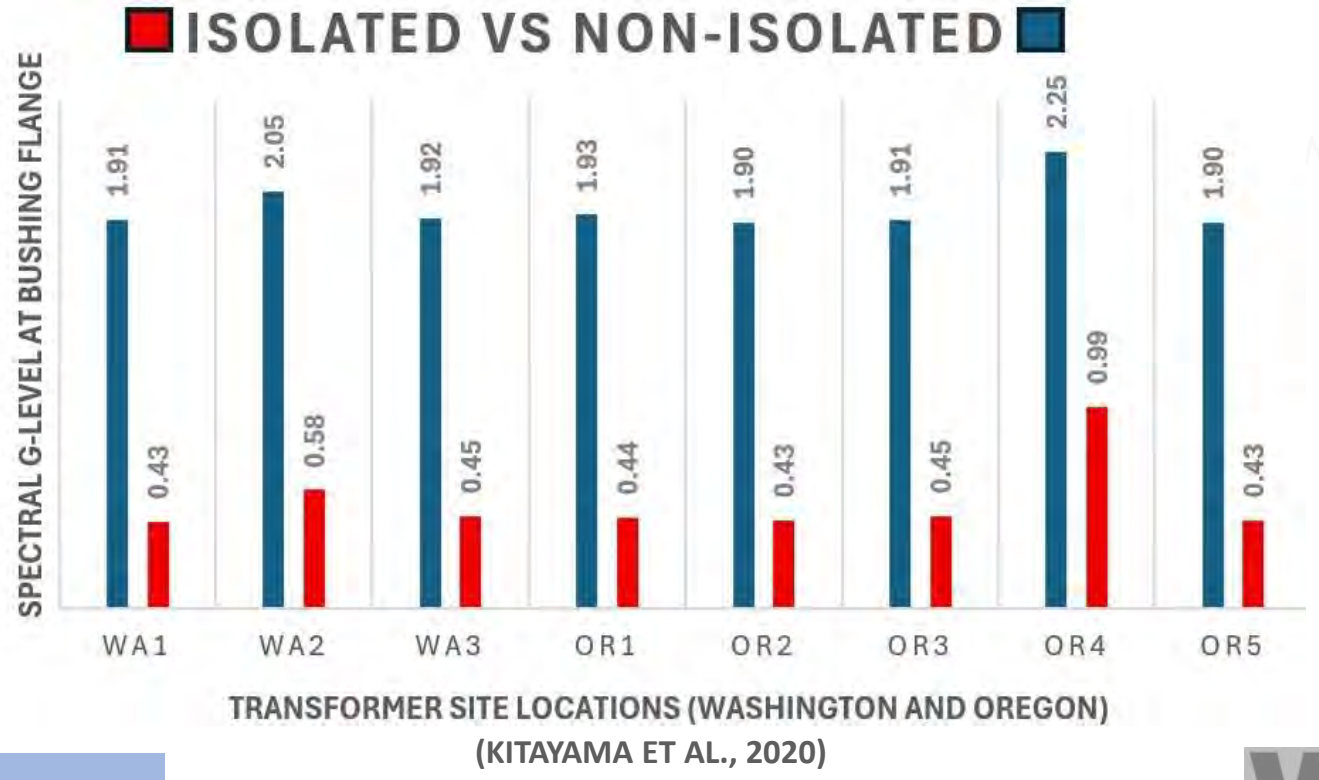
Improve bracing (e.g., Lonnie braces)



Structural Mitigations – Base Isolation

Transformer Base Isolation

- Bushing flange accelerations for base isolated and non-base isolated transformers across 8 sites in the U.S. Pacific Northwest

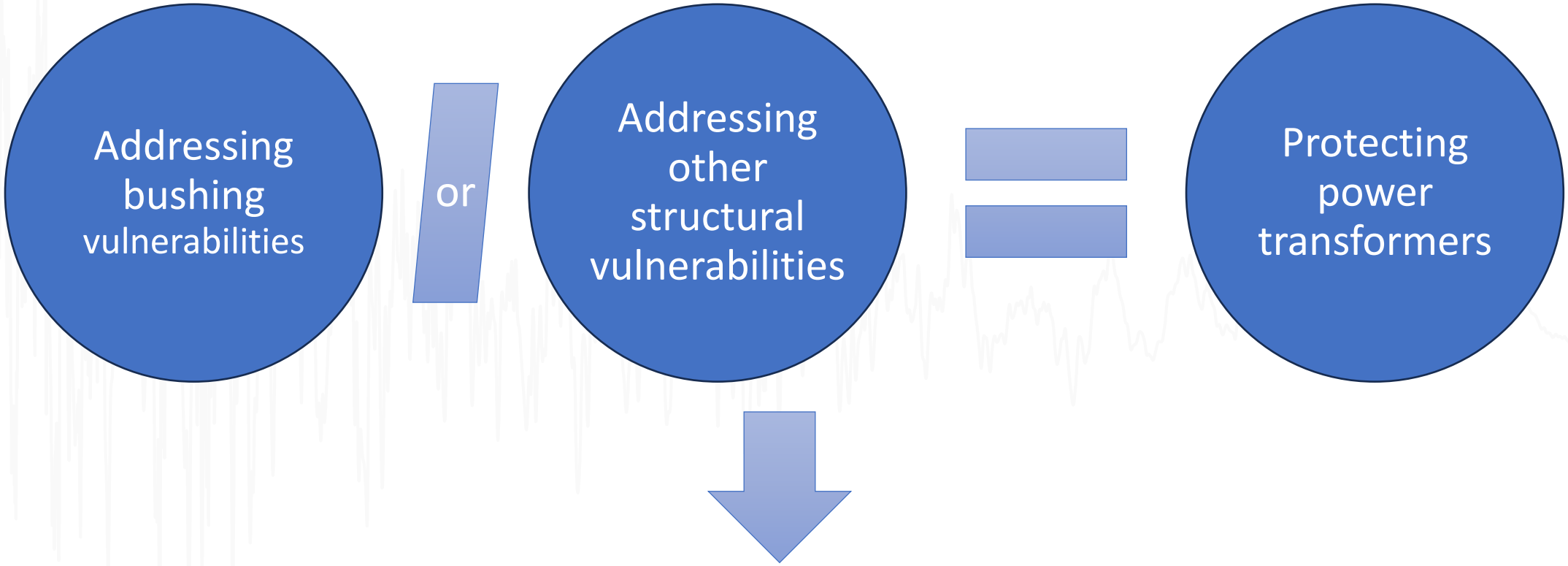


(KITAYAMA ET AL., 2020)

Seismic Mitigation – Seattle City Light

- Power transformer base isolation
- Use of dampers in equipment to reduce accelerations, including:
  - CVTs
  - Surge Arresters
  - Breakers
  - Capacitor Racks
  - Disconnect Switch Structures
  - Masonry Screen Walls
  - Generators
- Evaluating building upgrades
- Developing seismic standards within the organization to stay on track for the next 50 years
- Serving as a leader of seismic mitigation and educating others

Structural Vulnerabilities



How do we verify these solutions?

Shake Table Testing

How do we confirm how and which seismic mitigation solutions work?

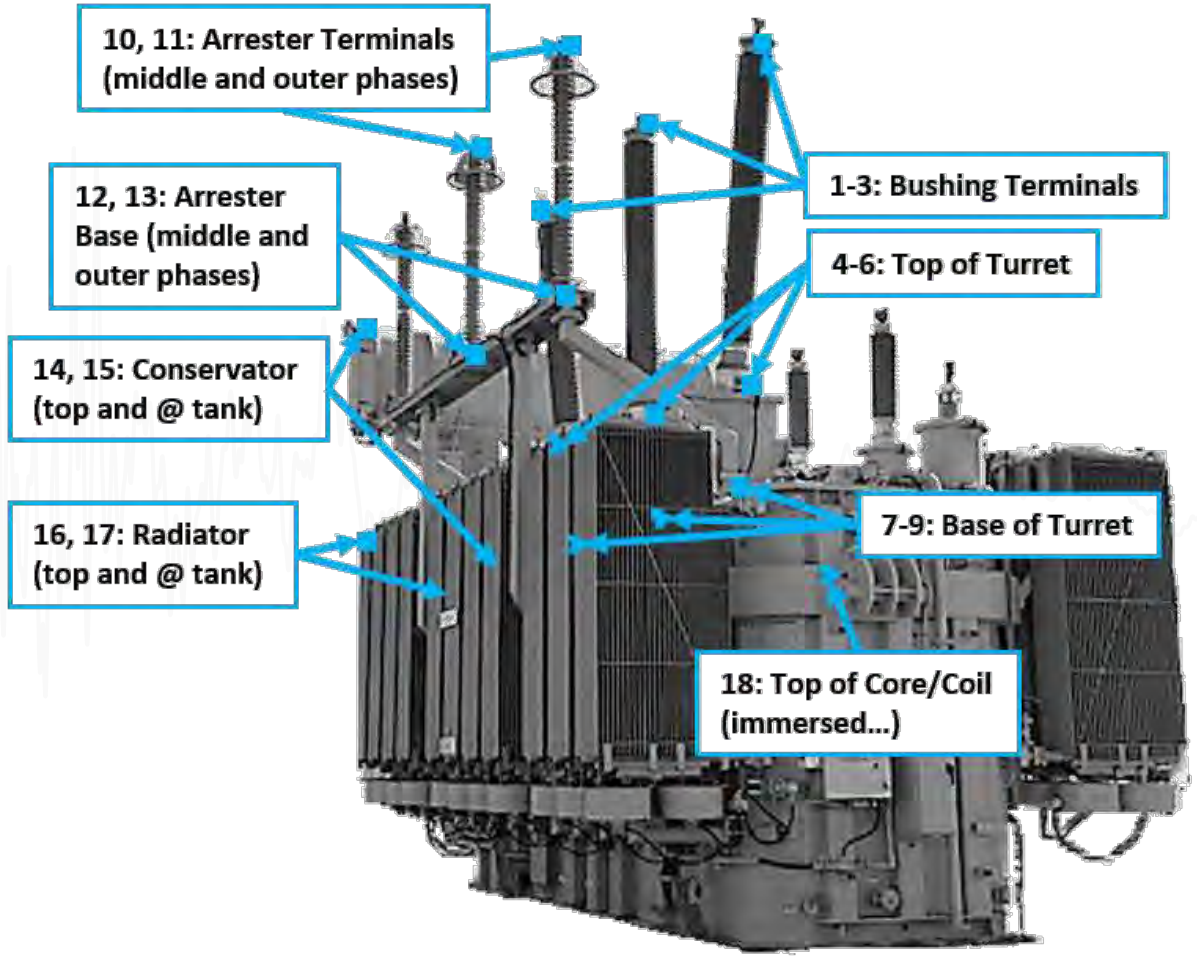
Shake Table Testing

- Shake testing is experimental gold standard for seismic analysis
- World's 1st full-scale, fully-dressed, test of a three-phase high voltage power transformer
  - 230kV, 3-Phase, 550kip Transformer
  - Relatively new unit, built in 2014
  - Suffered electrical failure but structurally intact

Siemens Transformer – Sister Unit

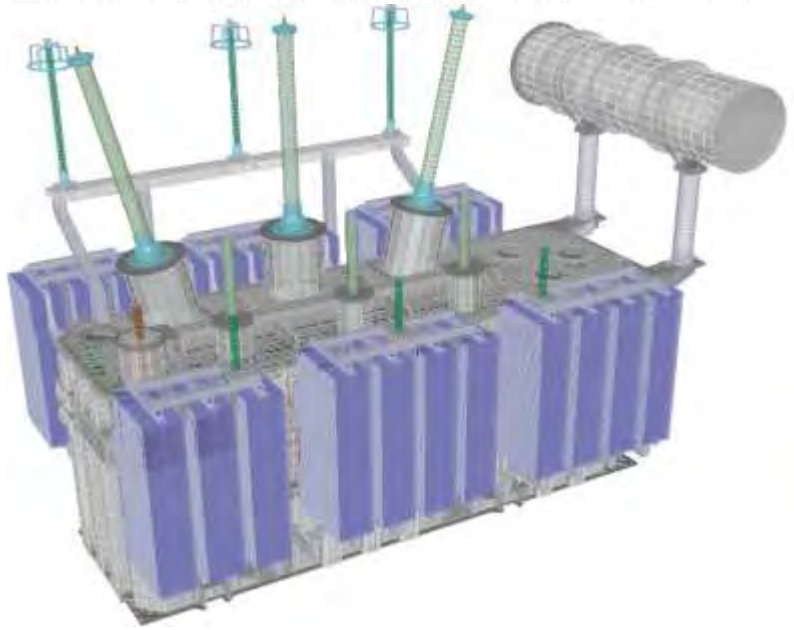
Shake Table Testing

- Goals:
  - Evaluate Bushing Decoupler Protection System
  - Test Base Isolation
  - Understand Power Transformer Seismic Behavior
    - Multiple bushing types
    - Monitoring live parts
    - Flexible bushing-conductor connections



Industry Days – Fall 2026

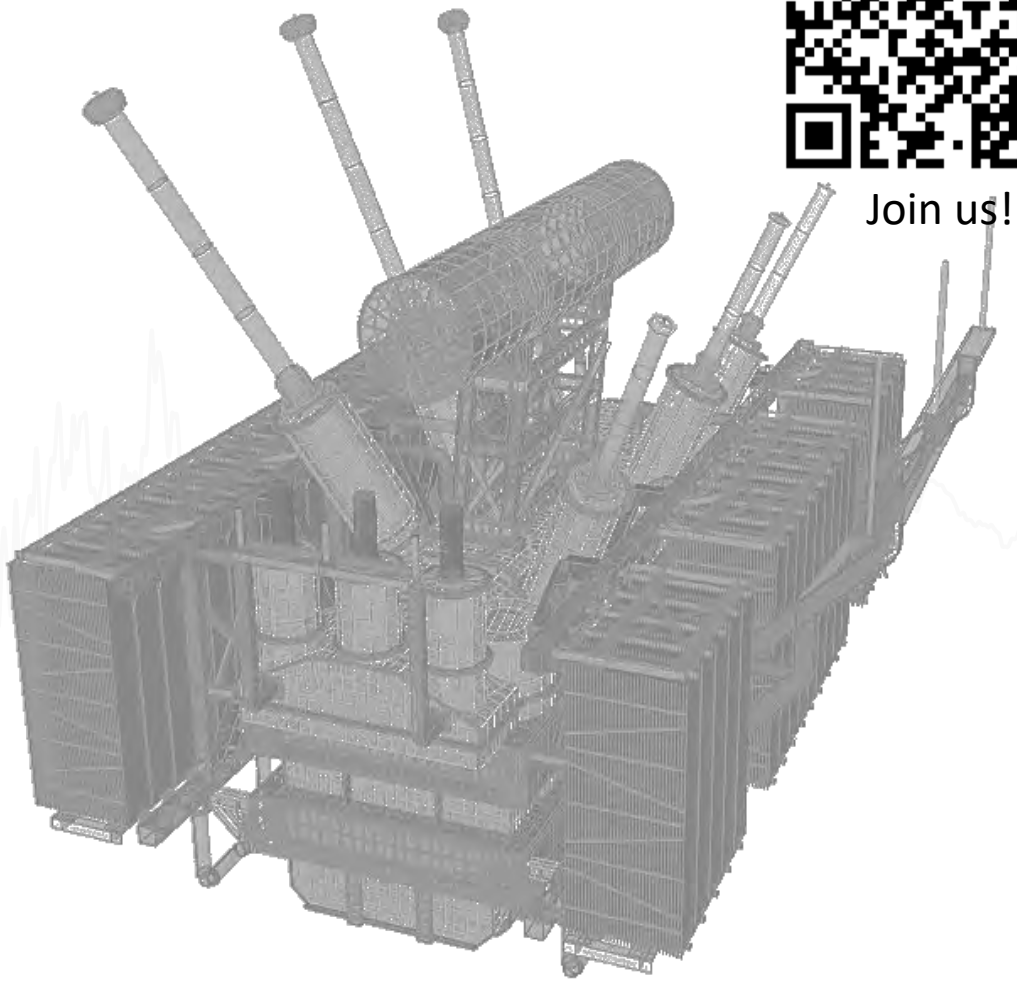
- Save the date!
  - Decoupler Demonstration: Tues Sept 22nd
  - Base Isolation Demonstration: Tues Oct 13th
- Connect with us to learn more about attending this test:



Join us!

Summary

- Transformers are seismically vulnerable but there's a lot we can do to protect them!
  - Bushings are most vulnerable
  - Lots of mitigation strategies available

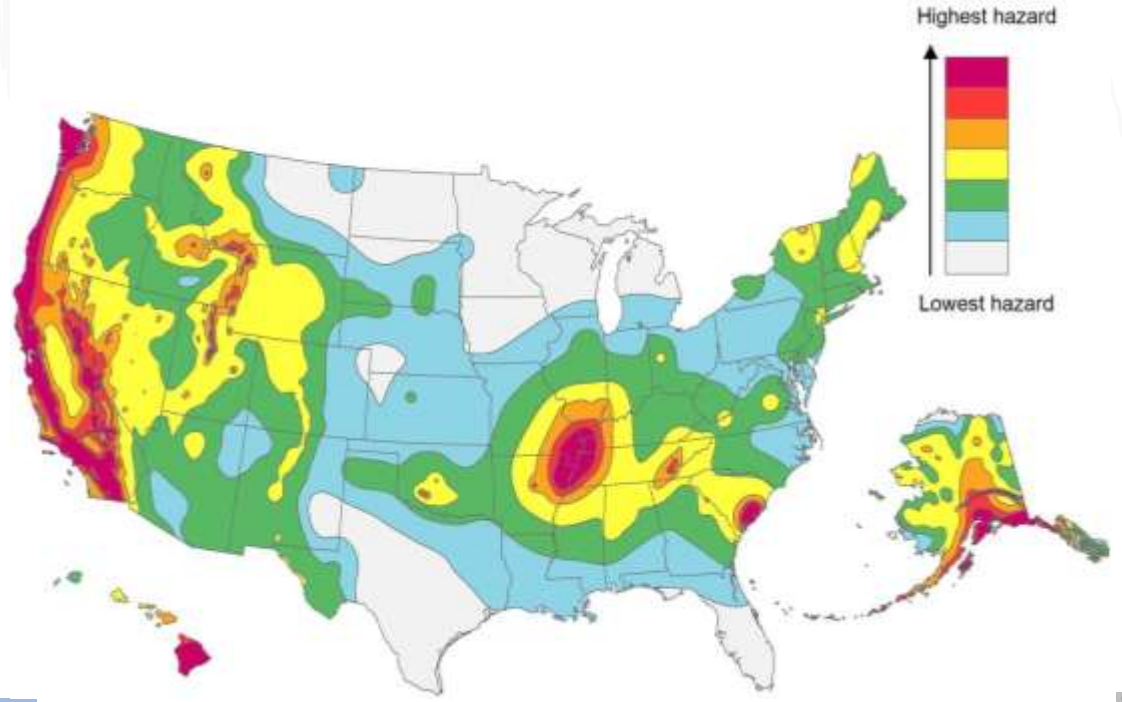


Join us!

Summary

- Potential for broad grid impact
  - Widespread seismic risk in the US (especially West Coast) and globally
  - Poor resiliency will elongate recovery and impact communities each day

Join us!



Idaho National Laboratory

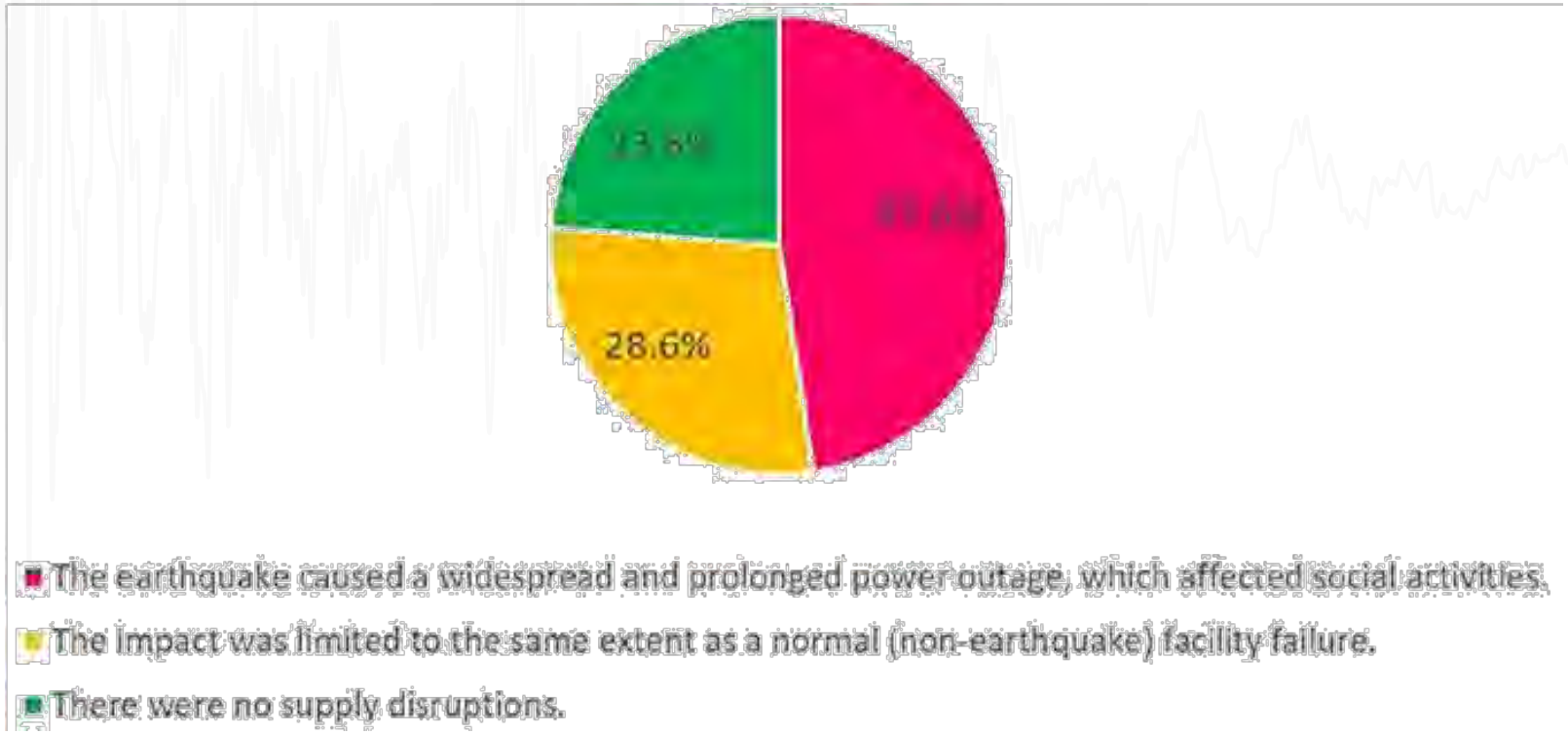
USGS
science for a changing world

WEGAI RESEARCH

Summary

- CIGRE survey: Has there been any impact on the power supply due to the damage caused by the earthquake?

Join us!



Questions?

Please reach out:

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- Jon Bender
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Join us for our Industry Days!