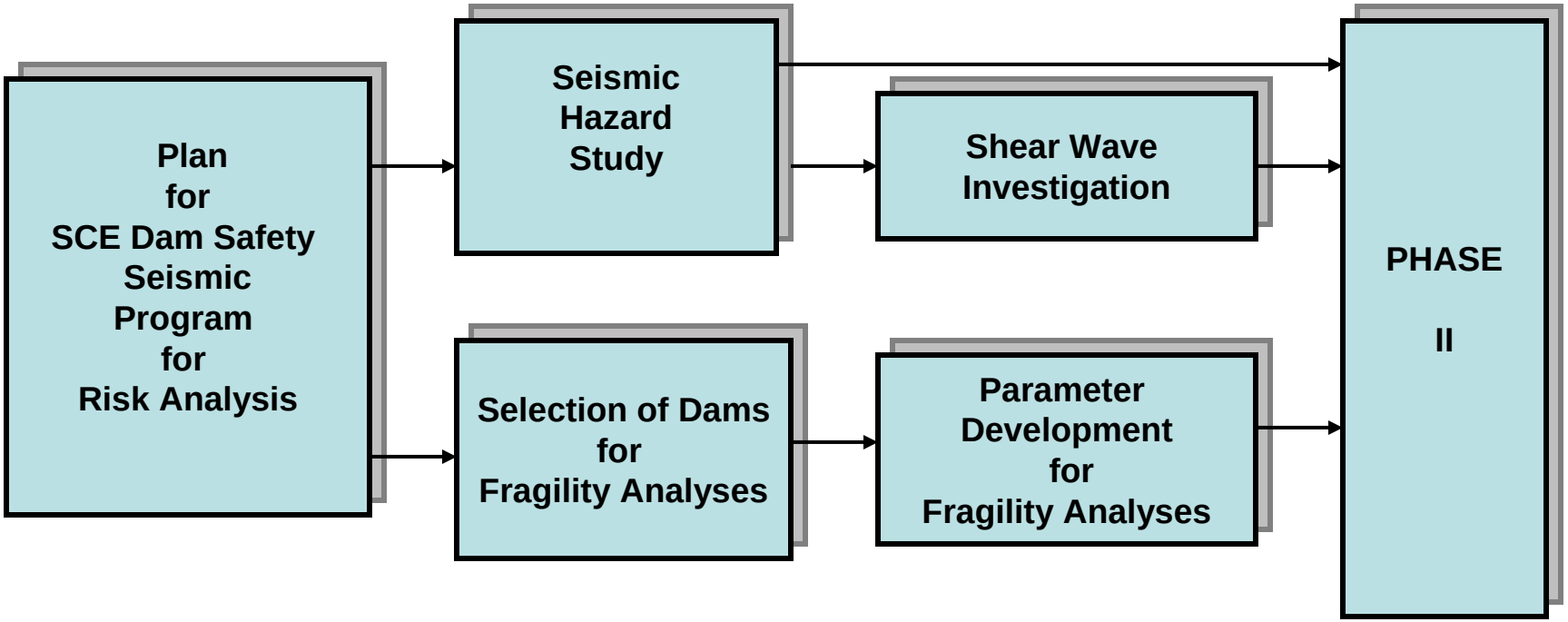
# FRAGILITY ANALYSES

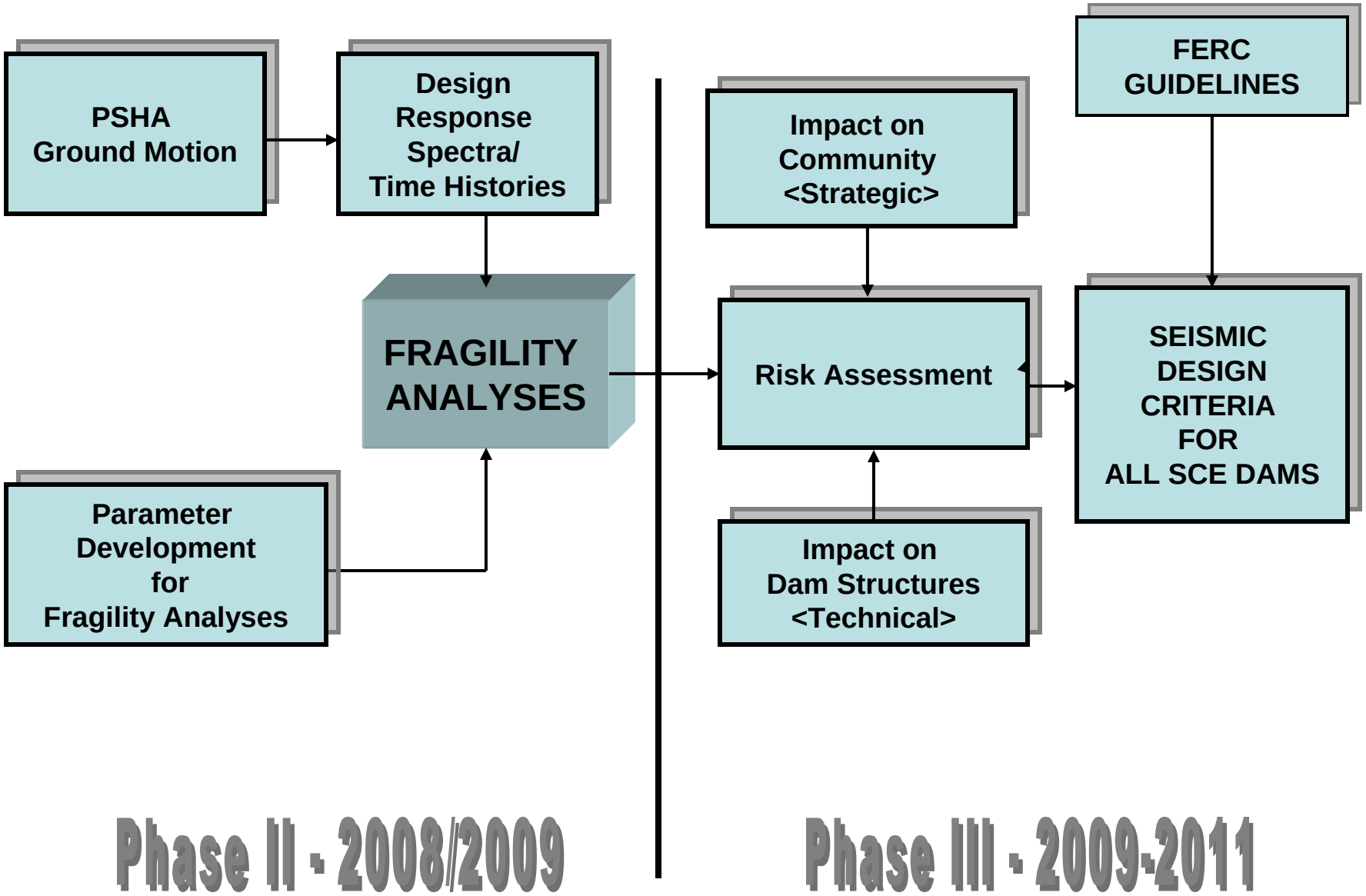
## SCE Dam Safety SEISMIC PROGRAM 2007 – 2012

# SEISMIC PROGRAM

Evaluate SCE's dams using a seismic hazard based on **probabilistic** methods as opposed to deterministic so that the consequences and risk of a dam failure can be better understood by SCE, by regulators and the community.




# Phase I - 2007/2008


PSHA
Ground Motion
Design
Response
Spectra/
Time Histories
FRAGILITY
ANALYSES
Parameter
Development
for
Fragility Analyses
Impact on
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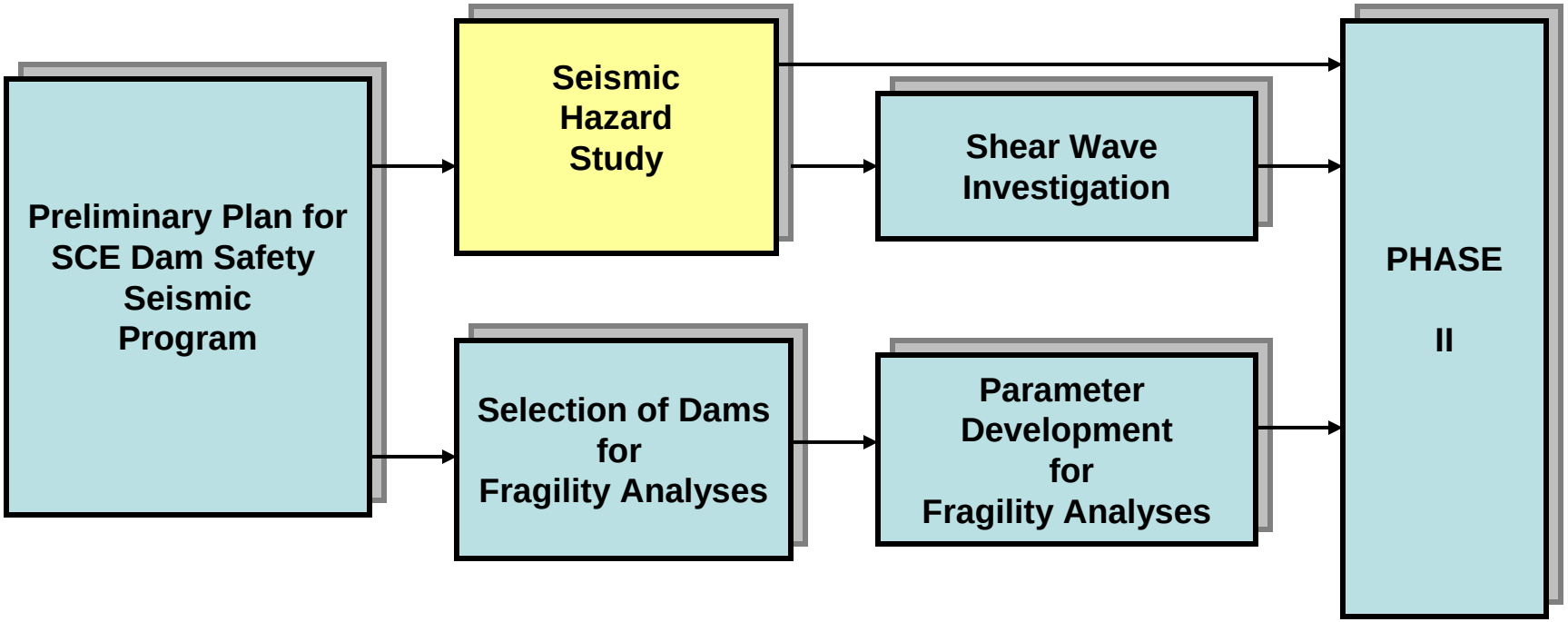
ALL SCE DAMS
Phase II - 2008/2009
Phase III - 2009-2011

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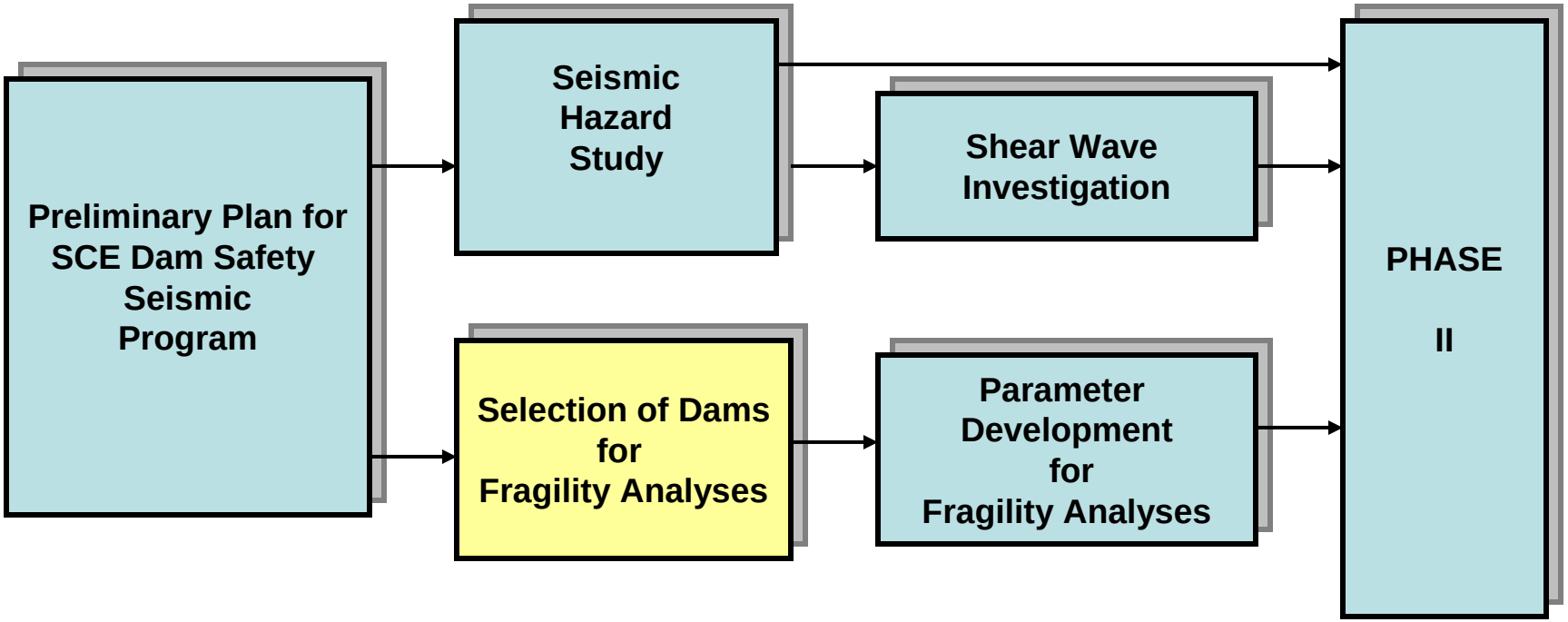



# Phase I - 2007/2008

# SELECTION OF DAMS FOR FRAGILITY ANALYSES

## SITE SELECTION CRITERIA

- Previous Reports - **PFMA**
- Emergency Action Plans
- STID – Supplemental Tech. Info. Data
- Type of Dam (concrete, earth-fill, etc)
- Condition of Dams
- Type of Foundation (Moraine, Granite, etc)
- Site Visits/Inspections
- Anticipated Performance

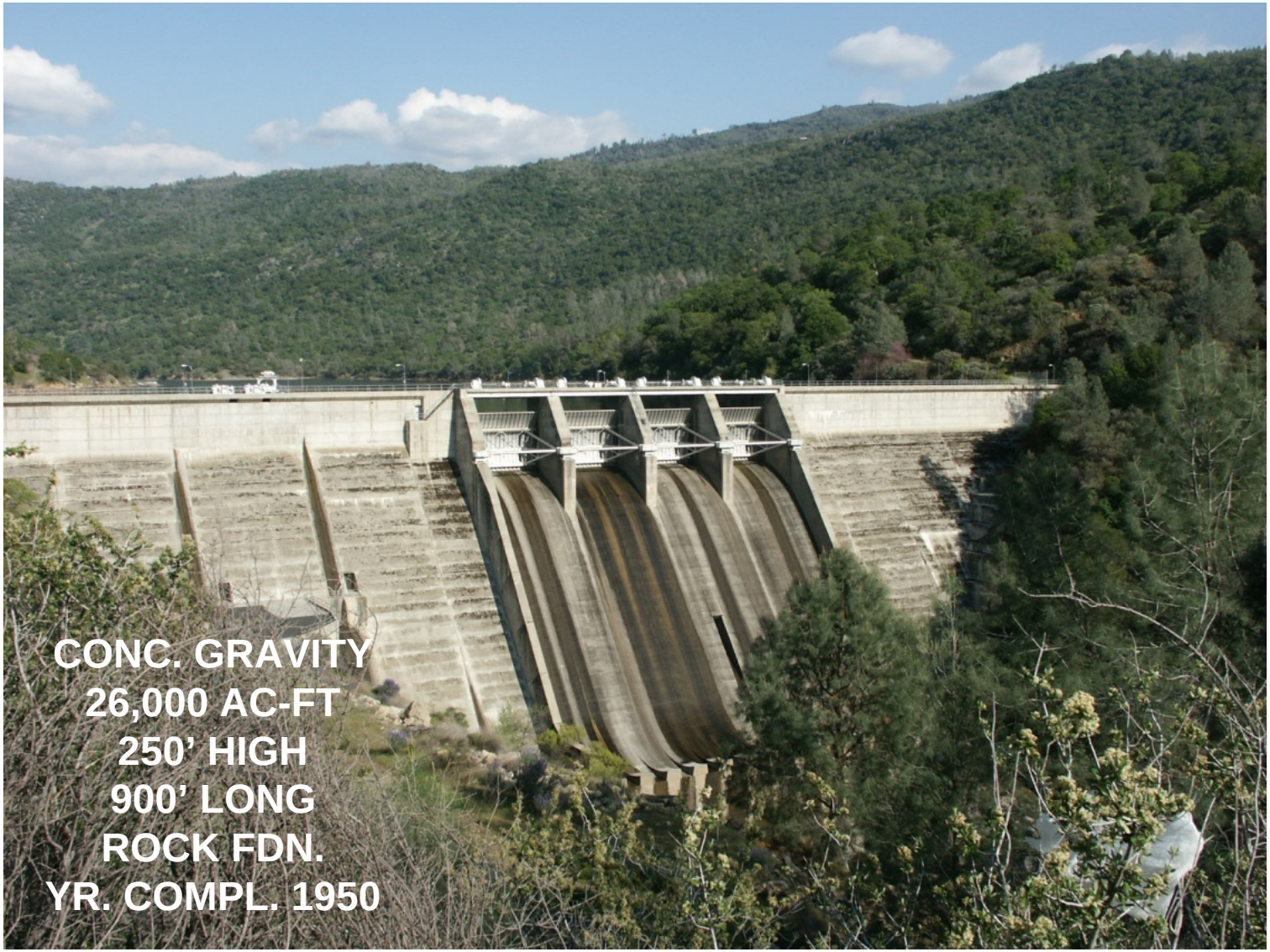
# STUDY DAMS

2008

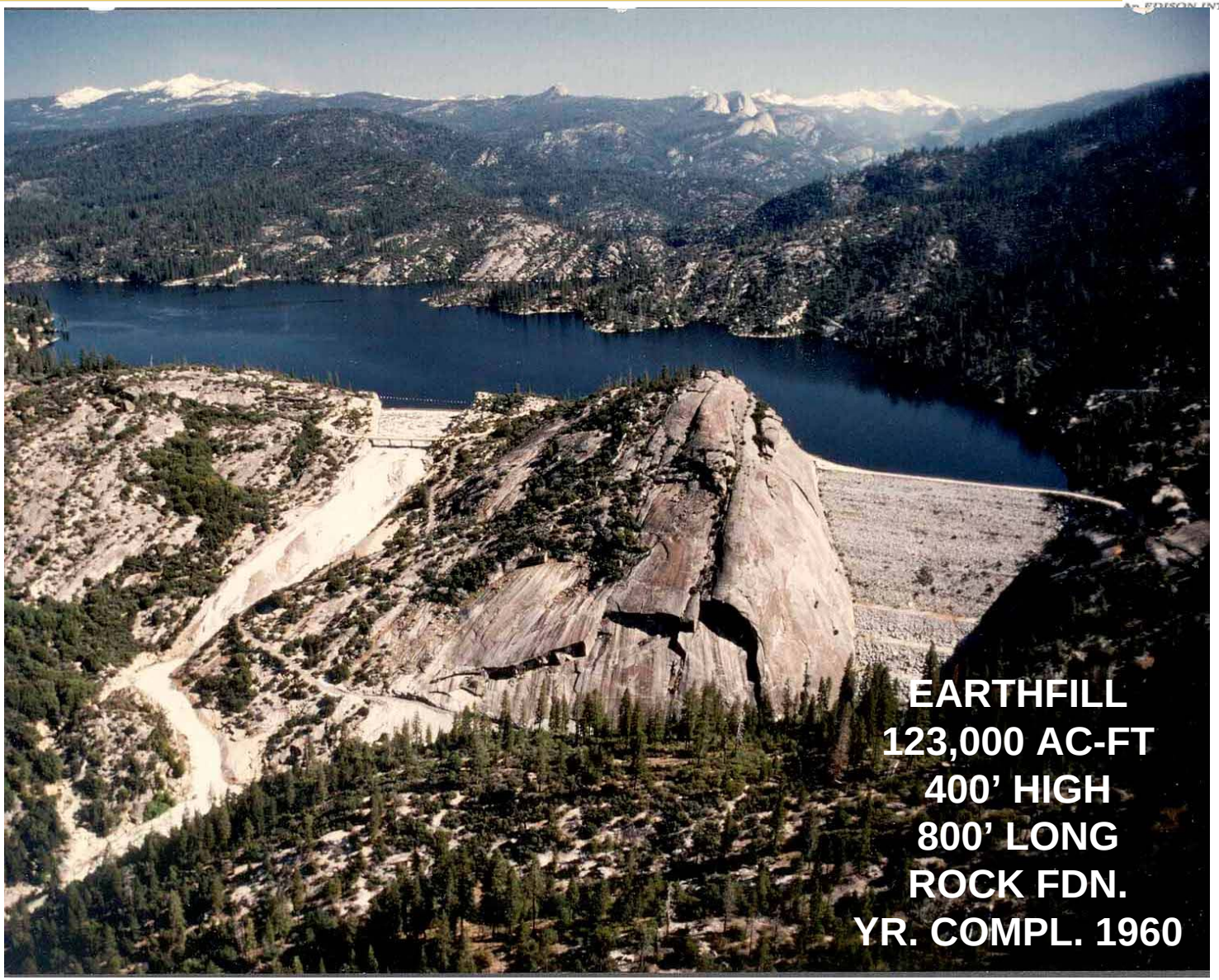
- Big Creek Dam #7 — Concrete Gravity
- Mammoth Pool Dam — Earthfill

2009

- Gem Lake Dam — Concrete Multiple-Arch
- Shaver Lake Dam — Concrete Gravity
- Vermilion Valley Dam — Earthfill



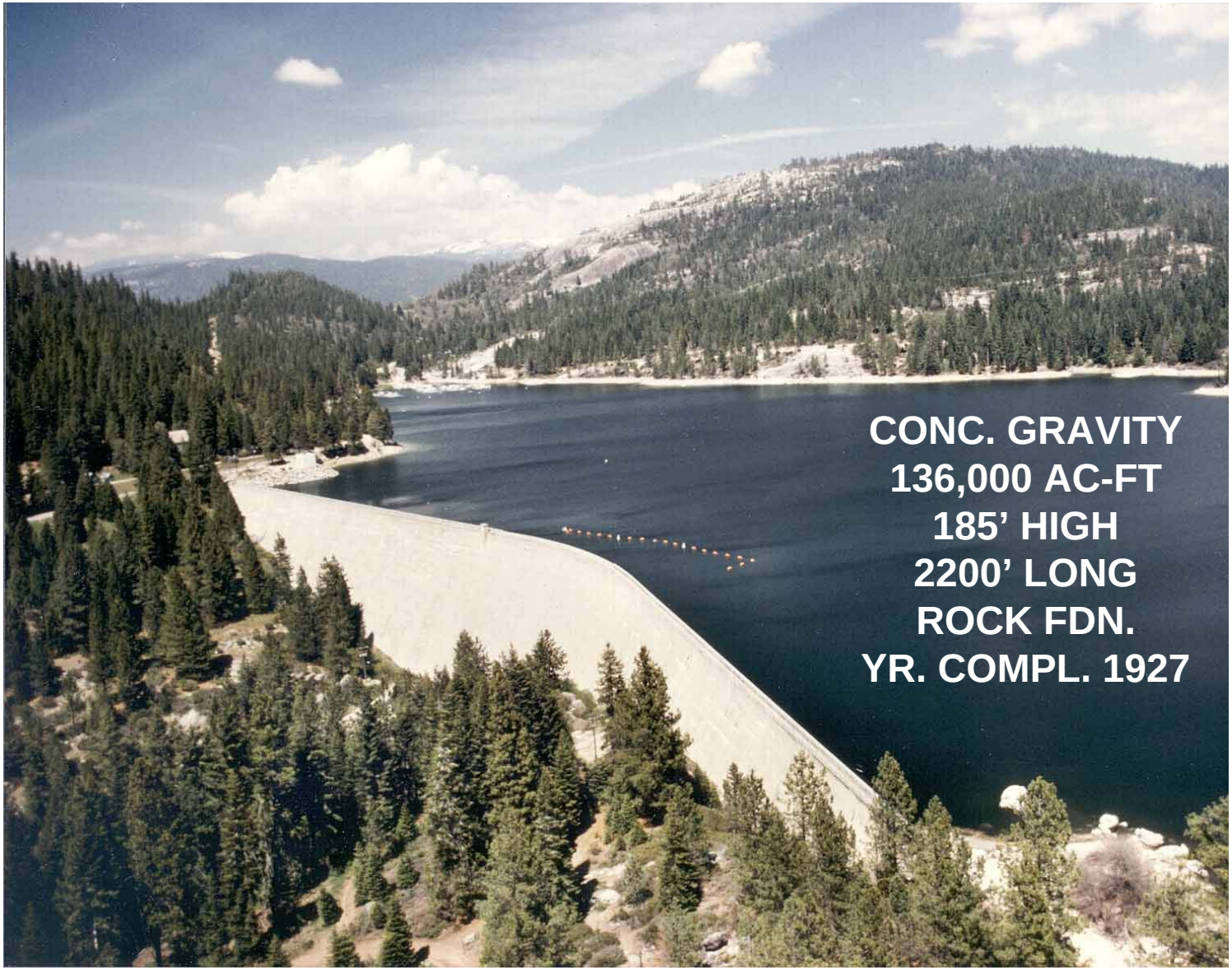

**BIG CREEK DAM 7**




**MAMMOTH POOL DAM**

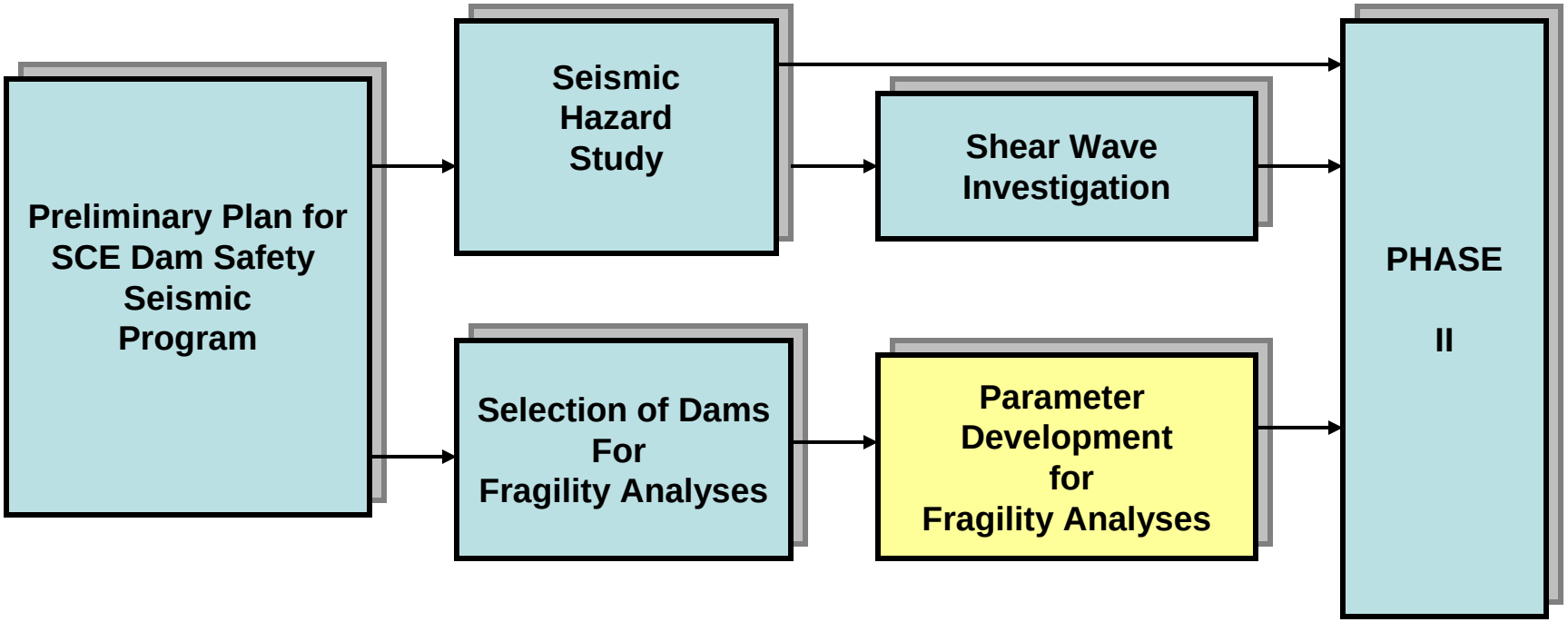
CONC. MULTI. ARCH
17,000 AC-FT
80' HIGH
700' LONG
ROCK FDN.
YR. COMPL. 1917

**GEM LAKE DAM**




**SHAVER LAKE DAM**

**VERMILION VALLEY DAM**




# Phase I - 2007/2008

# PARAMETER DEVELOPMENT

Material Properties

Published Values
Guidelines
Field Testing – most desired
"Best fit" Values

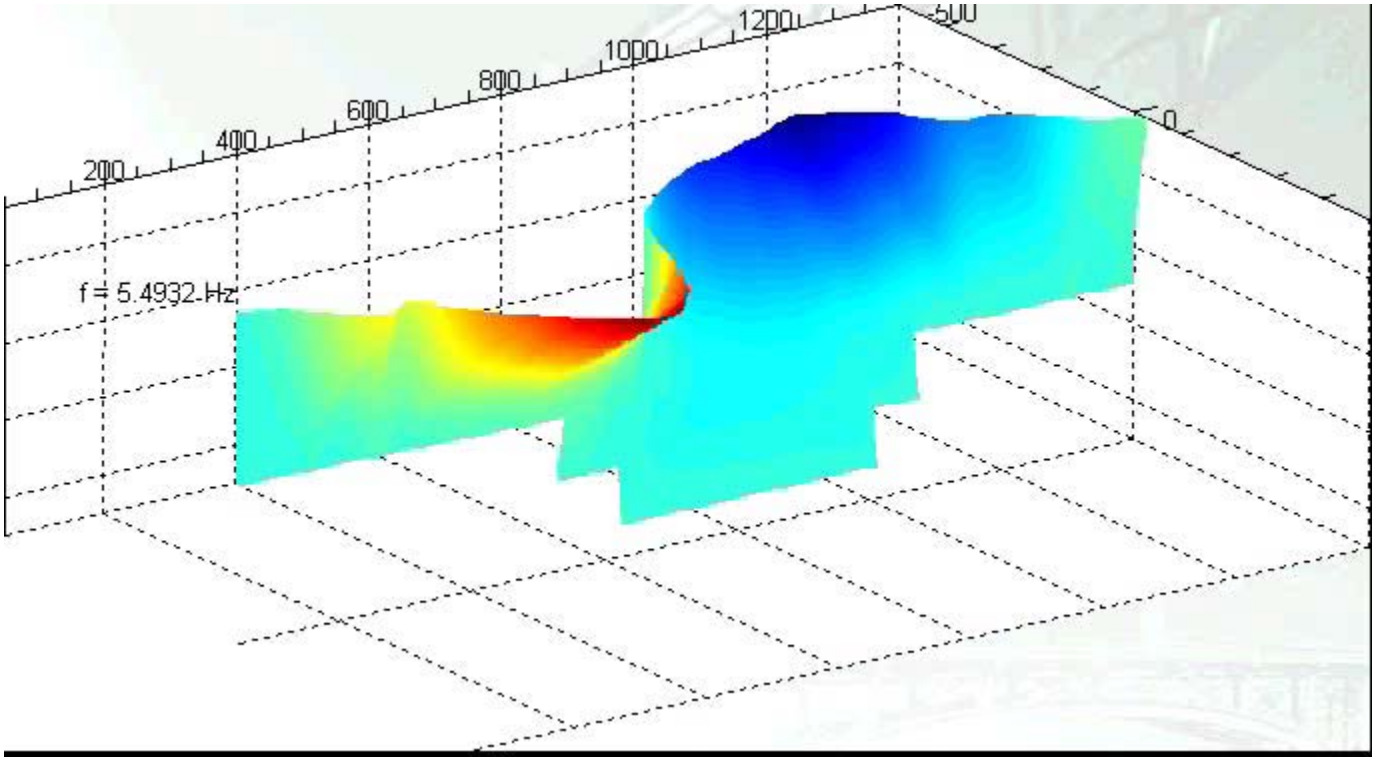
Dynamic Properties

Field Testing Program

- Consists of ambient, transient, and forced vibration testing
- Field measurements consist of
  - » Dam and dam/foundation interface accelerations
  - » Hydrodynamic pressures at dam upstream face
  - » Ancillary equipment, such as gates, bridge decks, gate towers, etc.

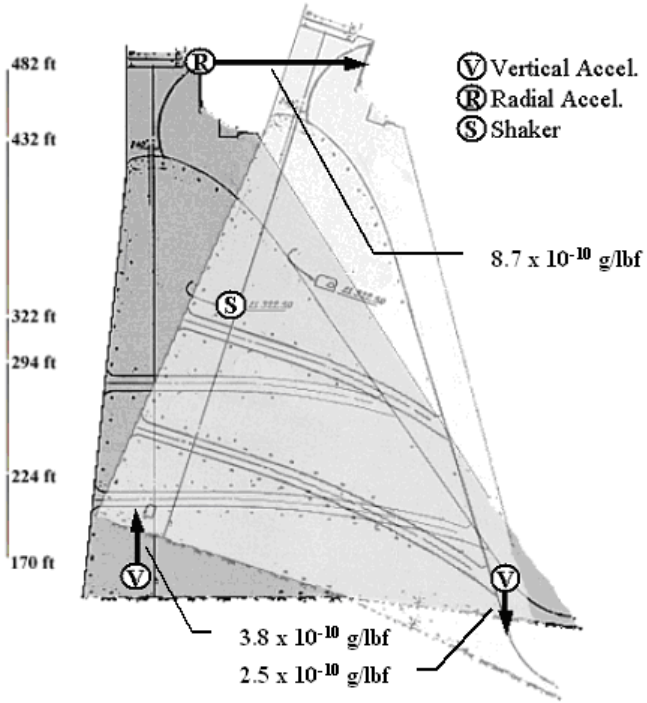
Dynamic Properties include:

- Resonant Frequencies
- Response Shapes
- Damping Estimates
- Reservoir Response
- Foundation Flexibility Effects

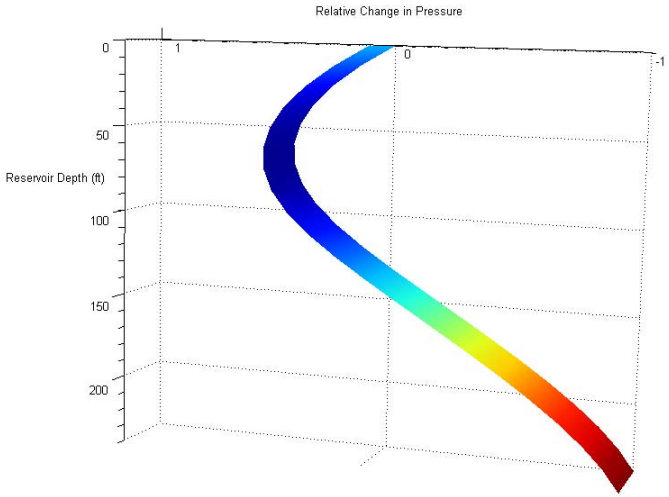



# Dynamic Characterization
# Folsom Dam

# Foundation and Reservoir Effects




ROCK MASS MODULUS




HYDRODYNAMIC RESPONSE

# Dynamic Testing at BC Dam 7

## Placing Accelerometers

# Forced Vibration
# Eccentric Mass Vibrator

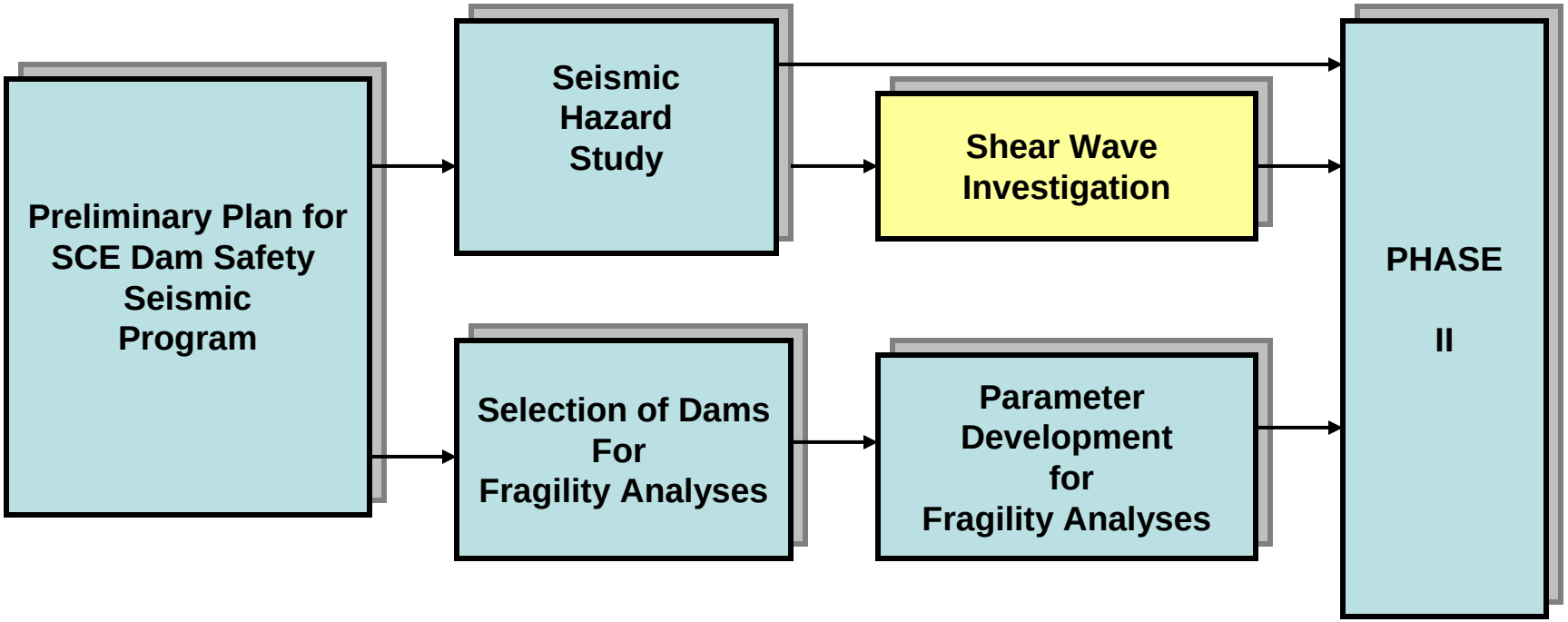
# Radial Gate Testing

# HMC Student Crew
# Reviewing Data Sampling

# Dynamic Testing – very valuable

Gem Lake Dam concrete core testing

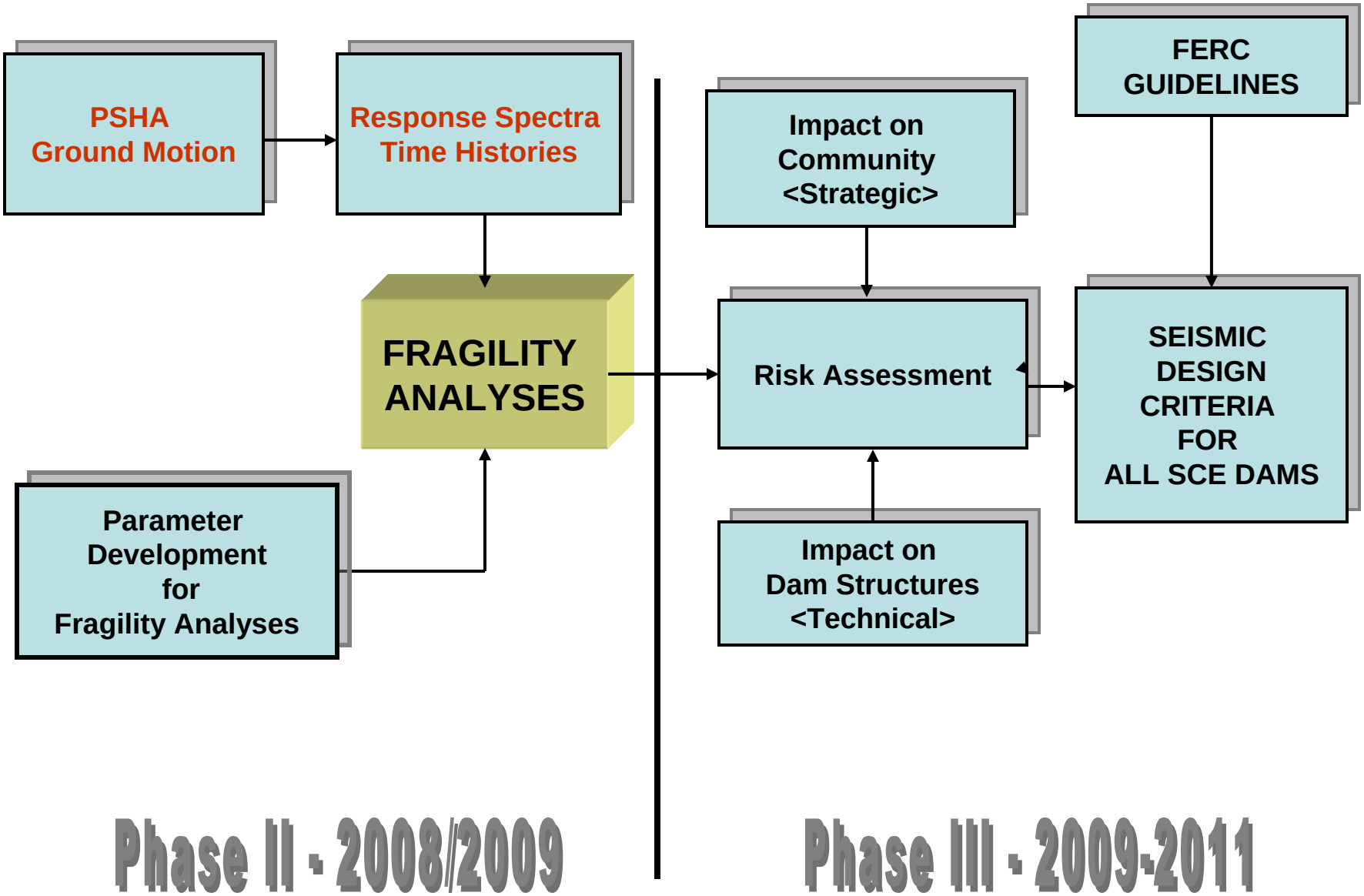
- Reasonable compression/tension
- Low modulus of elasticity




# Phase I - 2007/2008

# SHEAR WAVE INVESTIGATION

- Shear wave velocities critical to seismic hazard
- Perform shear wave studies at selected dams
  - -Borehole geophysics
  - -Spectral analysis of surface waves (SASW)
- Seismic hazard currently based on DSOD values
- Utilize appropriate values for seismic hazard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Phase II - 2008/2009
Phase III - 2009-2011

# FRAGILITY ANALYSIS

- **What is it? A technique for assessing in probabilistic terms the capability of an engineered system to withstand a specific event, which can be well in excess of the design-basis event**
- **For dams - it is basically structural analyses for various flood and earthquake return periods (e.g. 100, 500, 1000, 2500, 5000 and 10000 year or longer events)**
- **Somewhat like a Performance-Based approach for design**
- **Limit state for nuclear industry – Frequency of Onset of Significant Inelastic Deformation (FOSID)**
- **Limit state for dams – Uncontrolled Rapid Release of Water (URRW)**
- **It involves evaluating analysis parameter <u>uncertainties</u> and their impact on the performance and safety of a structure**

# **Uncertainties**:

- Flood and seismic hazard
- Material properties
- Structural modeling
- Analysis techniques
- Compilation of numerical results
- Performance criteria

# Uncertainties in flood and seismic hazard

- Predicting precipitation amounts, distribution and routing
- Ground shaking causing vibrations
- Fault movements in foundation or reservoir causing structural distortions

# Uncertainties in material properties

- Modulus of elasticity (long and short term)
- Compressive/tensile strengths (in-situ vs. lab, static and dynamic)
- Cohesion/friction
- Damping
- Lift and contraction joints

# Uncertainties in structural modeling

- Failure modes
- Representing foundation
- Dam-reservoir-foundation interaction (i.e. water compressibility, massless foundation)
- 3-D vs. 2-D (i.e. cross-canyon effects)
- Detailed FE vs. rigid block with joints and cracks

# Uncertainties in analysis techniques

- Software (dynamic analysis gives different results, especially for embankment dams)
- Nonlinear behavior (especially for post-cracking)
- Predicting deformations (equivalent linear vs. sophisticated elasto-plastic models)
- Soil-structure interaction (calculated vs. actual)
- Complex vs. simple

# Uncertainties in compilation of numerical results

- Response spectrum (conservative or unconservative)
- Time histories (how many are appropriate)

# Uncertainties in performance criteria

- Exceedance of tensile strength
- Strong ground shaking safety factors < 1 (safe or unsafe for short term)
- Deformations/crack openings

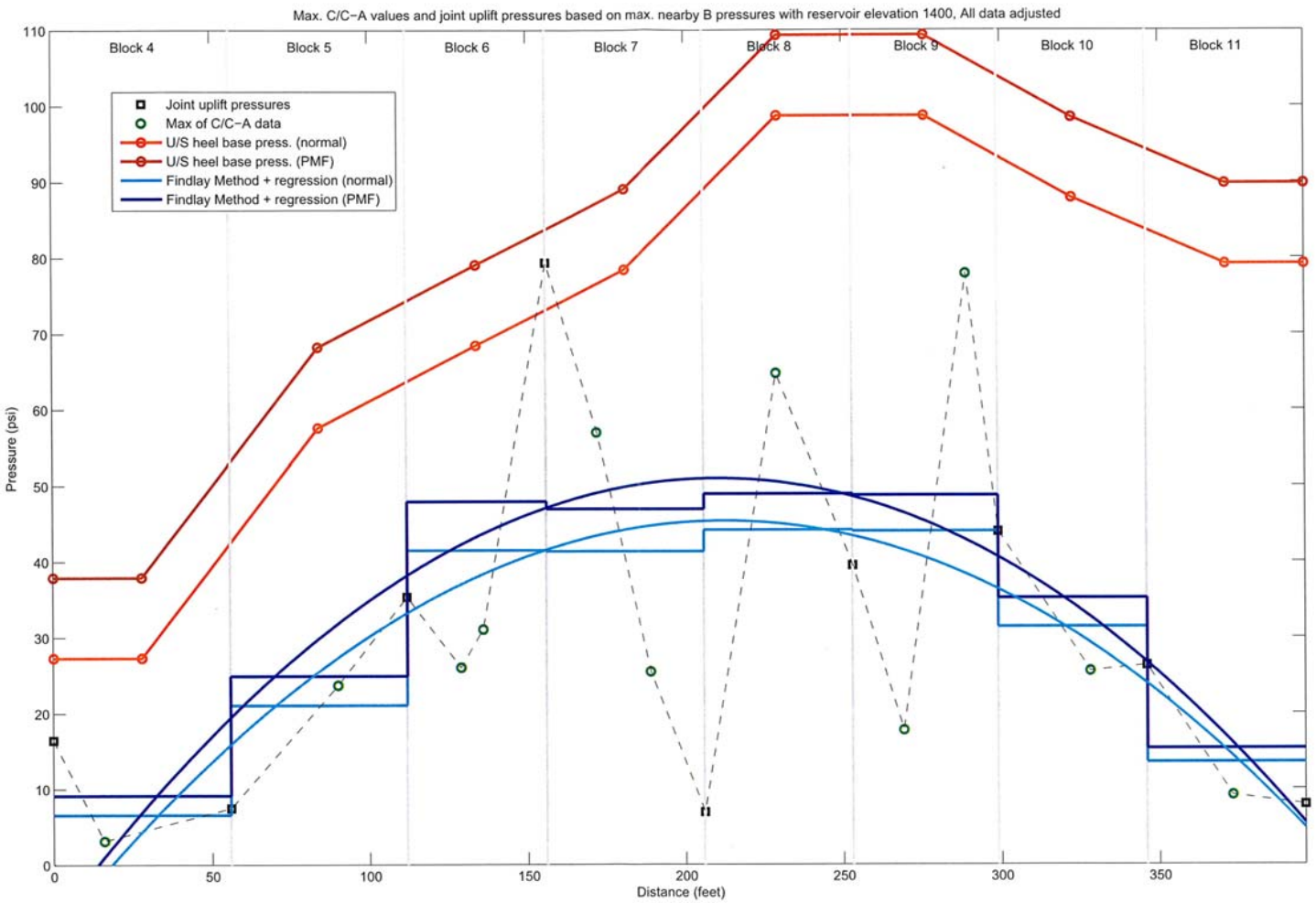
# Evaluating Analysis Uncertainties

- Typically establish range for each parameter
  - Some parameters important and some not
- Use alternative model and analysis techniques
- Try to reduce uncertainties – how?
  - Testing if practical and important
  - History and Experience
- Assign probabilities to uncertainties to establish confidence level in results (risk analysis)

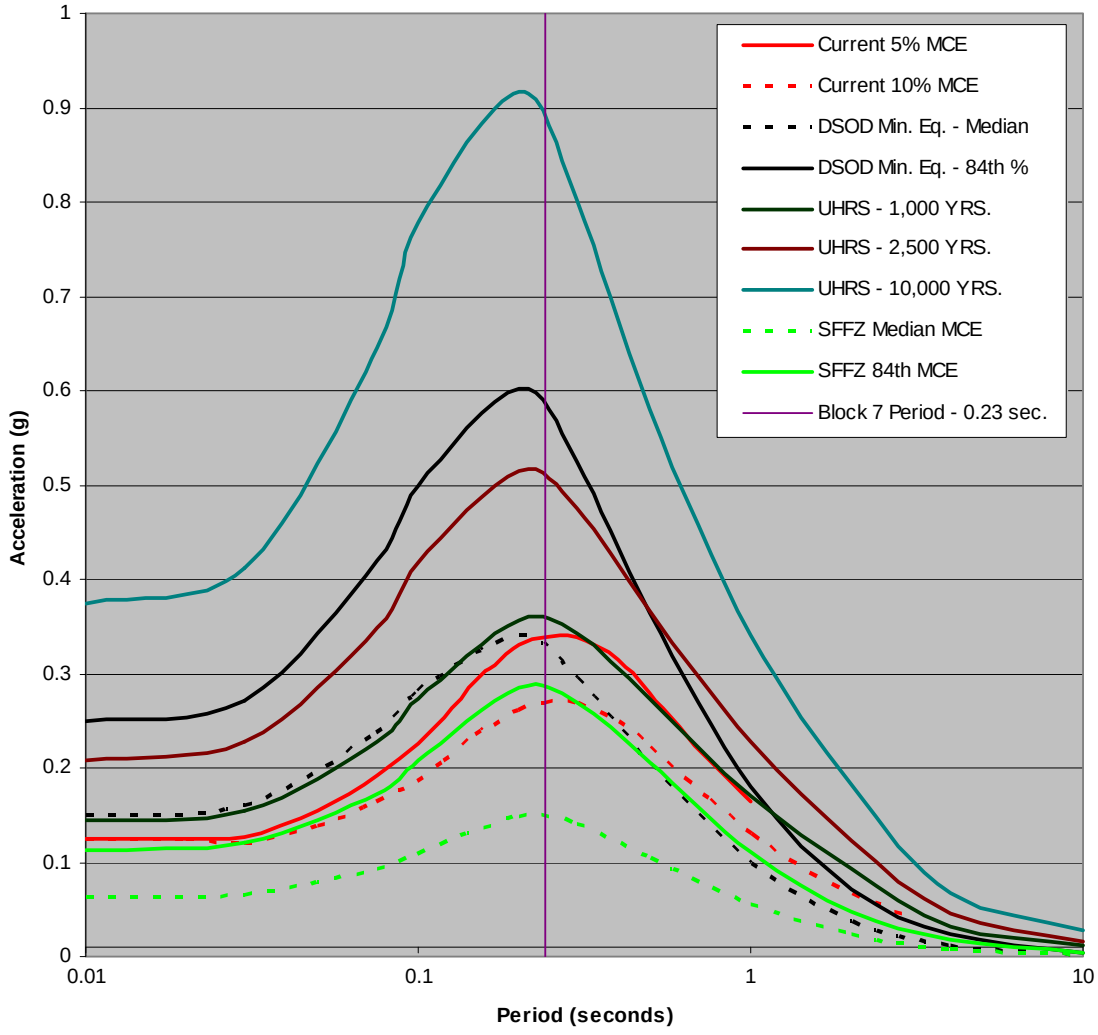
# Study Dam – SCE's Big Creek Dam 7

- Seismic hazard
- Flood hazard (overtopping level/duration)
- Material properties (concrete/rock)
- Construction joints (horizontal/vertical)
- Grouted/keyed joints
- Rock orientation/jointing
- Concrete/rock interface condition/orientation
- Water modeling (fluid elements/hydrophone data)
- Drain effectiveness (drains/galleries) / uplift
- Silt type/levels
- Tailwater levels
- Nappe pressures
- Radial gates
- Gate support piers
- Scouring due to flood overtopping

# BC DAM 7 DRAIN EFFECTIVENESS



# BIG CREEK DAM 7
## PSHA SPECTRA

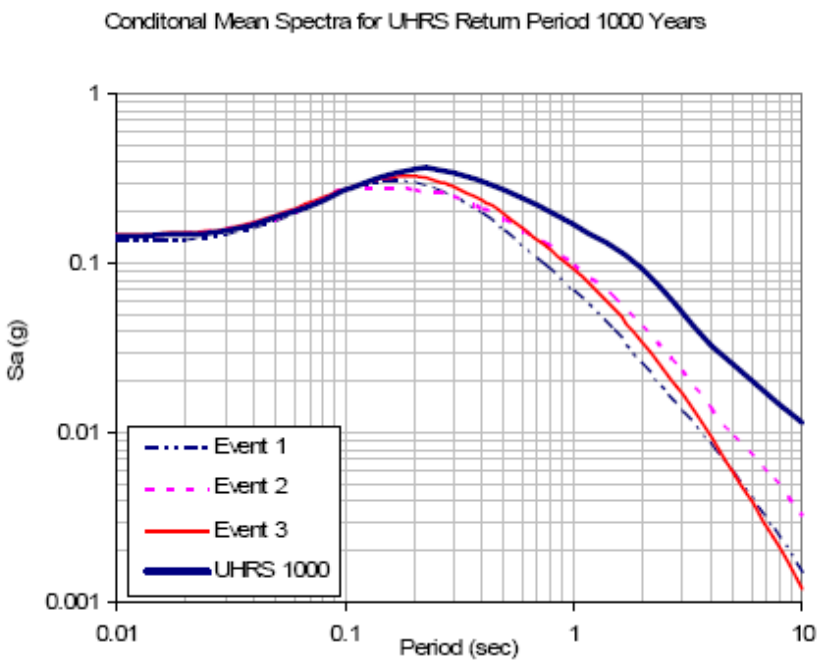


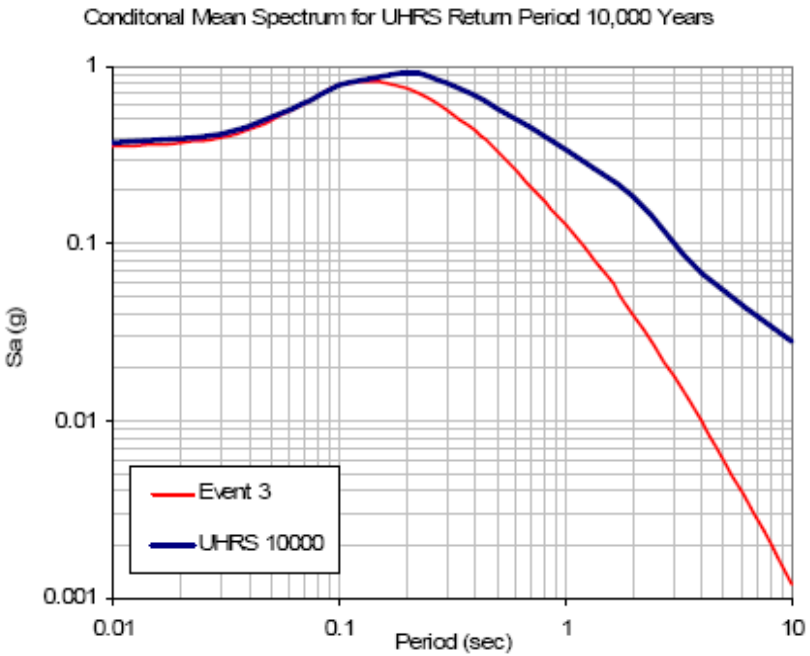
# Scenario Earthquake Spectra

Event 1: M6.6 earthquake at 44 km
Event 2: M7.9 earthquake at 173 km
Event 3: M5.8 earthquake at 7 km

NGA ground motion models
(Baker and Jayaram, 2008)
Conditional mean spectra
(Baker and Cornell, 2006)

# Conditional Mean Spectra



# Time Histories for Fragility Analyses

- Actual strong motion recordings from PEER- NGA database
- Rotated into fault-normal and fault-parallel orientations
- Three components (fault-normal, fault-parallel, vertical)
- Matched to hazard spectra in frequency range of interest
- Scaling factors used for various return periods (1000, 2500, 5000 and 10000 yrs.)

# Earthquake Records for Scenario Spectra

Event 1
- Northridge-01
- Loma Prieta
- Parkfield

Event 2
- Kocaeli-Turkey
- Hector Mine
- Landers

Event 3
- Morgan Hill
- Chi-Chi Taiwan
- Imperial Valley

Table 5 Time History File Names and Scaling Factors

**Event 1**

| NGA# | File name | | | Scaling factor for return period: | | | |
|---|---|---|---|---|---|---|---|
| | Fault | Fault | | 1000 | 2500 | 5000 | 10000 |
| | Normal | Parallel | Vertical | years | years | years | years |
| 974 | NORTHR.GLP_FN.acc | NORTHR.GLP_FP.acc | NORTHR.GLP-UP.acc | 0.410 | 0.612 | | |
| 31 | PARKF.C08_FN.acc | PARKF/C08_FP.acc | PARKF.C08DWN.acc | 0.548 | 0.819 | | |
| 811 | LOMAP.WAH_FN.acc | LOMAP.WAH_FP.acc | LOMAP.WAH-UP.acc | 0.196 | 0.292 | | |

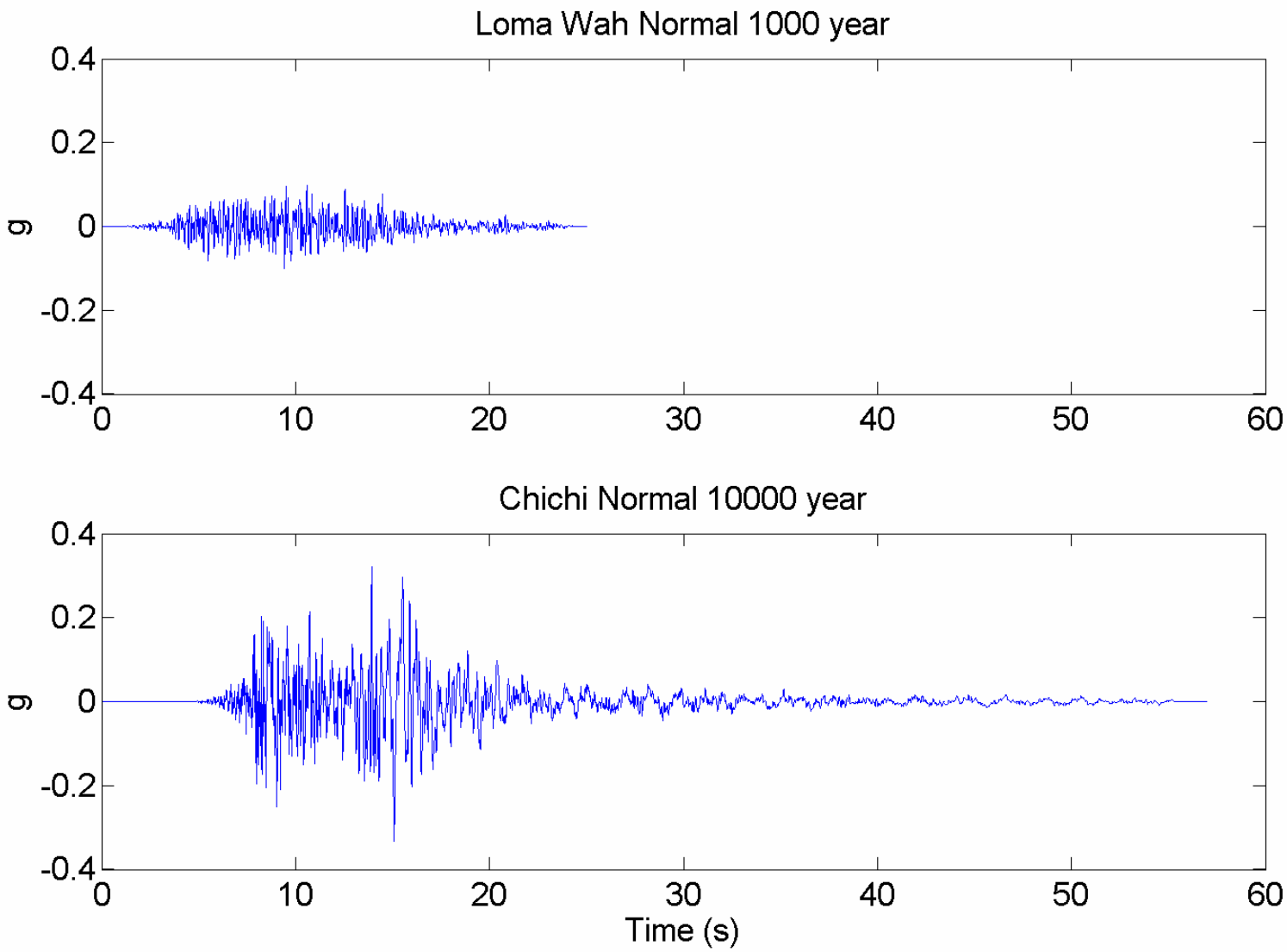
**Event 2**

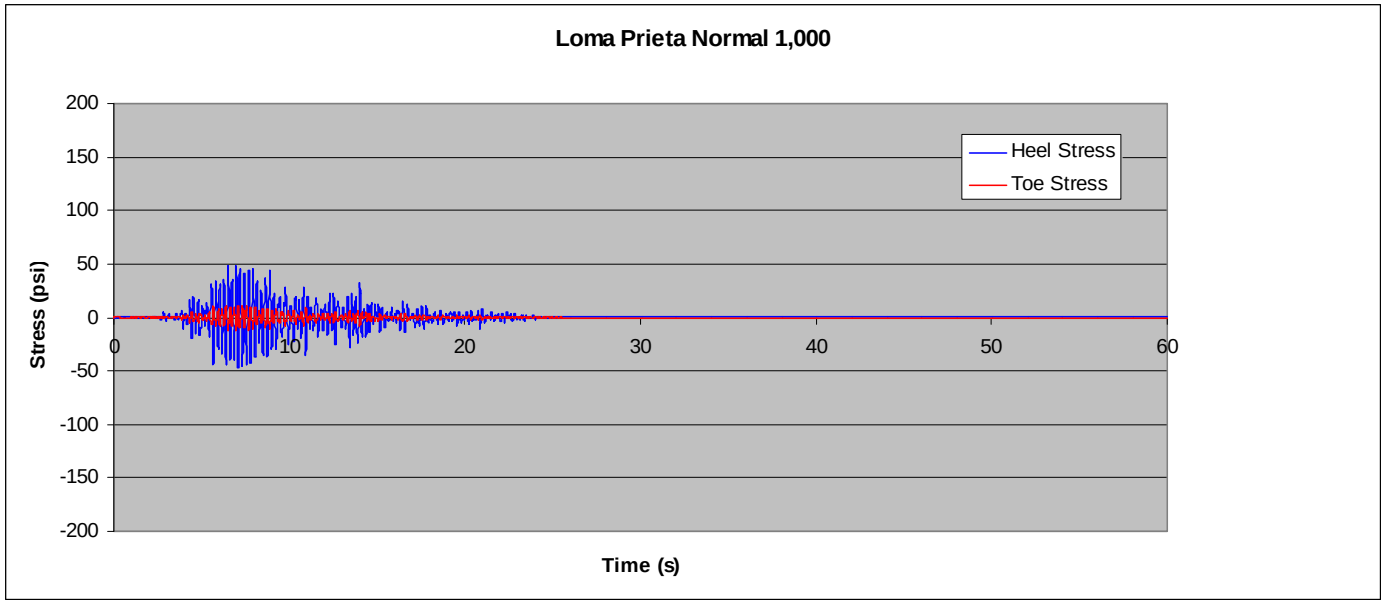
| NGA# | File name | | | Scaling factor for return period: | | | |
|---|---|---|---|---|---|---|---|
| | Fault | Fault | | 1000 | 2500 | 5000 | 10000 |
| | Normal | Parallel | Vertical | years | years | years | years |
| 1836 | HECTOR.22161_FN.acc | HECTOR.22161_FP.acc | HECTOR.22161-UP.acc | 1.999 | 2.984 | | |
| 1170 | KOCAELI.MCD_FN.acc | KOCAELI.MCD_FP.acc | KOCAELI.MCD--V.acc | 2.275 | 3.397 | | |
| 880 | LANDERS.MCF_FN.acc | LANDERS.MCF_FP.acc | LANDERS.MCF-UP.acc | 1.140 | 1.703 | | |

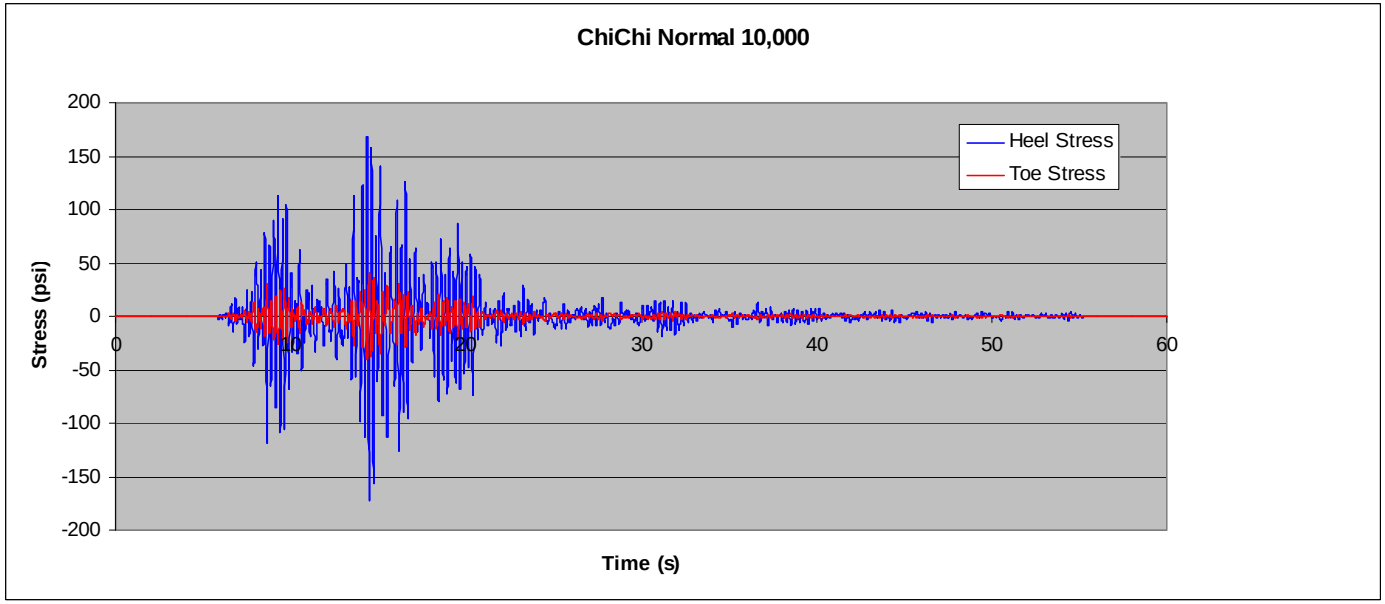
**Event 3**

| NGA# | File name | | | Scaling factor for return period: | | | |
|---|---|---|---|---|---|---|---|
| | Fault | Fault | | 1000 | 2500 | 5000 | 10000 |
| | Normal | Parallel | Vertical | years | years | years | years |
| 456 | MORGAN.G02_FN.acc | MORGAN.G02_FP.acc | MORGAN.G02-UP.acc | 0.872 | 1.302 | 1.775 | 2.3755 |
| 3472 | CHICHI06.TCU076_FN.acc | CHICHI06.TCU076_FP.acc | CHICHI.TCU076-V.acc | 1.018 | 1.520 | 2.072 | 2.7722 |
| 183 | IMPVALL.H-E08_FN.acc | IMPVALL.H-E08_FP.acc | IMPVALL.H-E08-UP.acc | 0.271 | 0.404 | 0.551 | 0.7373 |

**Large number of time histories required**
**Possibly 48 TH analyses for BC Dam 7**


Loma Wah Normal 1000 year
0.4
0.2
0
-0.2
-0.4
g
0
10
20
30
40
50
60
Chichi Normal 10000 year
0.4
0.2
0
-0.2
-0.4
g
0
10
20
30
40
50
60
Time (s)


Loma Prieta Normal 1,000
Heel Stress
Toe Stress
Stress (psi)
Time (s)
200
150
100
50
0
-50
-100
-150
-200
0
10
20
30
40
50
60

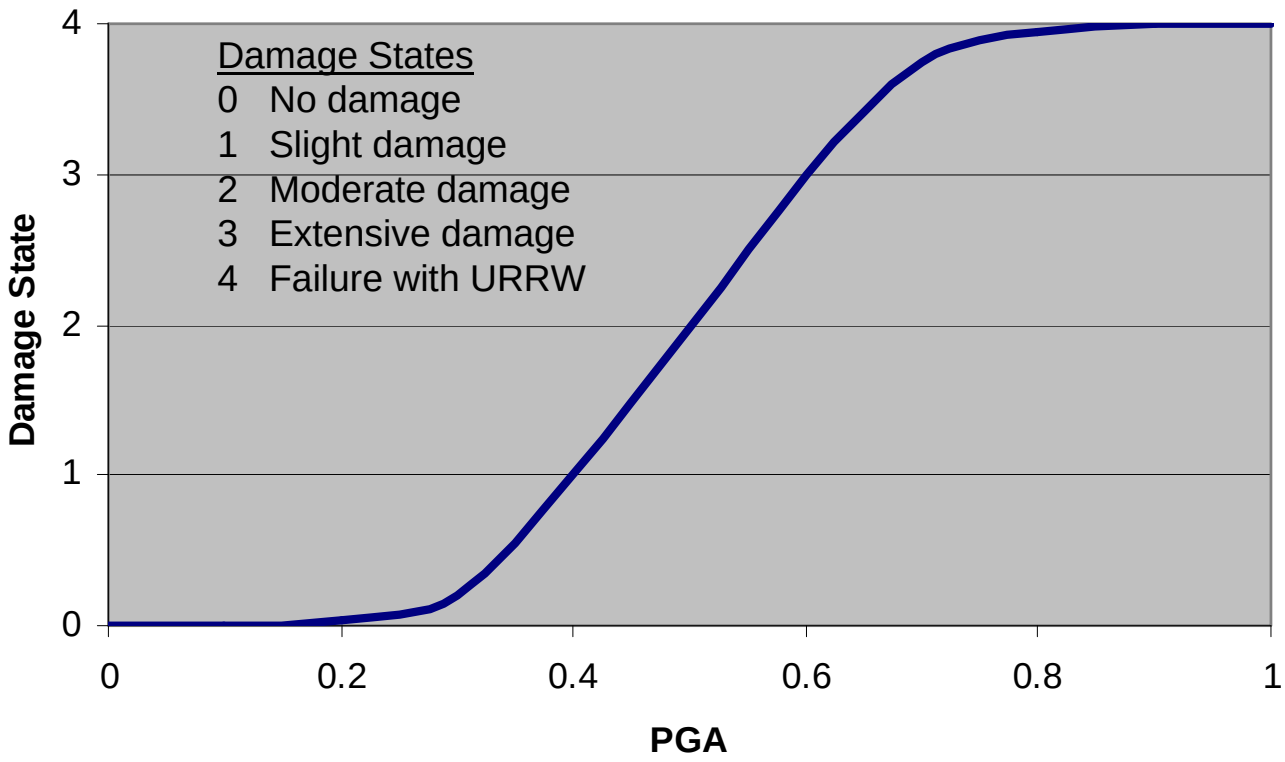

ChiChi Normal 10,000
Heel Stress
Toe Stress
Stress (psi)
Time (s)
200
150
100
50
0
-50
-100
-150
-200
0
10
20
30
40
50
60

# First Objective - Baseline Analysis

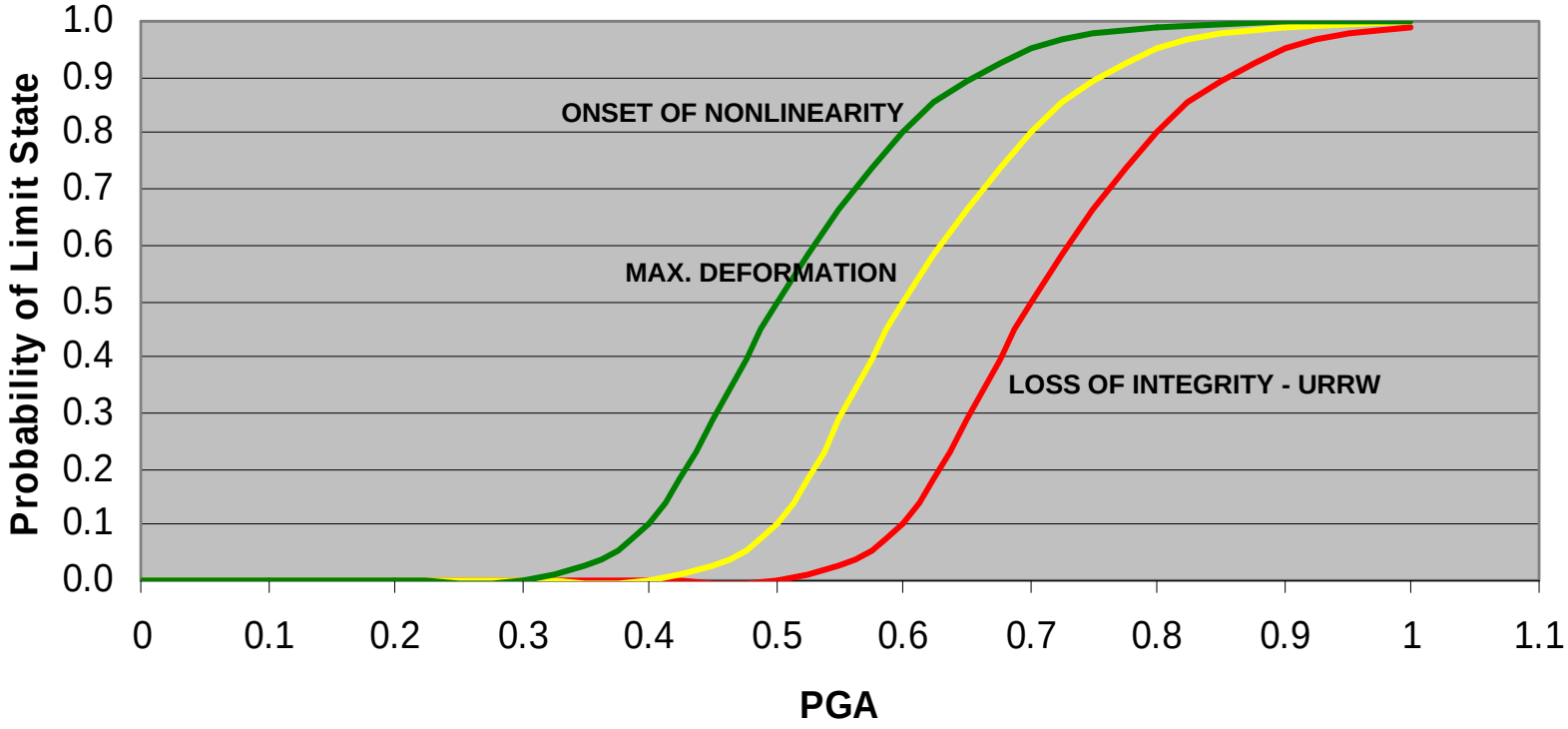
**Original Design Capability**

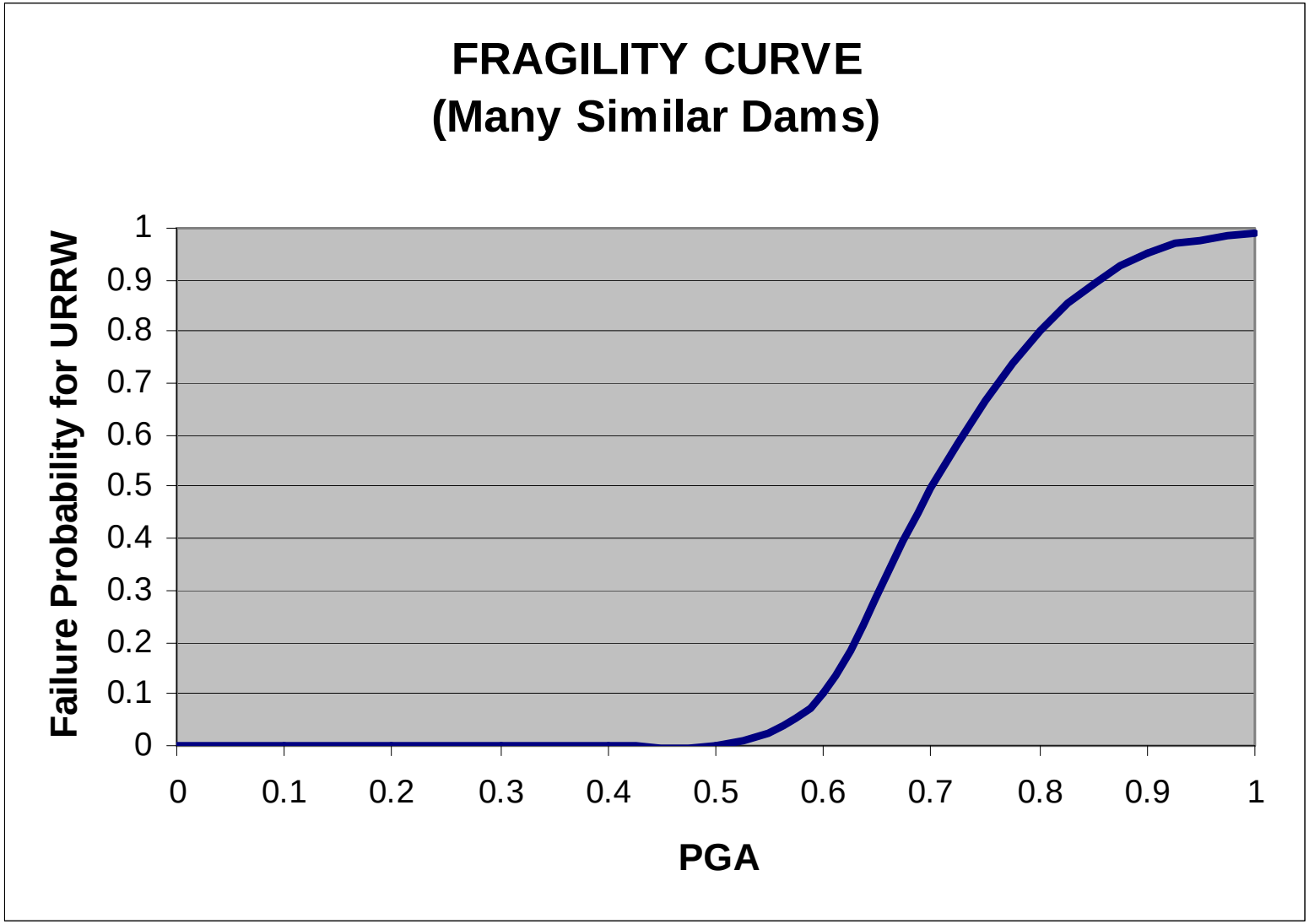
- Onset of damage, instability and URRW
- Older dams – many had no seismic design and very low design flood levels
- Less than or greater than original design basis, which may or may not be MCE or PMF
- Not always easy to establish

# FRAGILITY CURVE
## (Single Dam - Single Limit State)



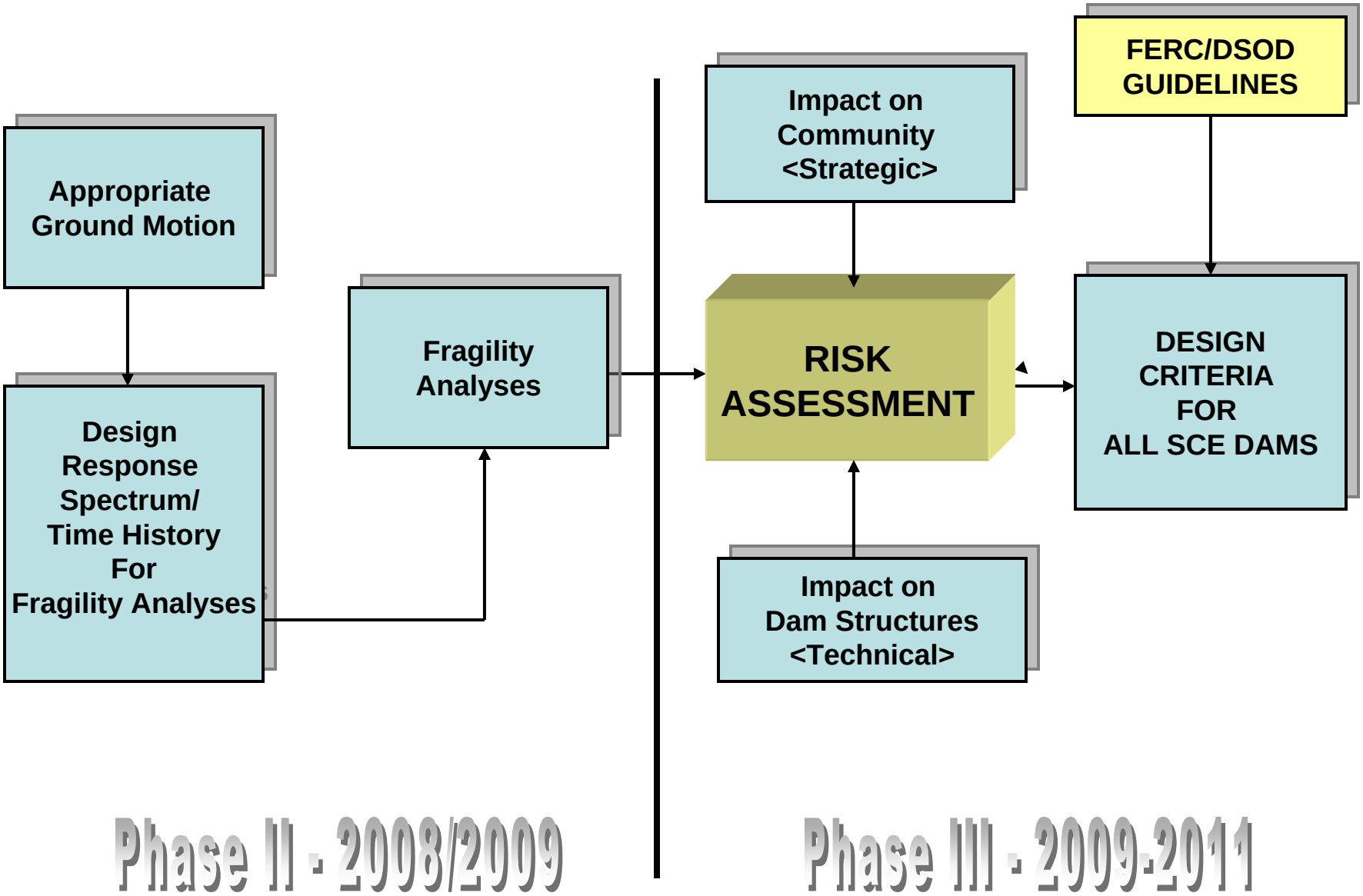
# FRAGILITY CURVE
## (Single Dam - Multiple Limit States)




FRAGILITY CURVE
(Many Similar Dams)
Failure Probability for URRW
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
PGA

# OBJECTIVES OF FRAGILITY ANALYSES FOR PURPOSES OF RISK ANALYSIS

- Assist with development of guidelines
- Determine parameters that are most important to risks
- Reduce uncertainties to reduce risks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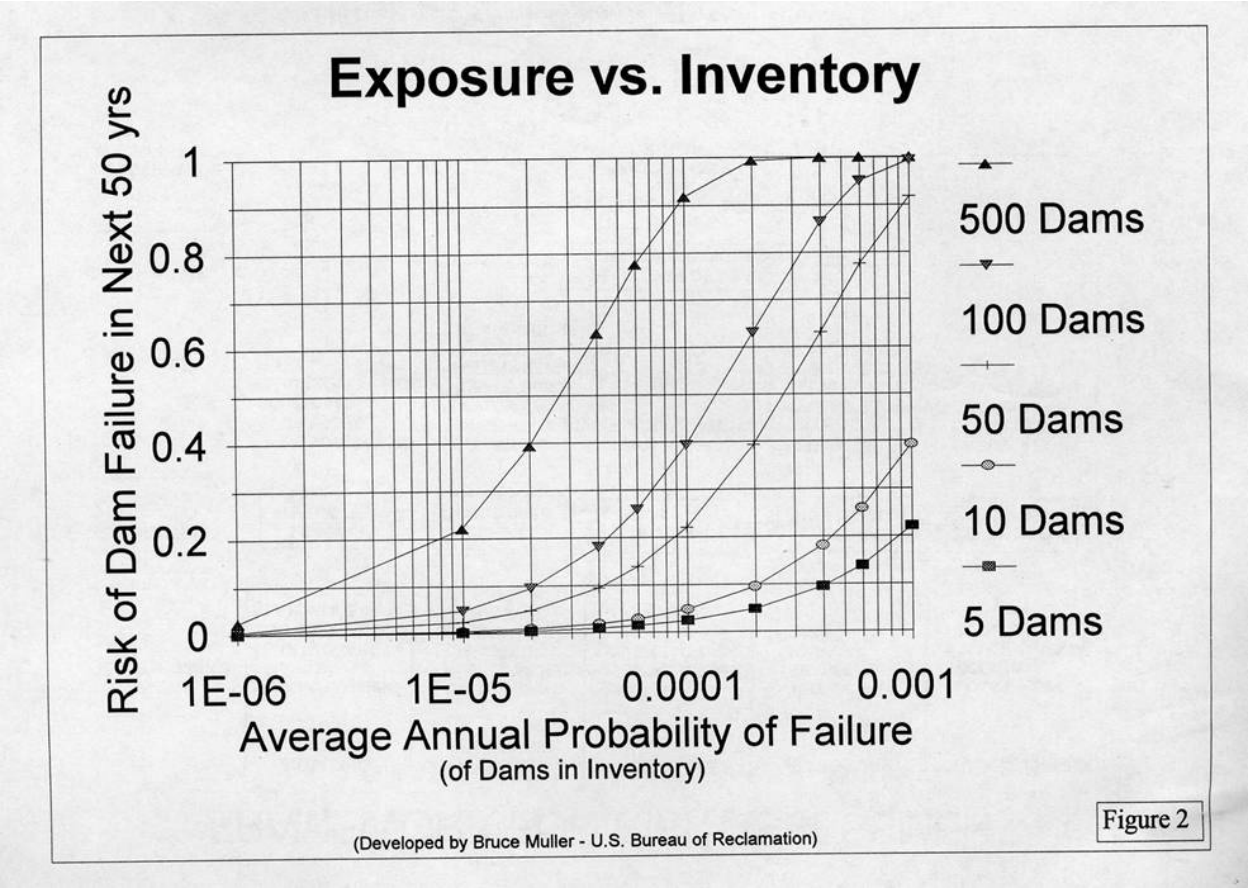
DESIGN CRITERIA FOR ALL SCE DAMS
Phase II - 2008/2009
Phase III - 2009-2011

# RISK ASSESSMENT GOALS

- **Prioritization**
- **Reduce risks**
- **Understand corporate exposure**
- **Spend more wisely**



NEW YORK TIMES

April 3, 1876

MASSACHUSETTS DAMS

"If the State neglects its proper work, there should be a wholesome public opinion among the citizens which would render it morally certain that henceforth no Massachusetts dam can burst without satisfactorily drowning its engineer."

# BOTTOM LINE

**HOPEFULLY**

**A LOT OF GOOD**

**ENGINEERING JUDGEMENT**