Report on US Activities

ICOLD 26th Congress and 86th Annual Meeting
Committee on Seismic Aspects of Dam Design

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Vice Chair, ICOLD Committee B

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Outline

- USSD Earthquakes Committee
  - Charter
  - Membership
  - Activities
- Dam Design Related News
- Selected US Seismic Projects
- Guidelines for Seismic Deformation Analysis of Embankment Dams

Charter

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- Established 1968
- Promote seismic safety of dams and development of knowledge on seismic analysis and design
  - Collect and disseminate information on earthquake recorded data and dam performance
  - Develop guidance on seismic design of dams and reservoirs
  - Disseminate knowledge through USSD reports, trade journal publications, and seminars
  - Collaborate with other USSD committees (e.g. Concrete Dams)
- Support ICOLD Committee on Seismic Aspects of Dam Design and provide liaison with US dam practice

Membership

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- 64 members
- 20% annual growth over past 4 years
- Representatives of private industry, government and academic entities
- Subcommittees for conference planning and specific projects

2021 Activities

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- Meetings
- Projects and initiatives
  - Guidelines
    - Analysis of seismic deformations of embankment dams (under peer review)
    - Updated selection of earthquake ground motion parameters of dams
    - Updated seismic design and evaluation of structures appurtenant to dams
  - Annual conference sessions
  - Workshop on Earthquake Shaking and Ground Failure Hazards for Dams and Automated Real-time inspection
  - Joint workshops with Concrete Dams committee

Dam Design Related News

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- No earthquakes of dam engineering significance
- General trend to use RIDM for dam safety management
- RIDM driven by large owners: USBR, USACE, FERC
- State owners slower to adopt
- FERC regulations and guidelines:
  - Engineering guidelines
  - Part 12D dam safety inspections
  - RIDM Risk guidelines
  - https://www.ferc.gov/dam-safety-and-inspections

Selected US Projects - Evaluation

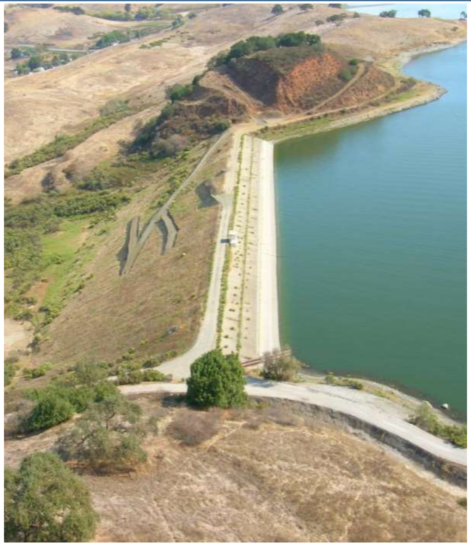
Oroville Dam, California

Yale Dam, Washington

Wanapum Dam, Washington

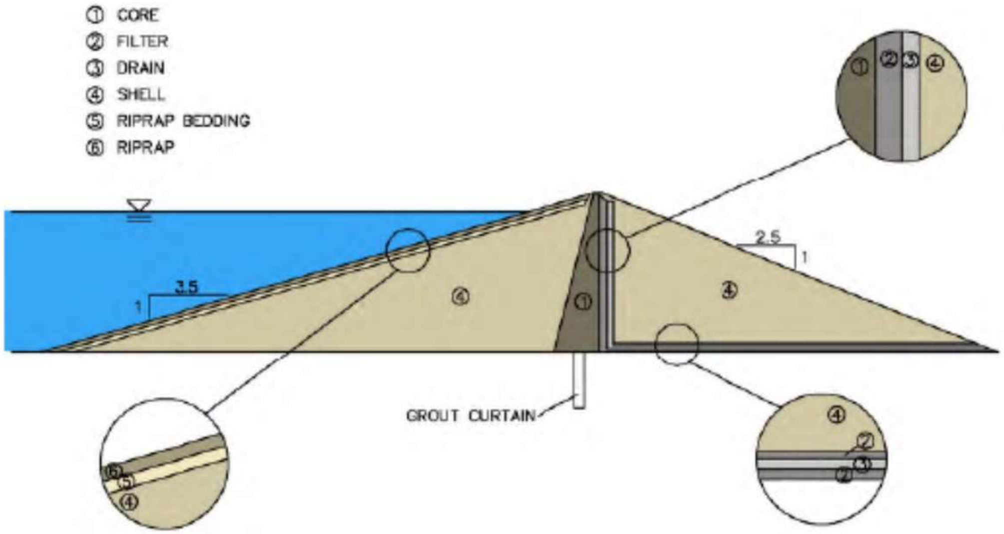
Blue Ridge Dam, Tennessee

Selected US Projects - Design



Calero Dam, California

Syphon Reservoir Dam, California



Del Puerto Dam, California

Scoggins Dam, Oregon

Selected US Projects - Construction

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Lake Isabella Dam, California

Priest Rapids Dam, Washington

B.F. Sisk Dam, California

Anderson Dam, California

- Introduction
- Seismic performance of embankment dams
- Overview of deformation analysis approaches
- Simplified analyses
- Sliding block analyses
- Non-linear deformation analyses
- Evaluation and documentation of analysis results
- Guidance on use of deformation analyses
- Summary

Simplified Analyses

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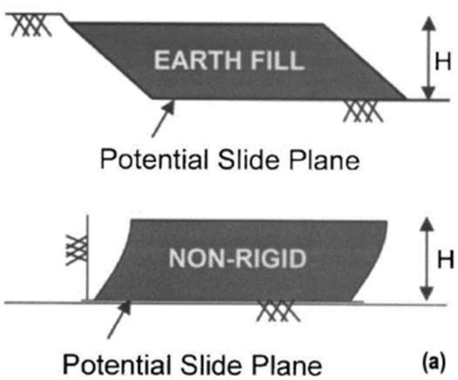
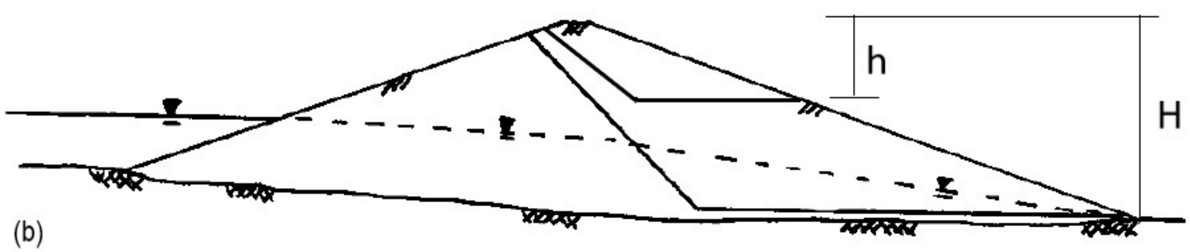
- Empirically-based correlations
- Analytically-based correlations
  - Makdisi and Seed
  - Bray and Travasarou
  - Sayjili and Rathje
  - Bray and Macedo



Bray et al analysis model



Example dam analysis model

Nonlinear Analysis Models

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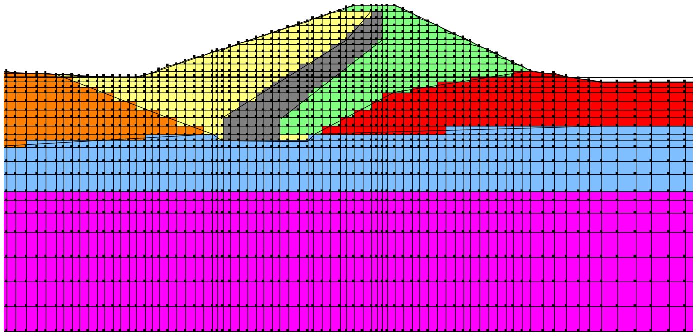
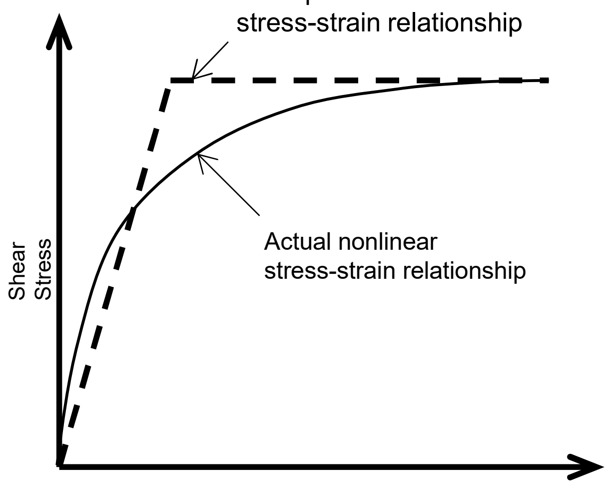
Model	Stress-strain Constitutive Framework	Pore-Pressure Response	Analysis Platform Availability	2D/3D Capability	Post-Liquefaction Strength Simulation	References
Mohr-Coulomb (Drucker-Prager)	Linear-elastic, perfectly-plastic	May include volumetric dilation	FLAC, FLAC3D, PLAXIS, OpenSees, LS-DYNA	2D, 3D	May use drained or undrained strengths	Itasca (2016), LTSC(2015), Plaxis (2016)
Roth Cyclic-Counting	Linear-elastic, perfectly-plastic	Effective Stress, Decoupled	FLAC, FLAC3D	2D, 3D	Strength reduces to residual strength after triggering	Roth et al., (1991) Dawson and Mejia, (2012)
UBCHYST	Linear-elastic, Softening after yield	May include volumetric dilation	FLAC	2D	May use drained or undrained strengths	Naesgaard et al. (2015), Naesgaard (2011)
UBCTOT	Linear-elastic, tri-linear yielding	Total Stress, Decoupled	FLAC	2D	Strength reduces to residual strength after triggering	Beaty and Byrne (2008)
PDMY	Nested Yield Surface Plasticity	Effective Stress, Coupled	CYCLIC, OpenSees	2D,3D	Not in model framework. Post-shaking analysis	Elgamal et al. (2003) Yang and Elgamal (2008)
PM4Sand	Bounding Surface Hypo-plasticity	Effective Stress, Coupled	FLAC, OpenSees	2D	Not in model framework. Post-shaking analysis	Boulanger and Ziotopoulou, (2015)
PM4Silt	Bounding Surface Hypo-plasticity	Effective Stress, Coupled	FLAC	2D	Not in model framework. Post-shaking analysis	Boulanger and Ziotopoulou (2017)
SANISAND	Bounding Surface Hypo-plasticity	Effective Stress, Coupled	FLAC3D	2D, 3D	Not in model framework. Post-shaking analysis	Taiebet and Dafalias (2008)
UBCSAND	Hyperbolic Hardening Plasticity	Effective Stress, Coupled	FLAC, PLAXIS	2D, 3D	Not in model framework. Post-shaking analysis	Beaty and Byrne (1998, 2011)
Wang2D and Wang3D	Bounding Surface Hypo-plasticity	Effective Stress, Coupled	FLAC, FLAC3D	2D, 3D	Not in model framework. Post-shaking analysis	Wang et al. (1990) Wang et al. (2006)

NON-LINEAR ANALYSIS

- Requires finite element / difference analyses employing nonlinear inelastic soil models
- Computation of deformations is coupled with analysis of dynamic response
- In effective stress analysis, stiffness and strength are dependent on pore water pressure response
  - Coupled pore pressures
  - Decoupled pore pressures



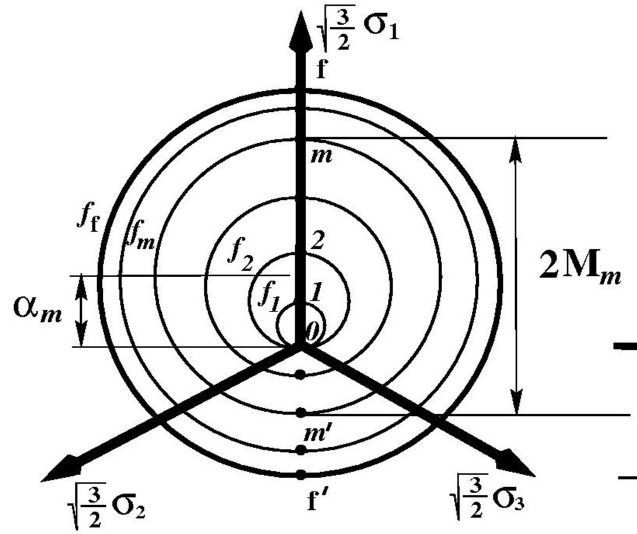


NONLINEAR STRESS-STRAIN MODELS

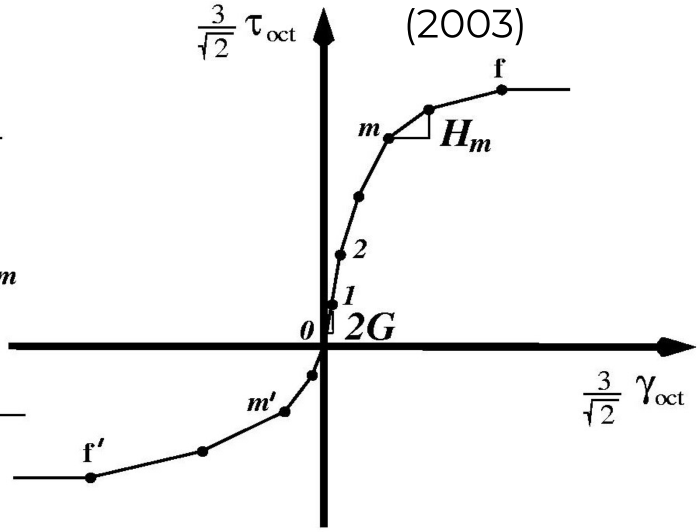
- Linear elasto-plastic
  - Mohr-coulomb
  - Drucker-Prager
  - Von Mises
- Hyperbolic elasto-plastic
  - UBC Sand (Byrne et al., 2006)
  - Finn and Yogendrakumar (1989)
- Multi-nested yield surface plasticity
  - Yang et al. (2003)
- Bounding surface plasticity
  - Wang et al. (1990)
  - PM4Sand (Boulanger and Ziotopoulou, 2013)
  - PM4Silt (Boulanger and Ziotopoulou, 2018)

MULTI-NESTED YIELD SURFACE MODEL

Yang et al. (2003)

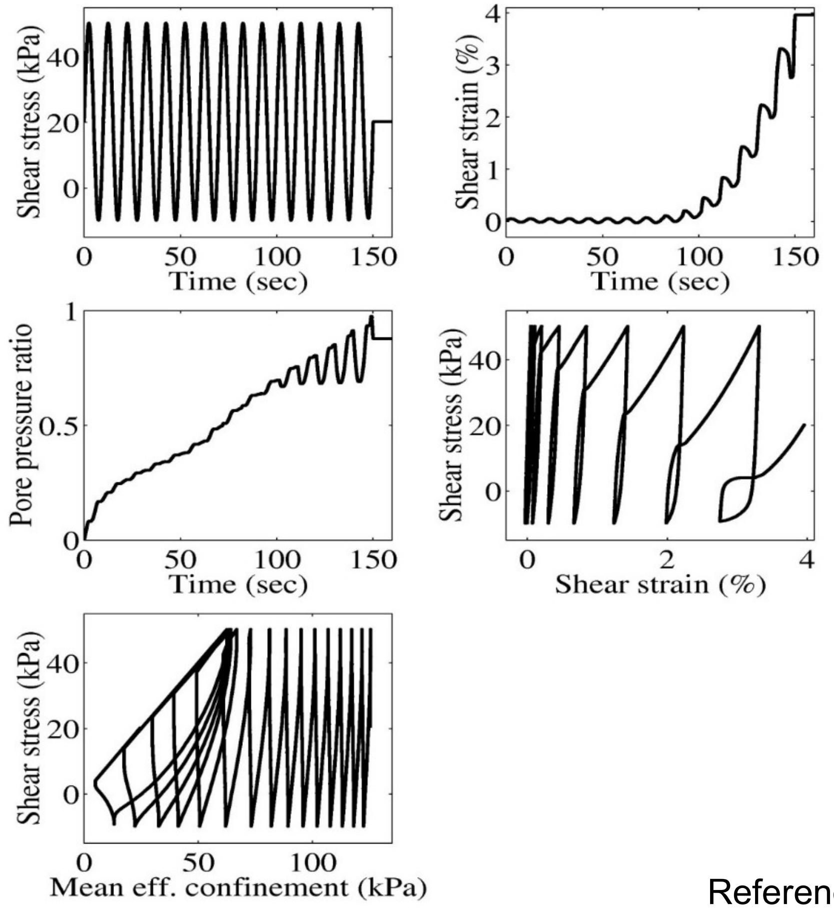


Deviatoric plane



Stress-strain curve

RESPONSE UNDER UNDRAINED BIASED CYCLIC LOADING

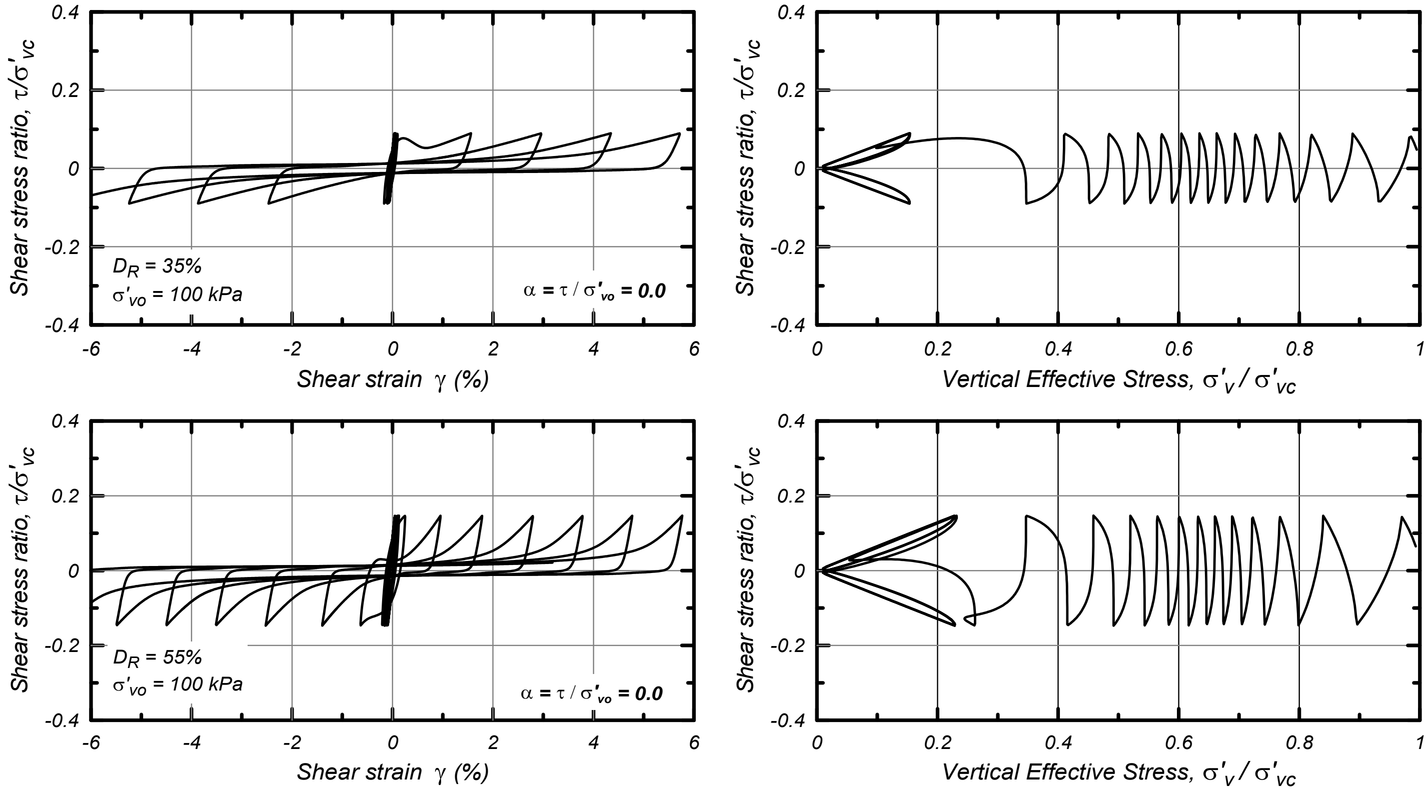


Reference: Yang et al. (2003)

BOUNDING SURFACE PLASTICITY

PM4Sand

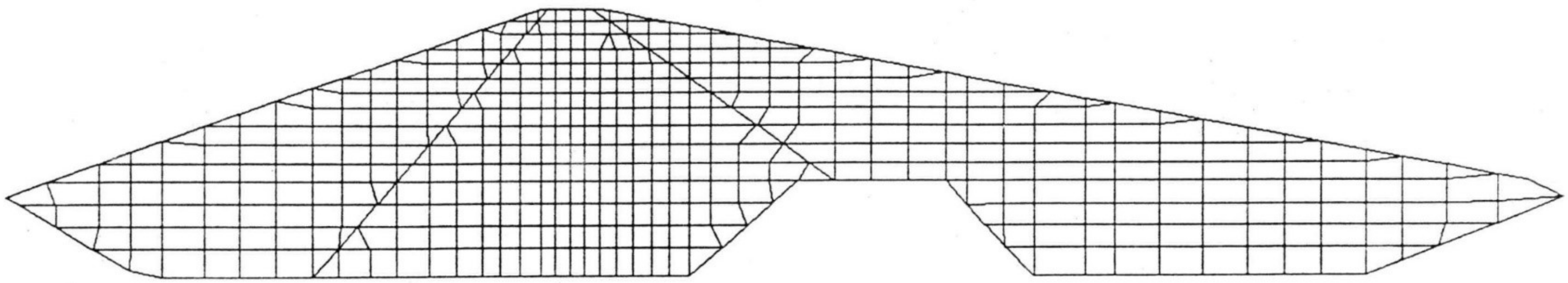
(Boulanger and Ziotopoulou (2013))



NONLINEAR ANALYSIS IMPLEMENTATION

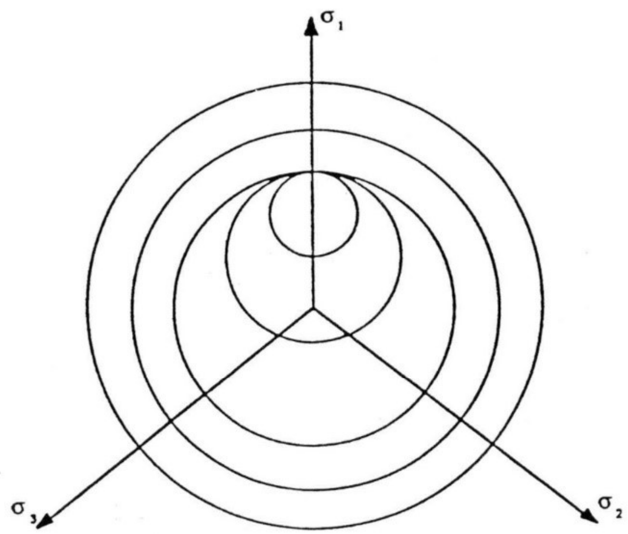
- Examples of types of analysis
  - Overview of implementation
  - Basic features (sections, analysis models, results)
- Case histories
  - Lenihan Dam
  - Austrian Dam

ANALYSIS OF LENIHAN DAM FOR LOMA PRIETA EARTHQUAKE

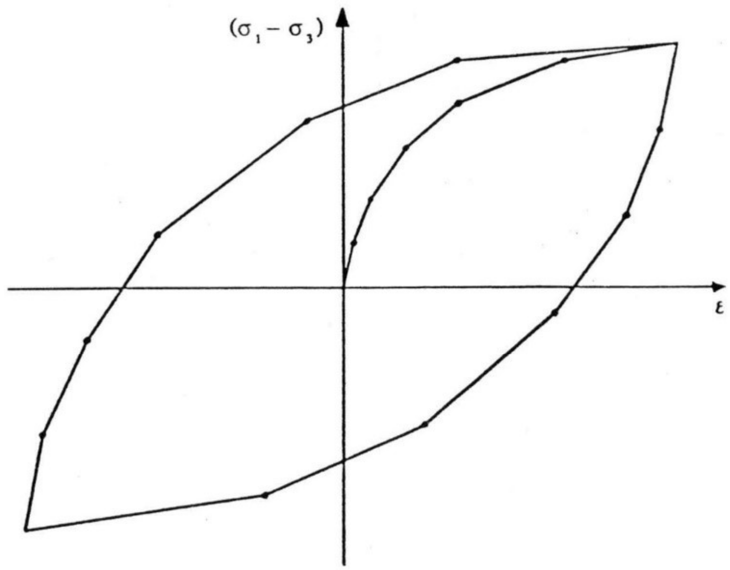


Reference: Mejia et al. (1992)

MULTI-NESTED YIELD SURFACE MODEL

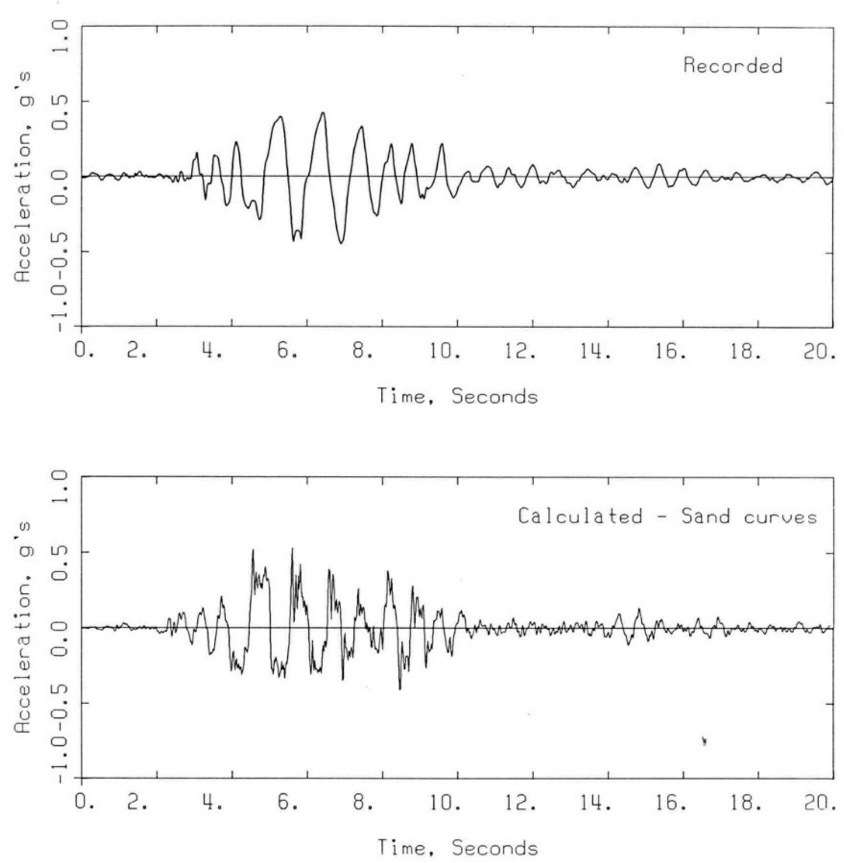


(a) Yield surfaces



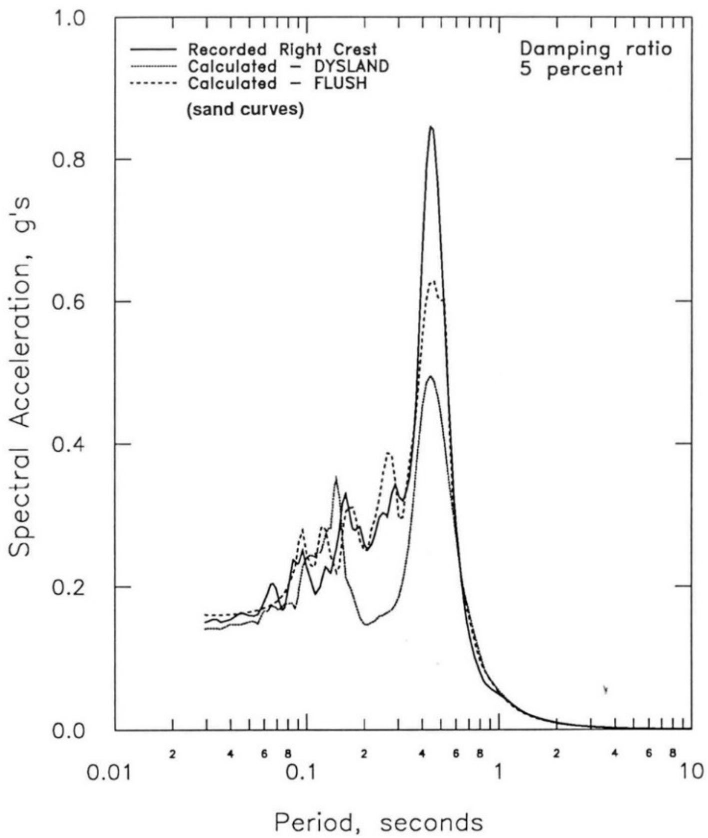
(b) Example hysteretic loop

RECORDED AND CALCULATED TIME HISTORIES

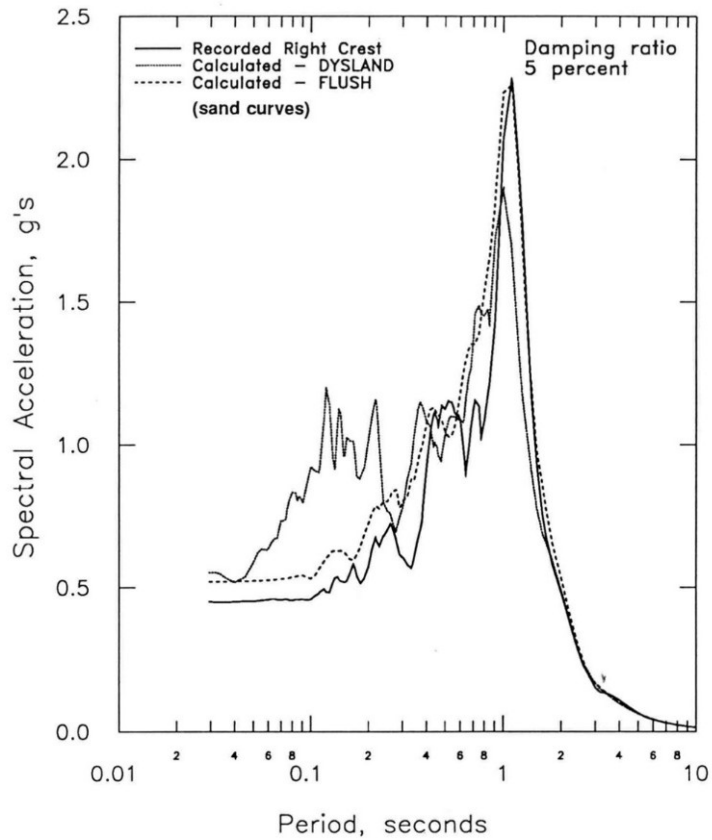


Nonlinear analysis with DYSLAND

RECORDED AND CALCULATED RESPONSE SPECTRA

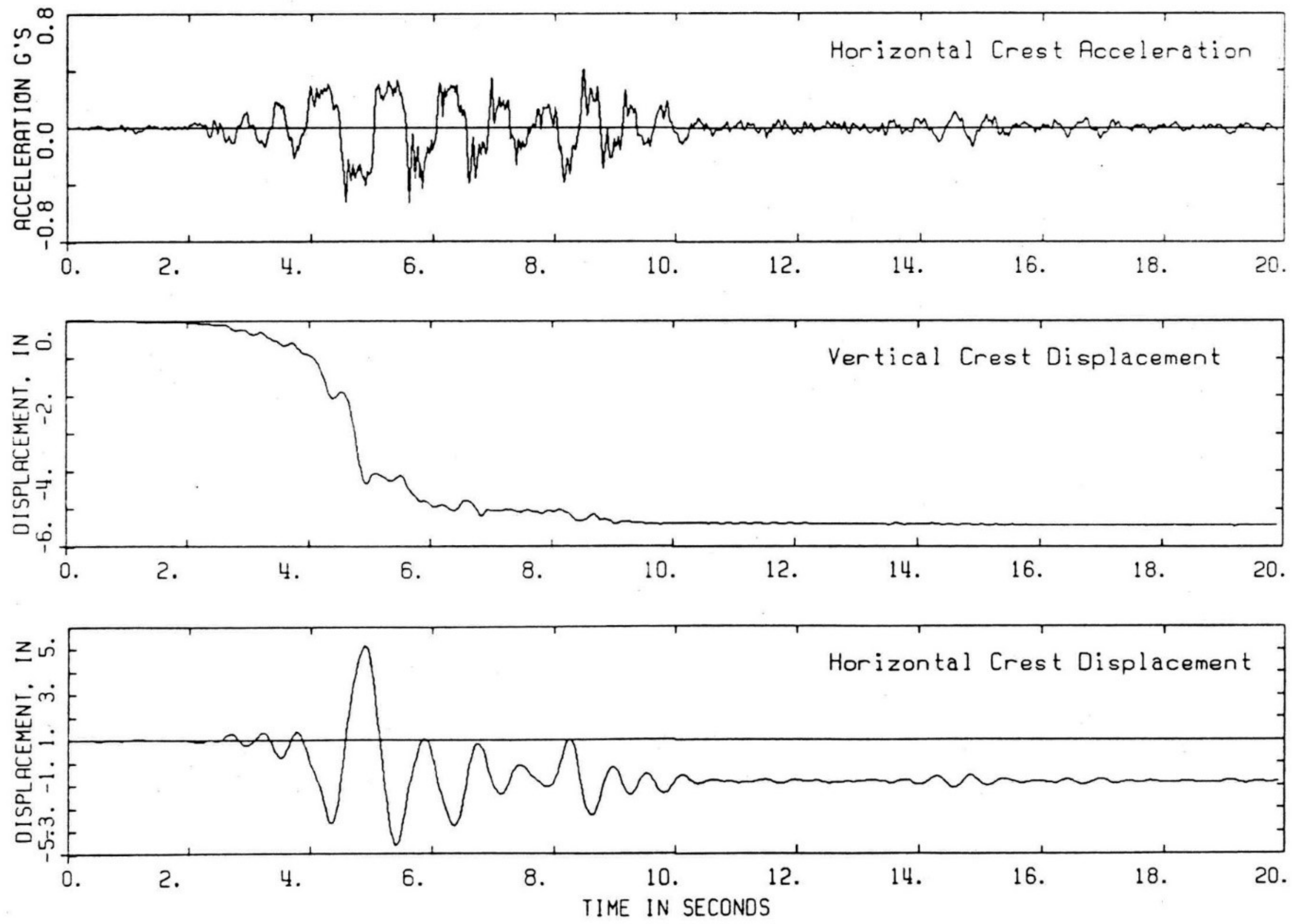


Lake Elsman Earthquake, 8/8/89

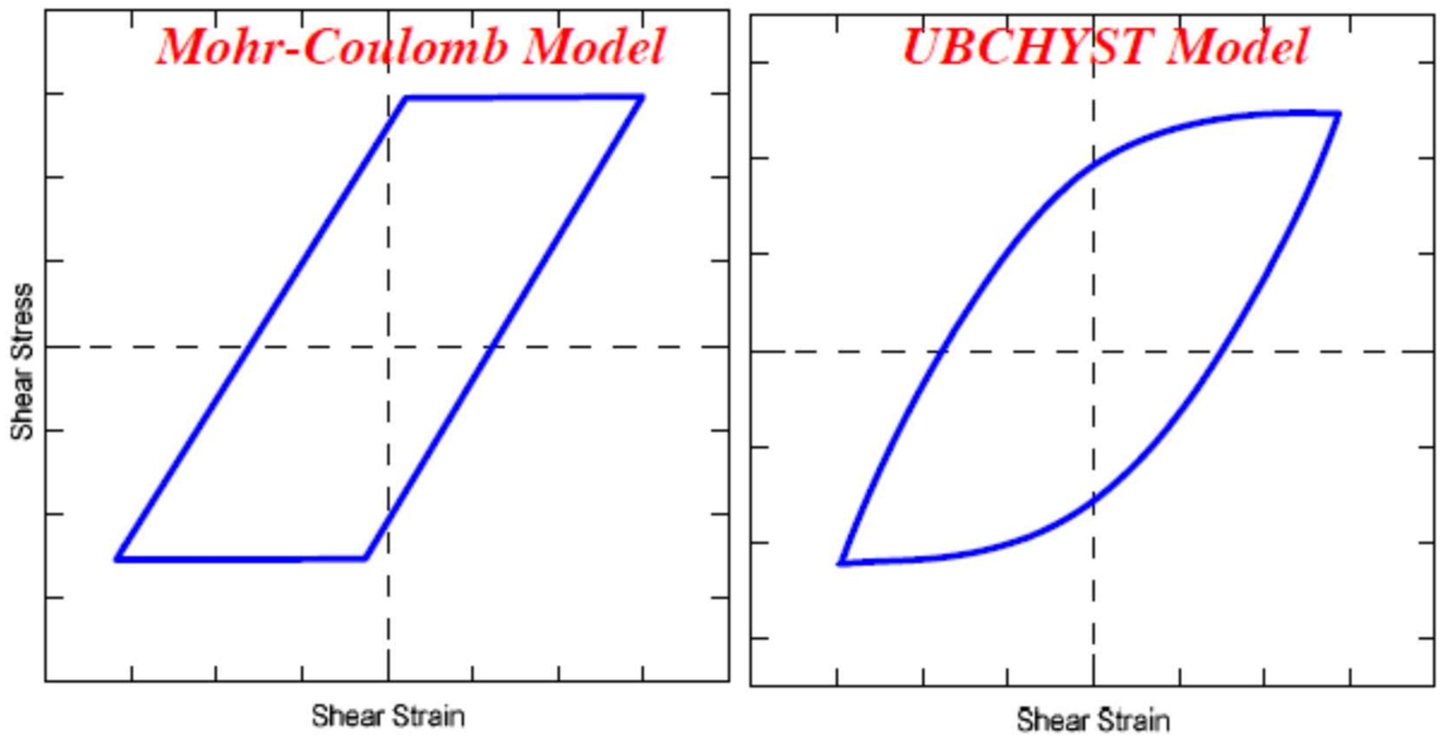


Loma Prieta Earthquake, 10/17/89

CALCULATED ACCELERATION AND DISPLACEMENT TIME HISTORIES

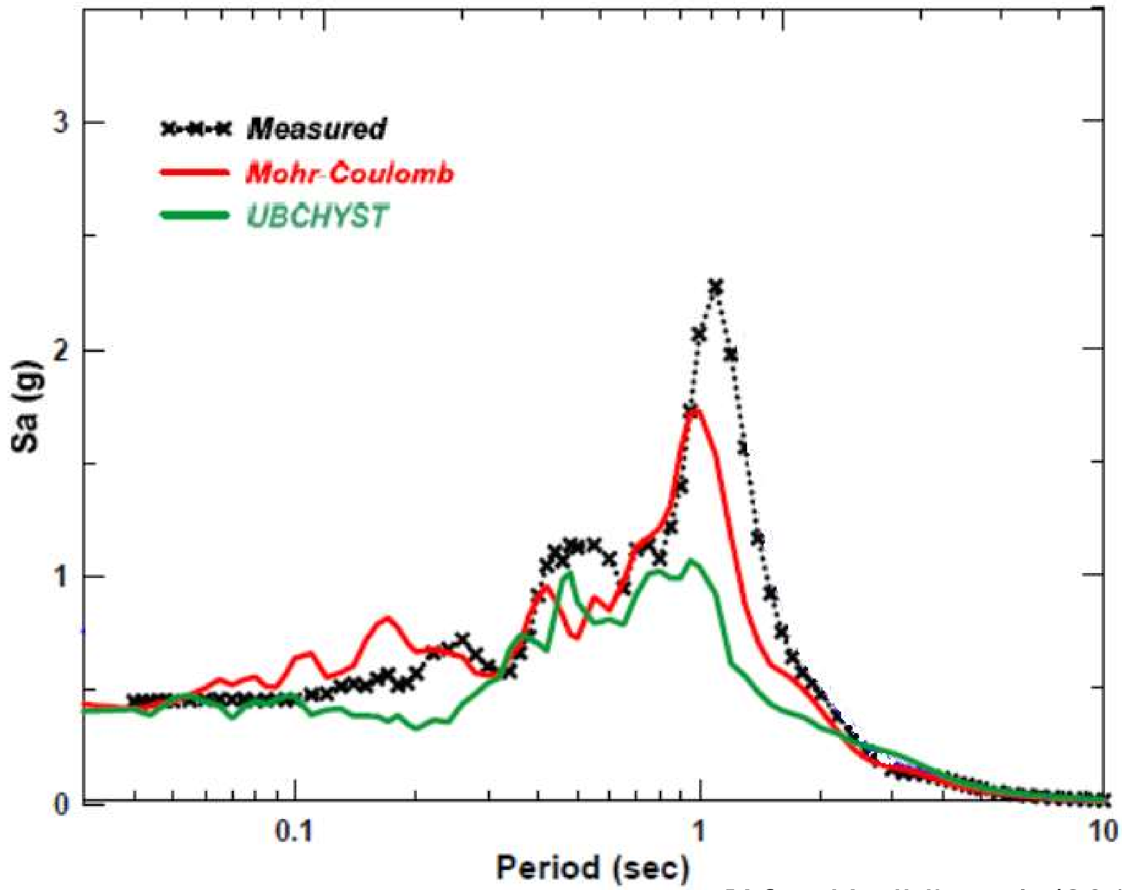


SENSITIVITY TO ANALYSIS CONSTITUTIVE MODEL



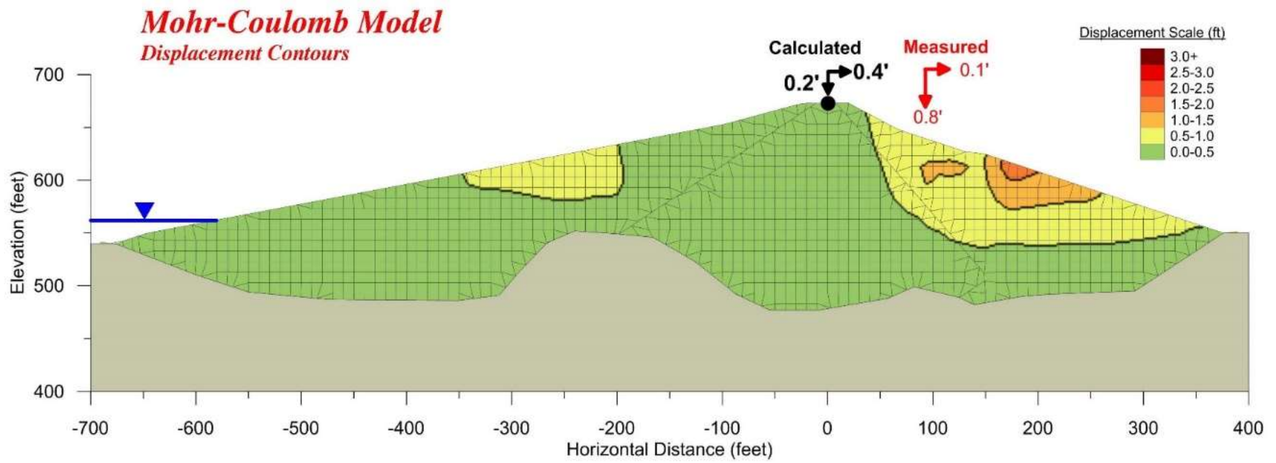
Reference: Hadidi et al. (2014)

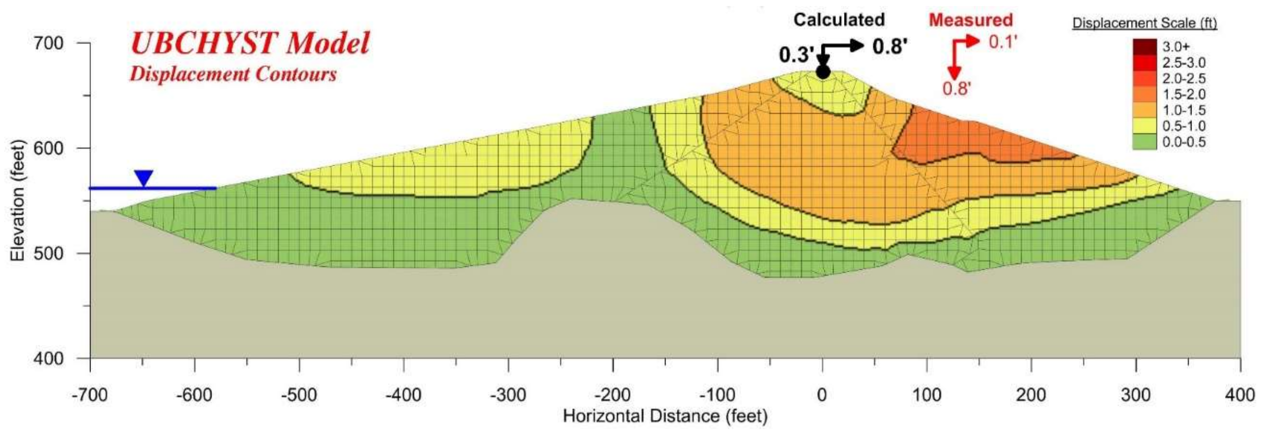
CALCULATED CREST ACCELERATION SPECTRA



[After Hadidi et al. (2014)]

CALCULATED SEISMIC DEFORMATIONS

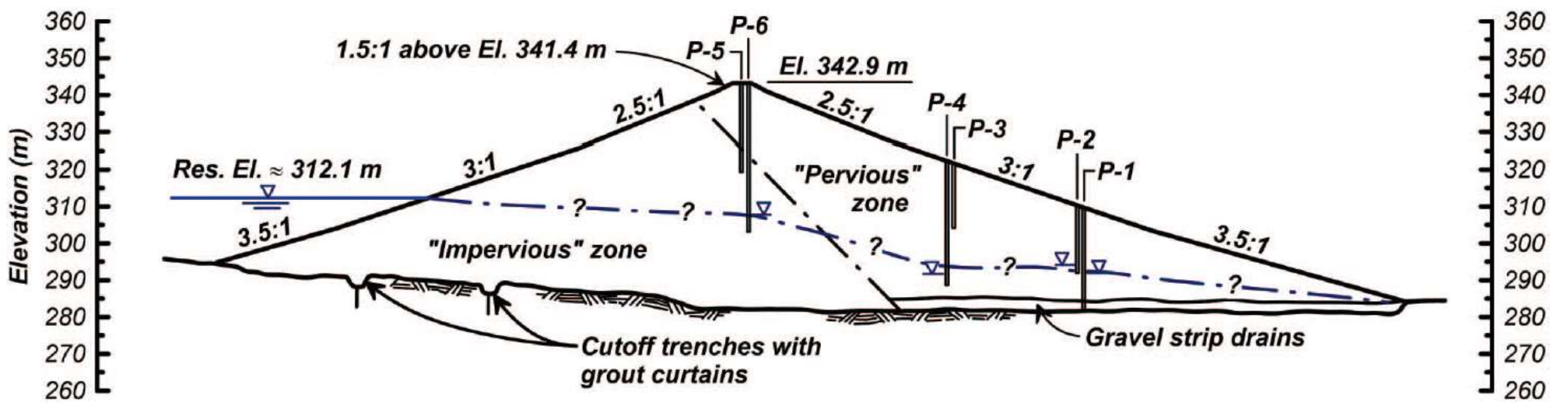




Reference: Hadidi et al. (2014)

ANALYSIS OF AUSTRIAN DAM

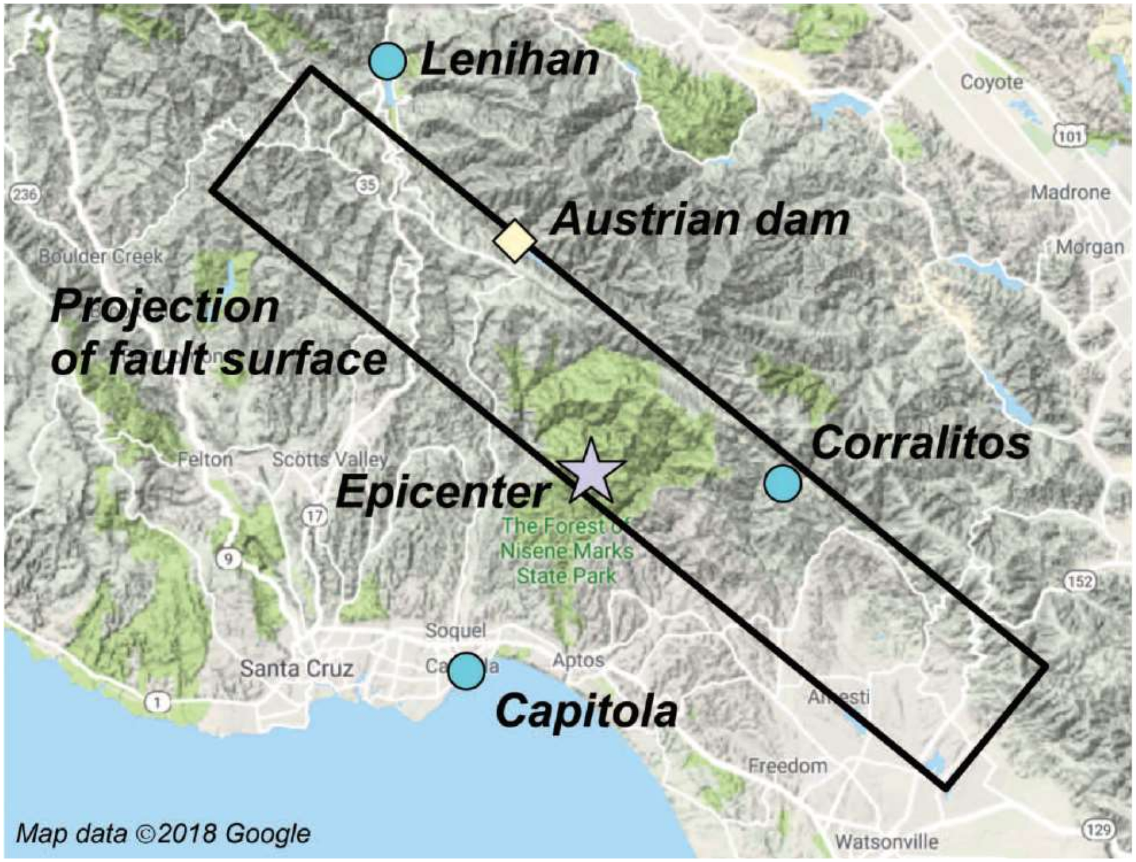
- 55-m-high compacted earthfill embankment
- Completed in 1951
- Freeboard of 4.6 m
- Zoned embankment but assumed to be generally homogenous as constructed



Reference: Boulanger (2019)

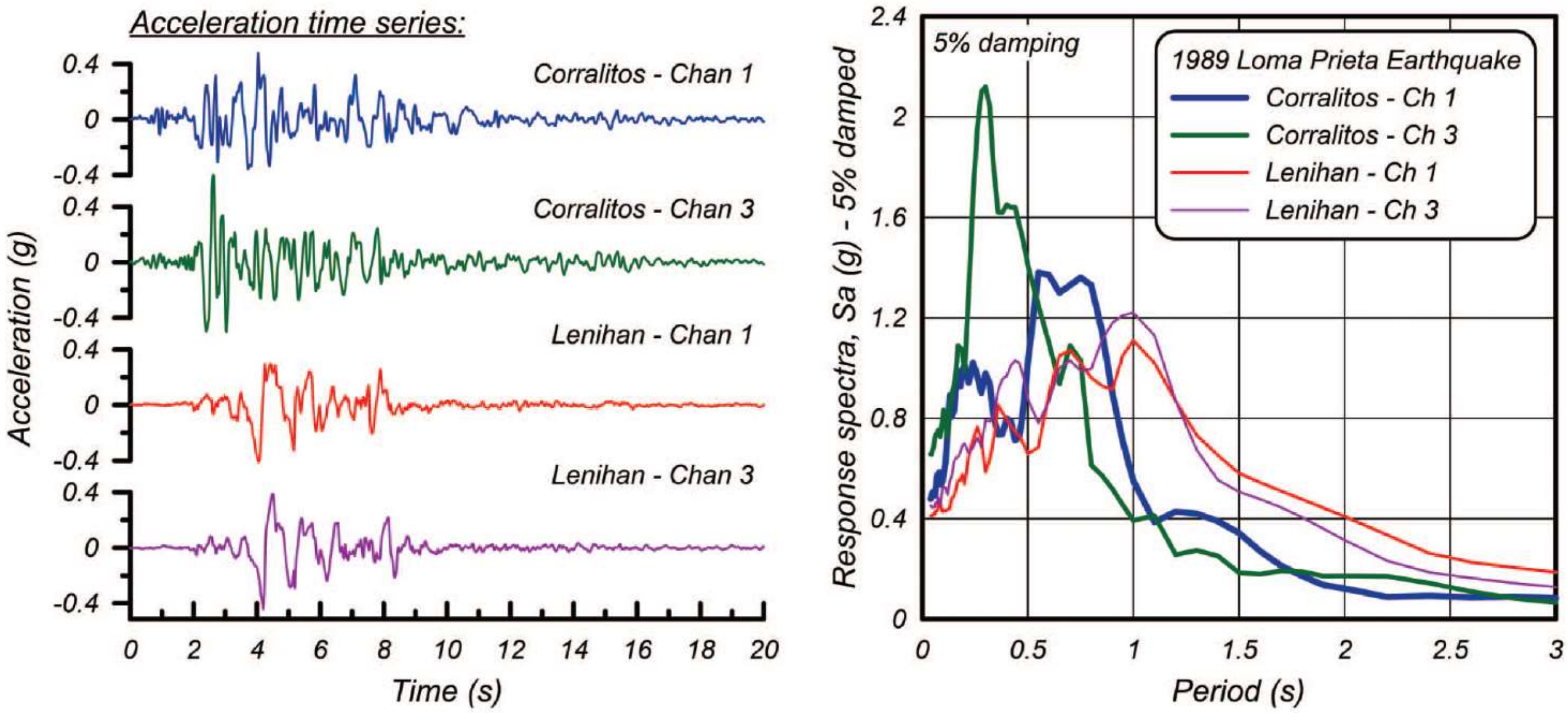
1989 LOMA PRIETA EARTHQUAKE

- Nearby recording stations



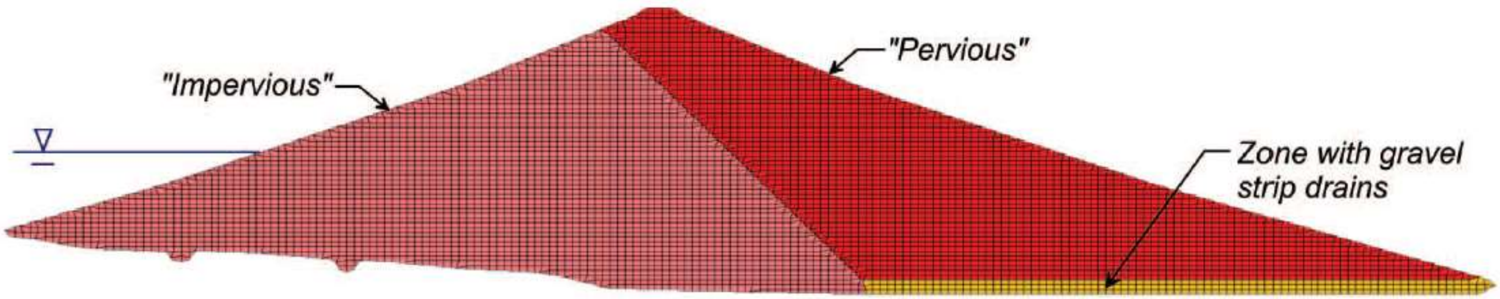
Reference: Boulanger (2019)

NEARBY RECORDED MOTIONS

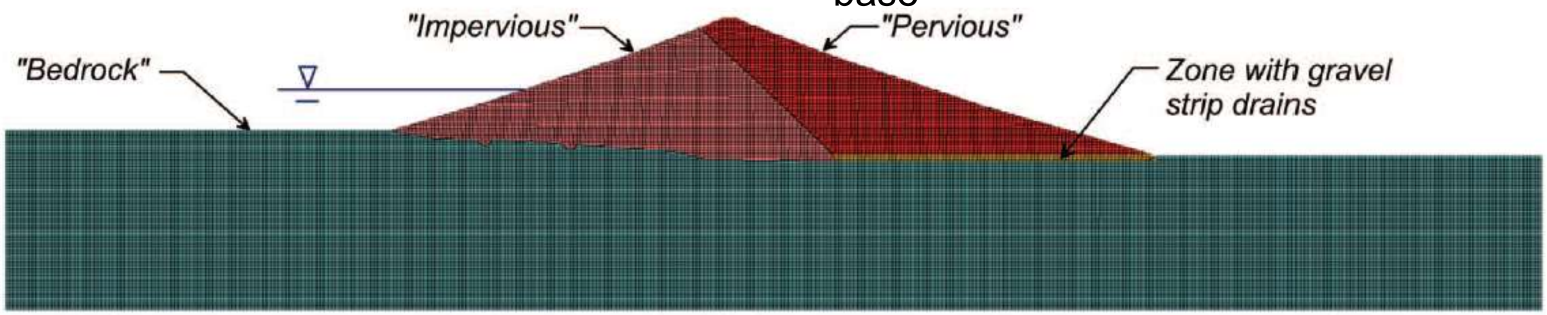


Reference: Boulanger (2019)

FLAC MODEL



(a) Rigid base



(b) Compliant base

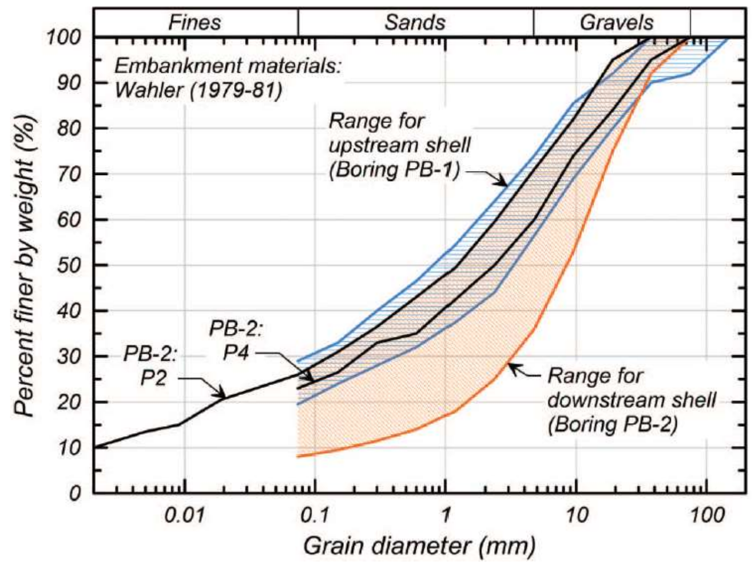
Reference: Boulanger (2019)

MATERIAL PROPERTIES

Table 1. Classification and compaction data for embankment materials

Property	Range	Mean
USCS classification	SC, GC	—
Percent coarser than No. 4 sieve (%)	26–72	46
Percent finer than No. 200 sieve (%)	16–44	32
Specific gravity, G_s	2.60–2.78	2.70
Liquid limit	28–32	31
Plasticity index	11–15	13
Water content as compacted in ~1950 (%)	9.5–19.5	14.5
Dry unit weight as compacted in ~1950 (kN/m^3)	16.90–20.75	19.04
Dry unit weight of samples in ~1989 (kN/m^3)	19.07–20.69	19.90

Sources: Data from Wahler Associates (1979, 1981).



Same mechanical properties used for upstream and downstream zones

Reference: Boulanger (2019)

CONSTITUTIVE MODEL

- PM4Silt
  - Stress-ratio controlled, critical state compatible, bounding surface plasticity model for clays and plastic silts
  - Selected based on PI and fines content
- Calibration
  - Primary and secondary parameters calibrated based on laboratory test data

Reference: Boulanger (2019)

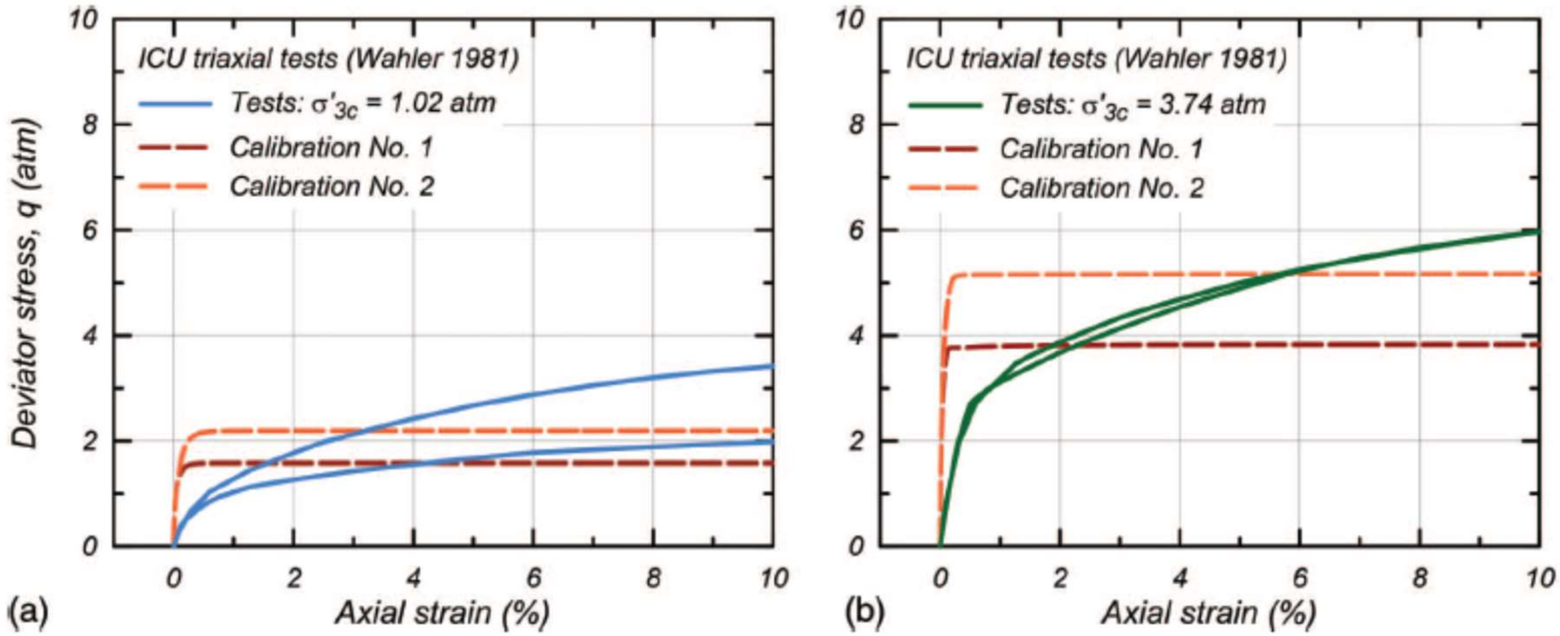
MODEL INPUT PARAMETERS

<table>
<tr><th>Input parameter</th><th>Default value</th><th>Calibration 1</th><th>Calibration 2</th></tr>
<tr><td>s_u at critical state, $s_{u,cs}$</td><td>[a]</td><td colspan="2">$f(\sigma'_{fc}, K_c)$[b]</td></tr>
<tr><td>Shear modulus coefficient, G_o</td><td>[a]</td><td colspan="2">2,280</td></tr>
<tr><td>Contraction rate parameter, h_{po}</td><td>[a]</td><td>40</td><td>80</td></tr>
<tr><td>Shear modulus exponent, n_G</td><td>0.75</td><td colspan="2">0.6</td></tr>
<tr><td>Plastic modulus ratio, h_o</td><td>0.5</td><td colspan="2">[c]</td></tr>
<tr><td>Initial void ratio, e_o</td><td>0.9</td><td colspan="2">0.394</td></tr>
<tr><td>Compressibility in e-ln(p') space, λ</td><td>0.06</td><td colspan="2">[c]</td></tr>
<tr><td>Critical state friction angle, ϕ'_{cv}</td><td>32°</td><td colspan="2">41°</td></tr>
<tr><td>Bounding surface parameter, n^{bwet}</td><td>0.8</td><td colspan="2">1.0</td></tr>
<tr><td>Bounding surface parameter, n^{bdry}</td><td>0.5</td><td colspan="2">[c]</td></tr>
<tr><td>Dilation surface parameter, n^d</td><td>0.3</td><td colspan="2">[c]</td></tr>
<tr><td>Dilatancy parameter, A_{do}</td><td>0.8</td><td colspan="2">[c]</td></tr>
<tr><td>Sets bounding p_{min}, $r_{u,max}$</td><td>$p_{min} = p_{cs}/8$</td><td colspan="2">—[c]</td></tr>
<tr><td>Fabric term, z_{max}</td><td>$10 \leq 40(s_u/\sigma'_{vc}) \leq 20$</td><td colspan="2">5</td></tr>
<tr><td>Fabric growth parameter, C_z</td><td>100</td><td colspan="2">50</td></tr>
<tr><td>Strain accumulation rate factor, C_ε</td><td>$0.5 \leq (1.2s_u/\sigma'_{vc} + 0.2) \leq 1.3$</td><td colspan="2">[c]</td></tr>
<tr><td>Modulus degradation factor, C_{GD}</td><td>3.0</td><td colspan="2">6.0</td></tr>
<tr><td>Plastic modulus factor, $C_{k\alpha f}$</td><td>4.0</td><td colspan="2">[c]</td></tr>
<tr><td>Poisson ratio, v_o</td><td>0.3</td><td colspan="2">[c]</td></tr>
</table>

[a]Required input parameter that does not have a default value.
[b]Computed using the strength parameters in Table 3.
[c]Retained default value.

Reference: Boulanger (2019)

MODEL COMPARISON TO LABORATORY TESTS

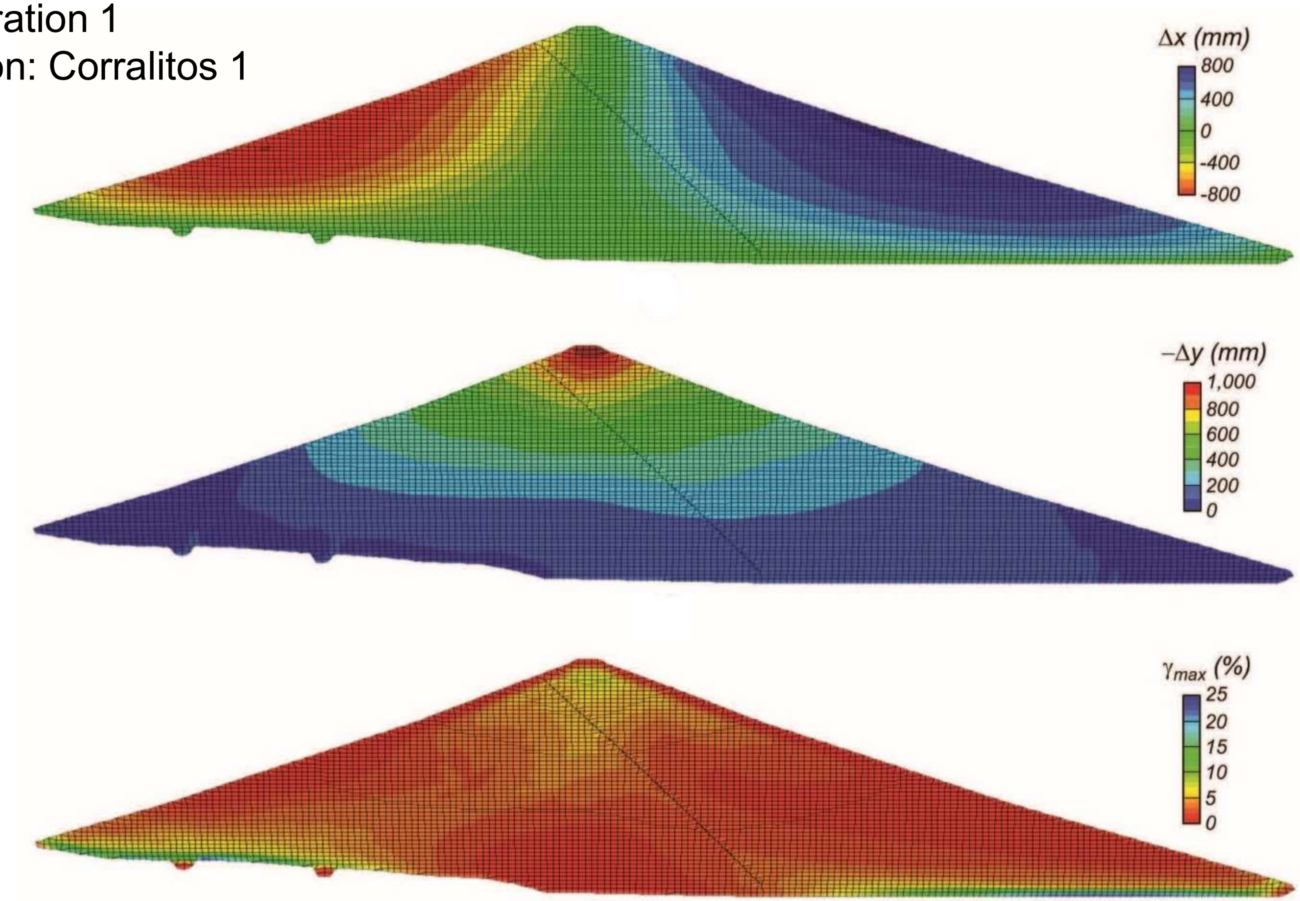


PM4Silt stress-strain simulations are for plane strain loading

Reference: Boulanger (2019)

CALCULATED SEISMIC DEFORMATIONS

Model: Calibration 1
H Input Motion: Corralitos 1



Reference: Boulanger (2019)

COMPARISON TO MEASURED CREST SETTLEMENT

Case	Peak horizontal base acceleration (*g*)	Dam crest settlement (mm)	
		Calibration 1	Calibration 2
Measured[a]	N/A	859	
Corralitos, Channel 1[b,c]	0.479	1,060	822
Corralitos, Channel 3[b]	0.630	1,048	874
Lenihan, Channel 1[b,c]	0.410	840	610
Lenihan, Channel 3[b]	0.442	853	638

[a]Survey data as reported in Harder et al. (1998).
[b]Recording station and horizontal component used for the input motion. The vertical component of the input motion was Channel 2 from the same recording station.
[c]Horizontal recording is oriented due east, which is approximately transverse to Austrian Dam.

Reference: Boulanger (2019)

THANK YOU

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