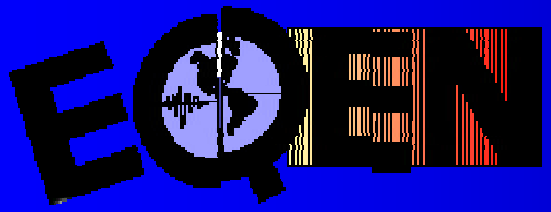
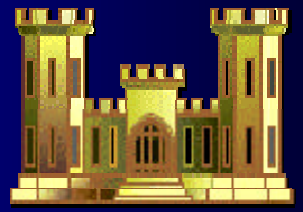
Earthquake Engineering Research Program





Overview & Accomplishments

Dr. Mary Ellen Hynes

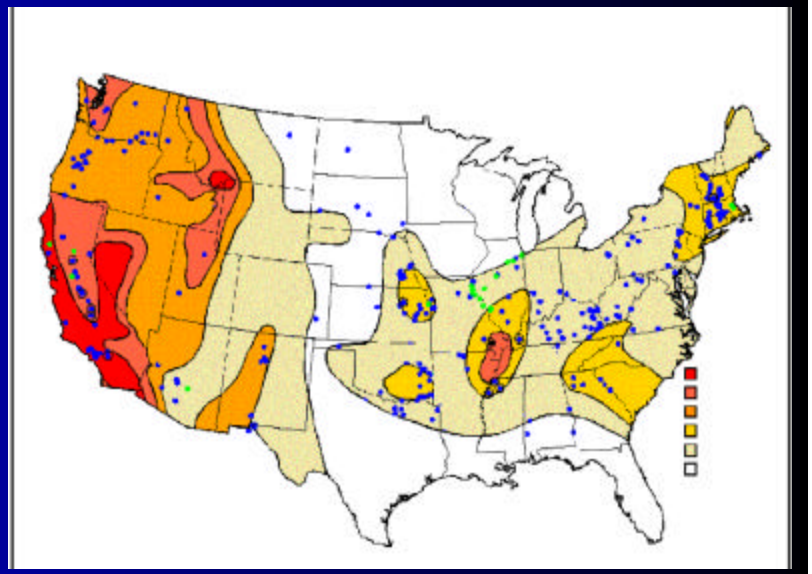
US Army Corps of Engineers

Engineering Research and Development Center

Earthquake Engineering Research Program

Problem

- Corps has 200 dams and 73 intake towers in areas with significant seismic hazards
- Most dams were constructed when earthquake engineering was in its infancy
- Using current technology, most of these would be judged seismically inadequate
- Remediation costs of these structures could reach $20 billion



Seismic zone map showing SMIP project sites

Purpose

- To improve our ability to predict the performance of a dam under seismic loads, and to improve our ability to design and construct cost-effective remediation

Mormon Island Dam, CA remediation

Major Thrusts

- Engineering geology / seismology
- Geotechnical earthquake engineering
- Structural earthquake engineering

Target Structures

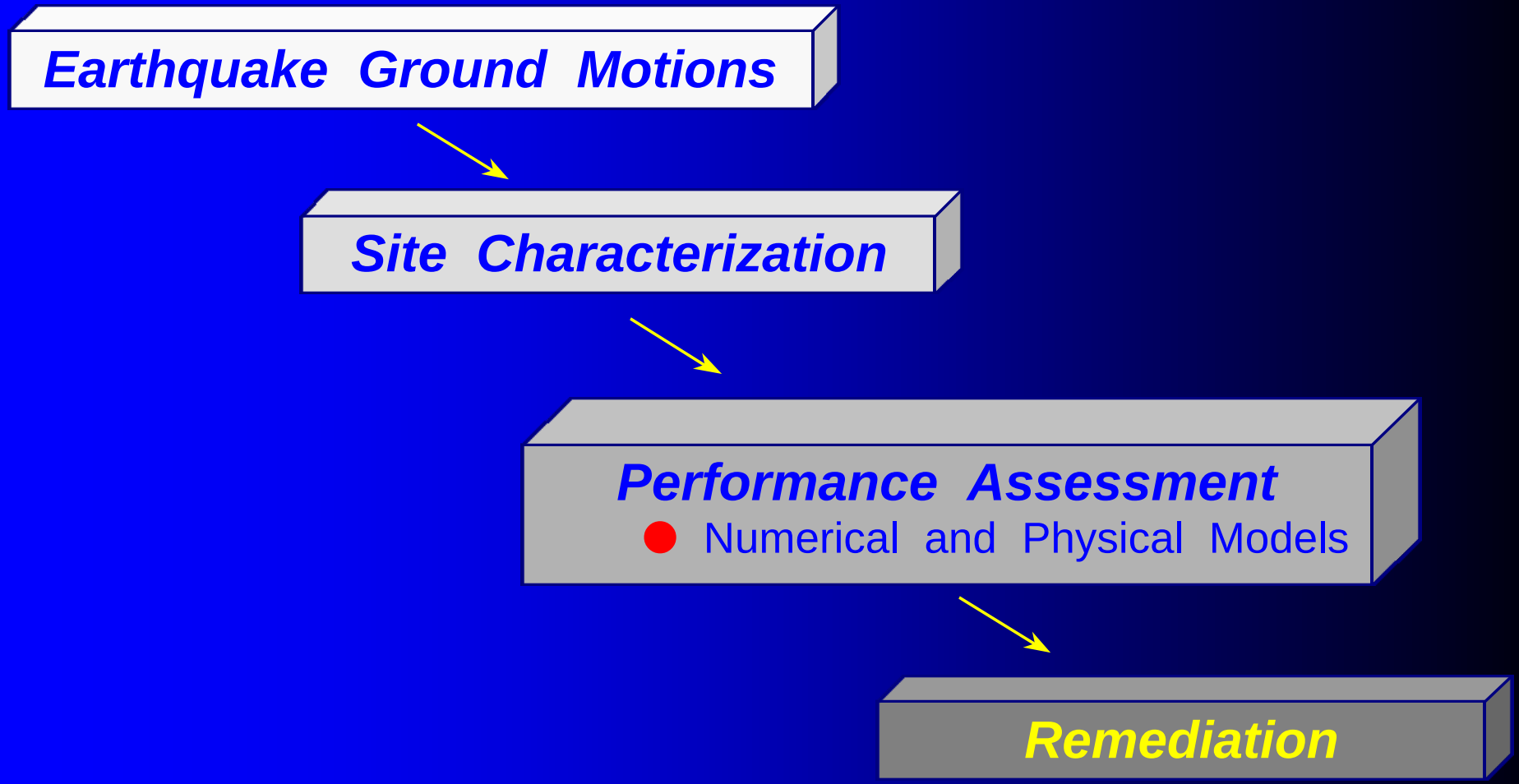
- Embankment dams
- Concrete dams
- Intake tower / outlet works

Sardis Dam, MS remediation

Interagency Coordination

- ***EQEN is only federal funded program focused on seismic safety of dams***
- National Earthquake Hazard Reduction Program, $120M/yr, focused on buildings and lifelines, BSSC, FEMA, USGS, NIST, NSF - MCEER , PEER, MAEC and universities
- FHWA Highway Seismic Research Program, $15M/5 yrs (MCEER)
- Leveraging with NSF, Corps Districts, US Bureau of Reclamation, BC Hydro
- UJNR US-Japan Panel on Wind and Seismic Effects, EPRI, CALTRANS, NSTC, SNDR

Earthquake Engineering Research Program



EQEN - Embankment Dams

Ground Motions

Geology / Seismology - Krinitzsky

Engrg Ground Motion Analysis System - Yule

Site Characterization

V_S Database - Yule
Geophysical Methods - Ballard
Penetration Testing - Koester

Performance Assessment

Newmark Analyses - Koester
Behavior of Liquefying Soils - Ledbetter / Sharp
Failure Mechanisms & Damage Assessment - Sharp

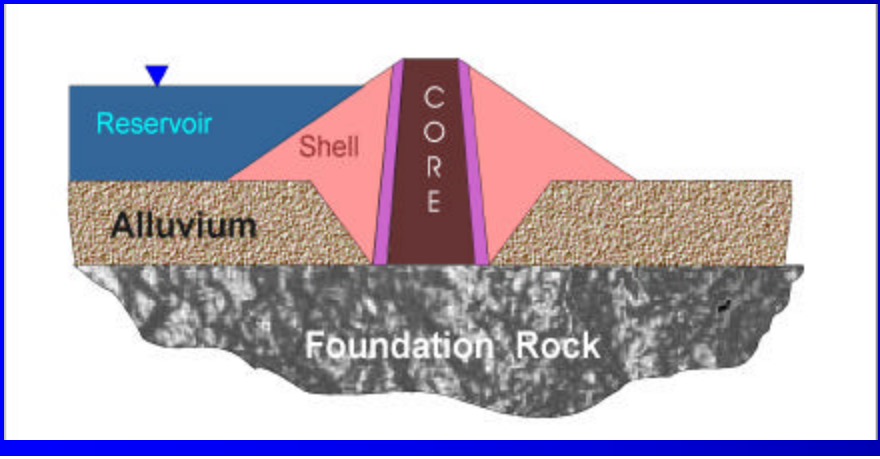
Primary Analysis Tool

Large Deformation Analysis of Embankment Dams - Peters

Assessment & Remediation

EQEN Phase II

Seismic Evaluation and Rehabilitation Program



EQEN - Concrete Dams and Outlet Works

Ground Motions

Intake Towers - Dove

Outlet Works - Woodson

— Quantify Ductility

Subbottom Absorption - DeBajar

Conventional Concrete Dams - Hall / Chowdhury

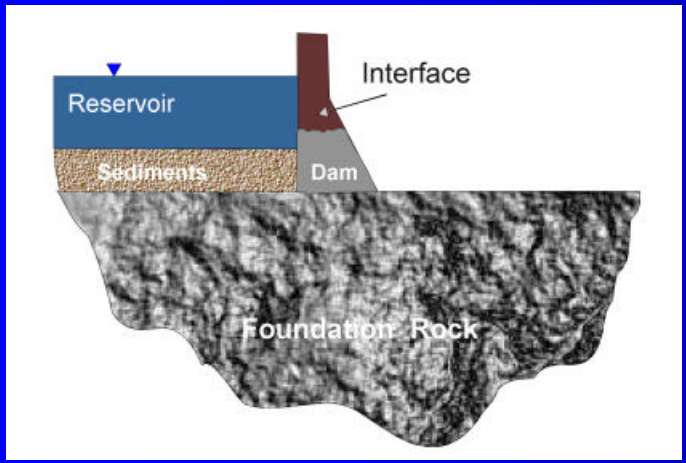
Roller Compacted Concrete - DeBejar

Primary Analysis Tool

Time - History Non - Linear Analysis - Ebeling / Bevins

Moment / Shear / Thrust - Merrill

Post - Processors - Merrill



EQEN Program Structure - Geotechnical Work Units

Policy: ER 1806 ER 1155	Seismic Safety Review	Phase I	Phase II	Phase III	Guidance Documents
Ground Motions	Geology / Seismology - Hynes / Krinitzsky Engineering Ground Motion Analysis System - Yule				EM 6000
Site Characterization	V Database	Geophysical Methods - Ballard Penetration Testing - Koester			
Performance Assessment	Newmark Analyses - Koester	Behavior of Liquefying Soils - Ledbetter / Sharp Failure Mechanisms and Damage Assessment - Sharp Large Deformation Analysis of Embankment Dams - Peters			EM 6001
Remediation	*EQEN II Eval. & Rehabilitation*				

@

EQEN Program Structure – Structural Work Units

Policy: ER 1806 ER 1155	Seismic Safety Review	Phase I	Phase II	Phase III	Guidance Documents
Ground Motions					EM 6000 EC 6050 EC 60XX
Site Characterization	Subbottom Absorption - DeBajar Intake Towers - Dove Outlet Works - Woodson				
Performance Assessment	Conventional Concrete Dams - Hall / Chowdhury Roller Compacted Concrete - DeBejar Time - History Analysis - Ebeling / Bevins				EM 60XX
Remediation	Moment / Shear / Thrust - Merrill Post - Processors - Merrill				

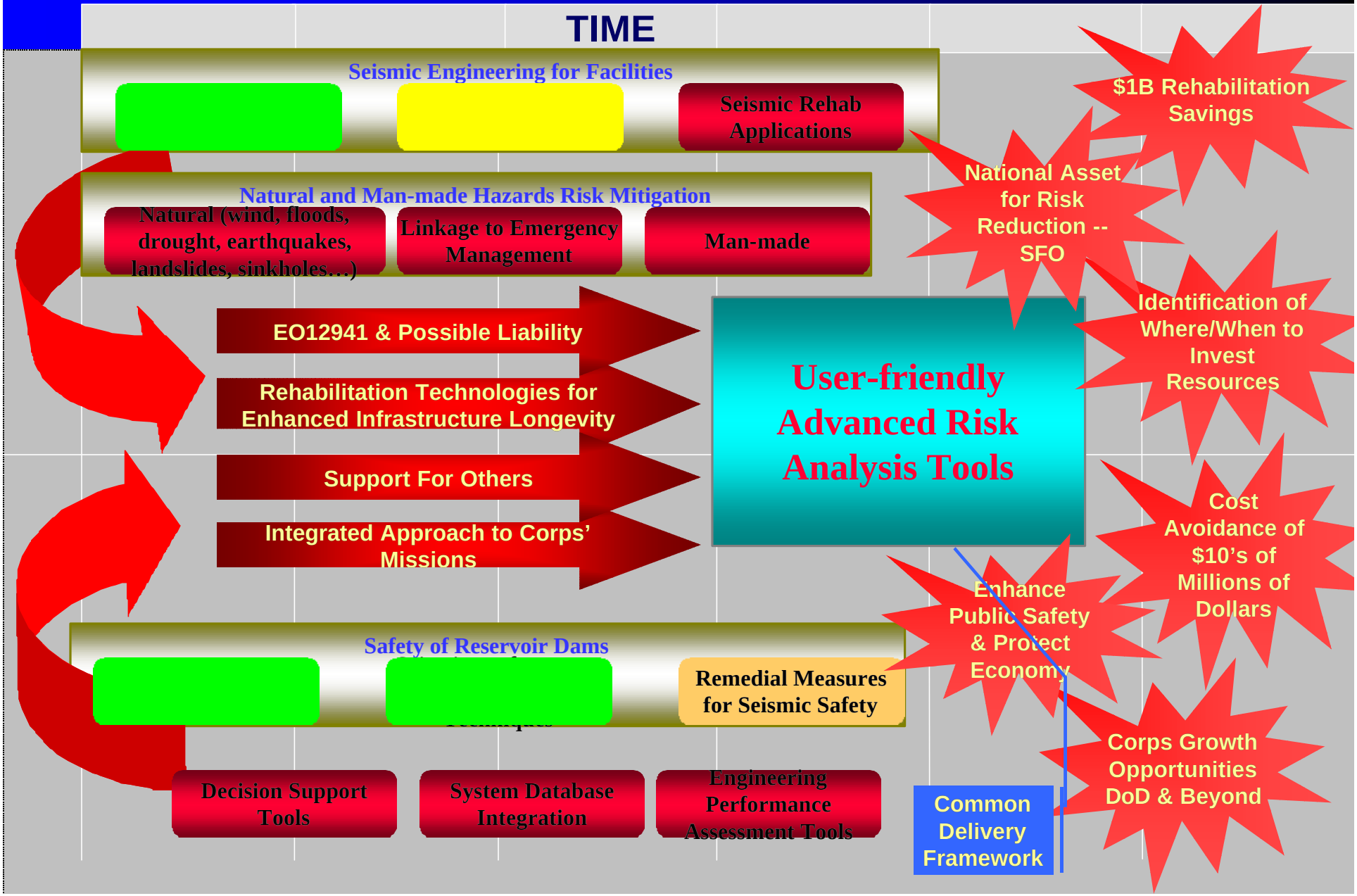
EQEN Cost Avoidance and Savings

Thrust Areas and Work Units	Cost Avoidance To Date	Future or Potential Cost Avoidance		Project	Description
	CG	O&M	CG		
Reservoir Control Structures Non-linear Dynamic Response of Intake Towers	$30M			Wappapello, Sardis, Enid, Arkabutla, Gathright, Rend	Cost Avoidance for retrofits from evaluations using improved techniques
			$200M	40 (Rectangular)	If 50% of these evaluate safe then savings still a significant $180M
			$155M	31 (Complex)	
Concrete Dams Subbottom Absorption	$100M+			Folsom Concrete Dam from unsafe to safe	Cost avoidance for retrofit using theoretically validated and field measured alpha values, estimate fix >$100M
			$800M+	8 remaining concrete dams in sesimic Zone > 2	Expect all concrete dams will be found safe from cracking under earthquake loads
Earthquake Ground Motions Engineering Seismology & Engineering Ground Motion Analysis System		$2.8M		Total Dam Inventory, 579 dams	$50K * 579 Dams $2.8M (Total Inventory) - Reduced time to evaluate ground motions - Developed OBE map for U.S. - Provided USGS input parameters and deaggregated results for all dams in inventory, for rapid assessment of the need for additional PSHA - Above result in >$50k cost-avoidance / dam
Site Characterization Geophysical Methods Shear Wave Velocity Data Base	$10M			Success	Tomography and penetration testing identified limited zone requiring a fix; reduced construction costs from $20M to $10M Shear wave velocity database shortened SSR and Phase I studies (this will be true for all embankment dam studies)
		$10M+		191 embankment dams in Zone $\geq$ 2, 480 dams in entire inventory	Reduces cost of field investigations by about 50%. Estimate $100k+ savings x 100+ dams = $10M+
Penetration Testing	$20M			Terminus - from unsafe to safe	Increased accuracy of penetration interpretation in gravelly soils resulted in Terminus declared safe, limited fix at Success, counted above
Page Totals	$160M	$12.8M	$1.155B		

EQEN Cost Avoidance and Savings

Newmark Sliding Block	$0.5M+ O&M				Verified analysis with 130 case histories. Rapid screening analysis applied to all embankment dams. Reduces time investment from 2 months to 2 weeks
Behavior of Liquefying Soils			$200M+ new emb $10M+ fix *$30B+ to replace* *$1.5B+ to fix*	Success Dam Enid Dam Tuttle Creek Dam ... and >150 more potential benefit to levees	Verify depth limit for liquefaction (<80 ft upstream slope, <40 ft downstream slope) to significantly reduce the needed remediation zone for all embankment dams. Reduces the cost of investigation, since deep borings through the upstream and downstream shells would not be needed. Eliminates need for replacement, $0.5-1B per dam, 190 dams Reduces remediation costs of $20-50M per embankment dam by >$10M/dam
Liquefaction of clayey soils	$500M			Fix, not replace Sardis	
Large strain deformation Analysis for embankment dams	$20M above TBD $500M $500M		$20M fix	Arkabutla - unsafe to safe Yatesville - unsafe to safe Sardis - fix not replace Success -fix not replace Mormon Island - fix not replace Clemson - fix not replace	Work on residual strength and improved numerical methods mean we can remediate dams rather than replace and begin to distinguish safe from unsafe dams according to the amount of deformation Replacement costs typically $500M to $1B per dam. Remediation costs typically $20M to $50M per dam.
		$0.5M+ install cost license: $25k/yr /copy			Non-proprietary, well-verified 2-D FEM dynamic analysis software
Page totals	$1.5B+	$0.6M+	$32B+		
Program totals	$1.8B+	$14M+	$32B+		

Risk Reduction Measures Program
FOC: Infrastructure Asset Delivery



Earthquake Engineering Research Program

Accomplishments and Breakthroughs

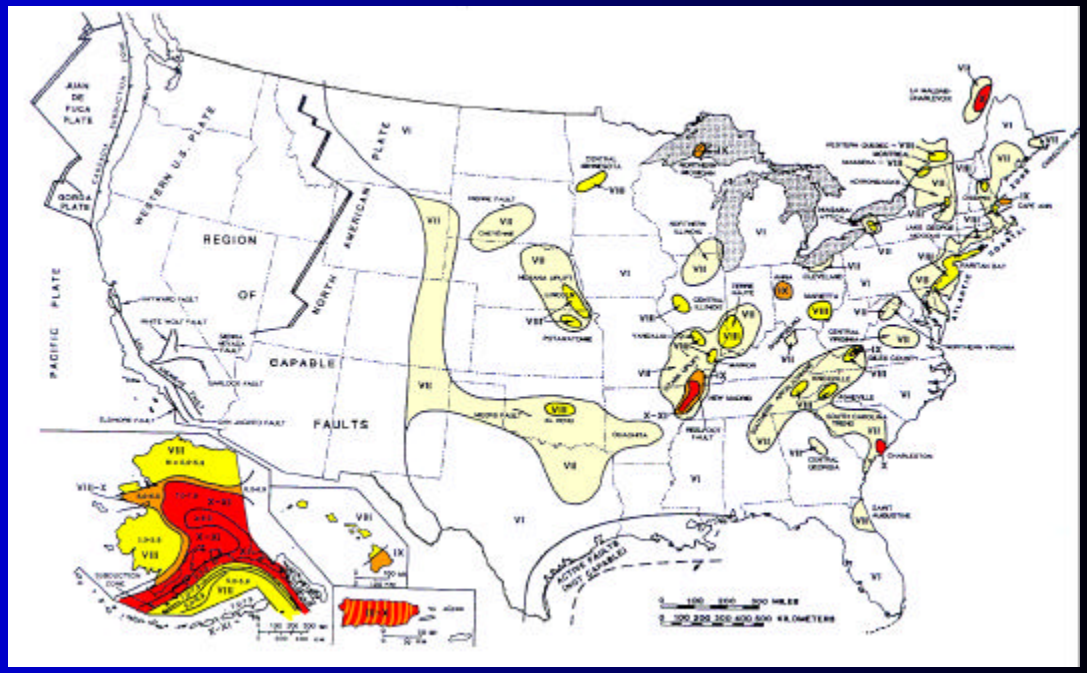
Near failure of Lower San Fernando Dam
San Fernando Earthquake - 1971

Mormon Island Dam, CA

Sardis Dam, MS

Geological-Seismological Investigations

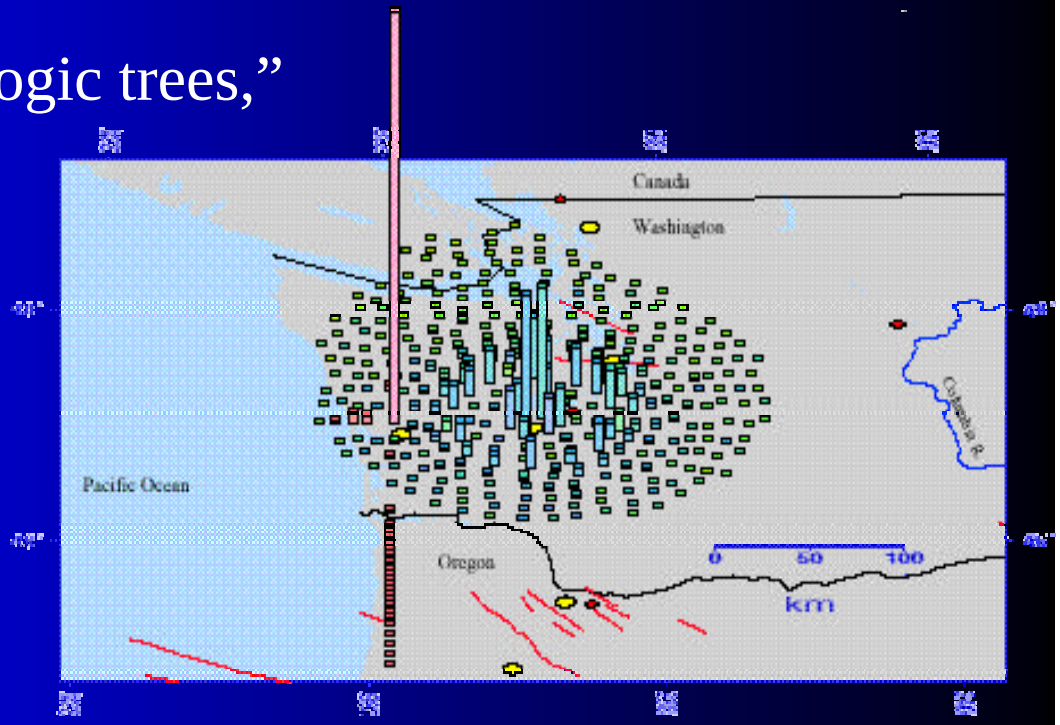
- Continuing transition of geologic & seismologic research to engineering-relevant data
- Incorporated latest knowledge into methods for geological-seismological evaluations of earthquake hazards enabling accurate site-specific ground motions for potential earthquakes affecting Corps projects



Seismic source zones for U.S.

Earthquake Engineering Research Program

- Deaggregated PSHA for entire Corps Dam Inventory, USGS data
- Developed Annual P[Liquefaction / N1,60] for all dams, NRC approach
- Identified problem with "logic trees," guaranteed to result in suboptimal recommendations (discrete, not continuous optimization problem)



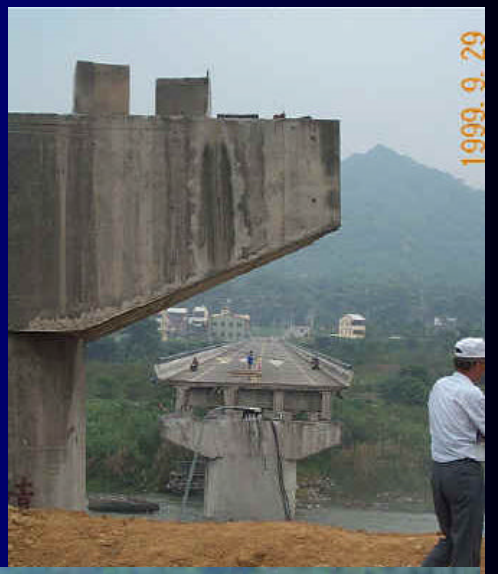
Azimuth Decomposition of Seismic Hazard, Ft. Lewis, WA

Earthquake Reconnaissance

Turkey

- Observed silt liquefaction
- Delayed settlement
- Fires from burps

Taiwan Earthquake Photos

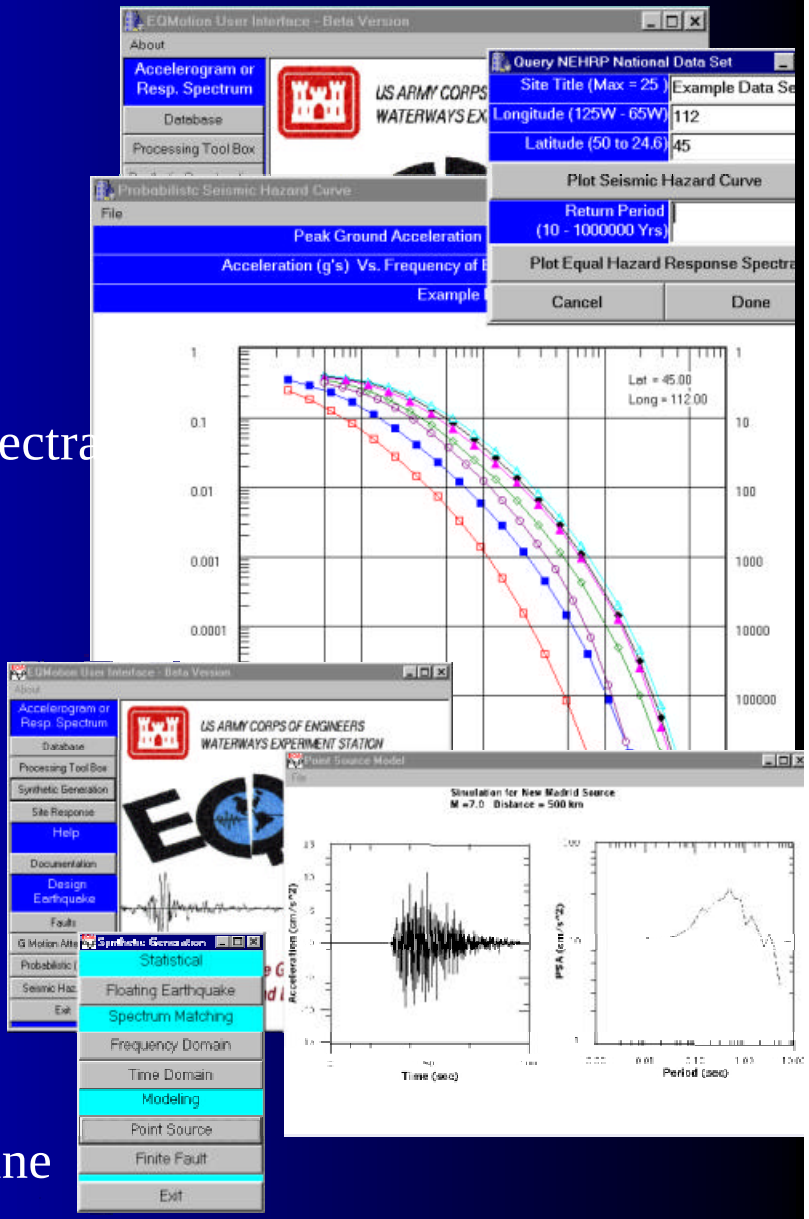


Taiwan

- Best data from large event ground motions
- Full-scale test of dam performance with hydrodynamics

Engineering Ground Motion Analysis System

- Modular, Windows-based tool box
- Site-specific seismic hazard assessment
- Sources updated as new data develop
- Select policy compliant ground motions, spectra
- Corps Guidance on-line
- Modify spectra and records
- >15,000 records on-line
- Large suite of attenuation functions on-line
- Site response module (SHAKE)
- PSHA module
- USGS input data and results on-line
- Deaggregated data for cities and dams on-line

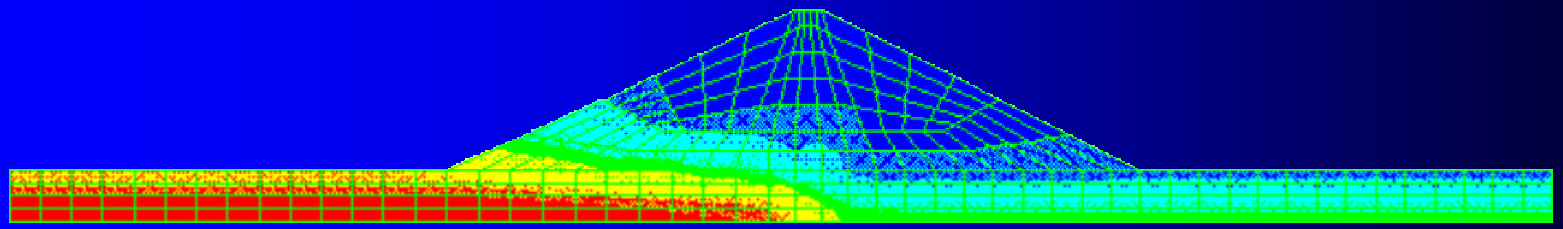


Earthquake Engineering Research Program
Embankment Dams

Research Thrust Areas

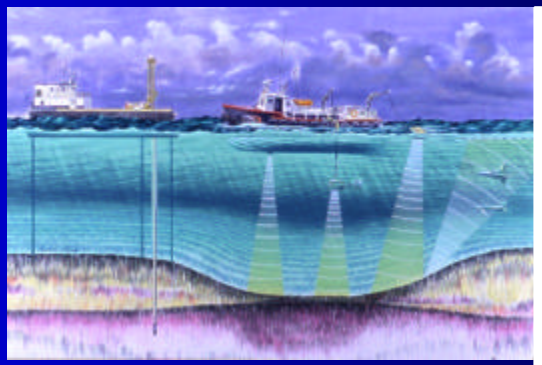
- Site characterization
- Liquefaction
- Large deformation analysis

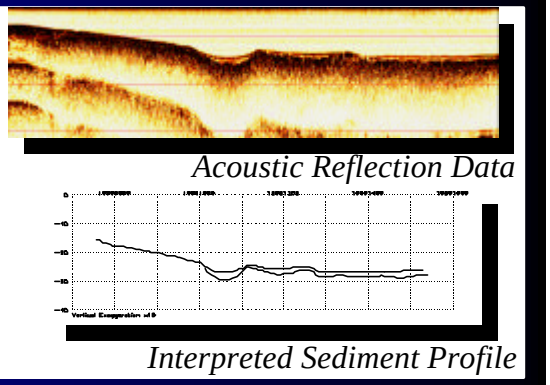
Slide in Lower San Fernando Dam - 1971



Geophysical Methods for Site Characterization and Measurement of Material Properties: Waterborne Geophysics

- Subsurface stratigraphy
  - Material type
  - Distribution
  - Volume
  - Total density
  - Stiffness, elastic properties
  - Void ratio
- High-resolution side- scan image mosaics
  - Pre- and post- earthquake conditions, underwater





Acoustic Reflection Data

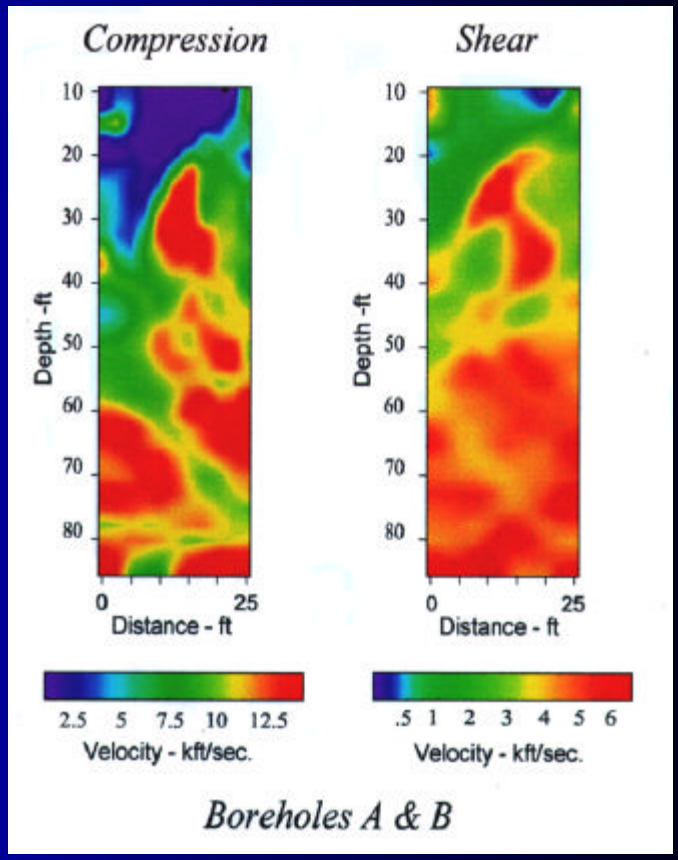
Interpreted Sediment Profile

Subbottom Profiling System

Side scan sonar, Arkabutla control structure

Geophysical Methods for Site Characterization and Measurement of Material Properties: Land-based Geophysics

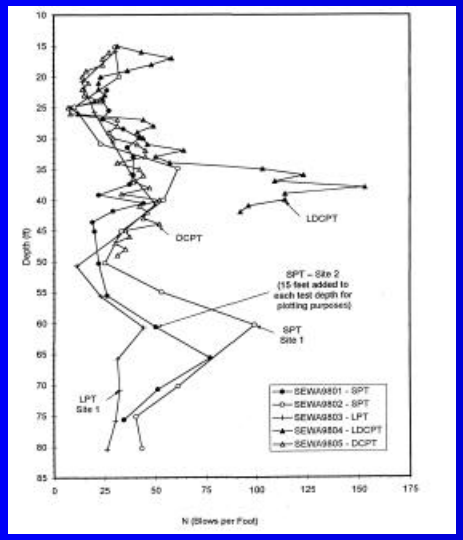
- High-resolution tomography
- 3-D stratigraphy
- Engineering properties
- Liquefaction properties



Success Dam, CA
borehole tomography

Site Characterization: Penetration Testing

- BPT, LPT, SPT, Chamber Tests, Alaska
- CPT- Olsen, Material type, peak strength, residual strength, CRR1, N1,60



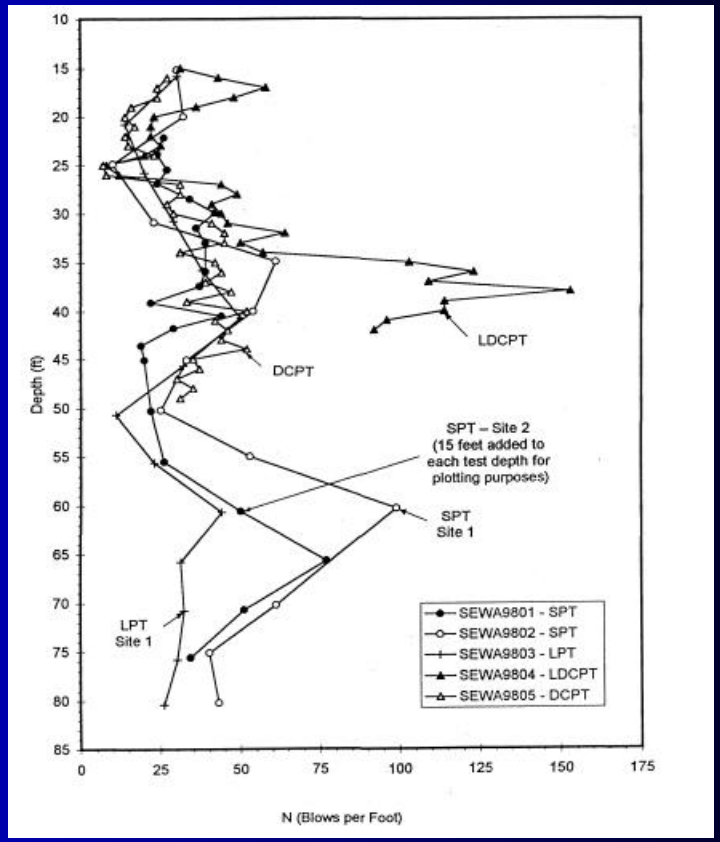
Comparison of Penetration Tests

BPT Drill Rig

Site Characterization: Penetration Testing

BPT, LPT, SPT, Chamber Tests, Alaska

- Harder vs Sy
- Friction effects
- Mud injection
- Alaska: LPT, Vs
- Field procedures

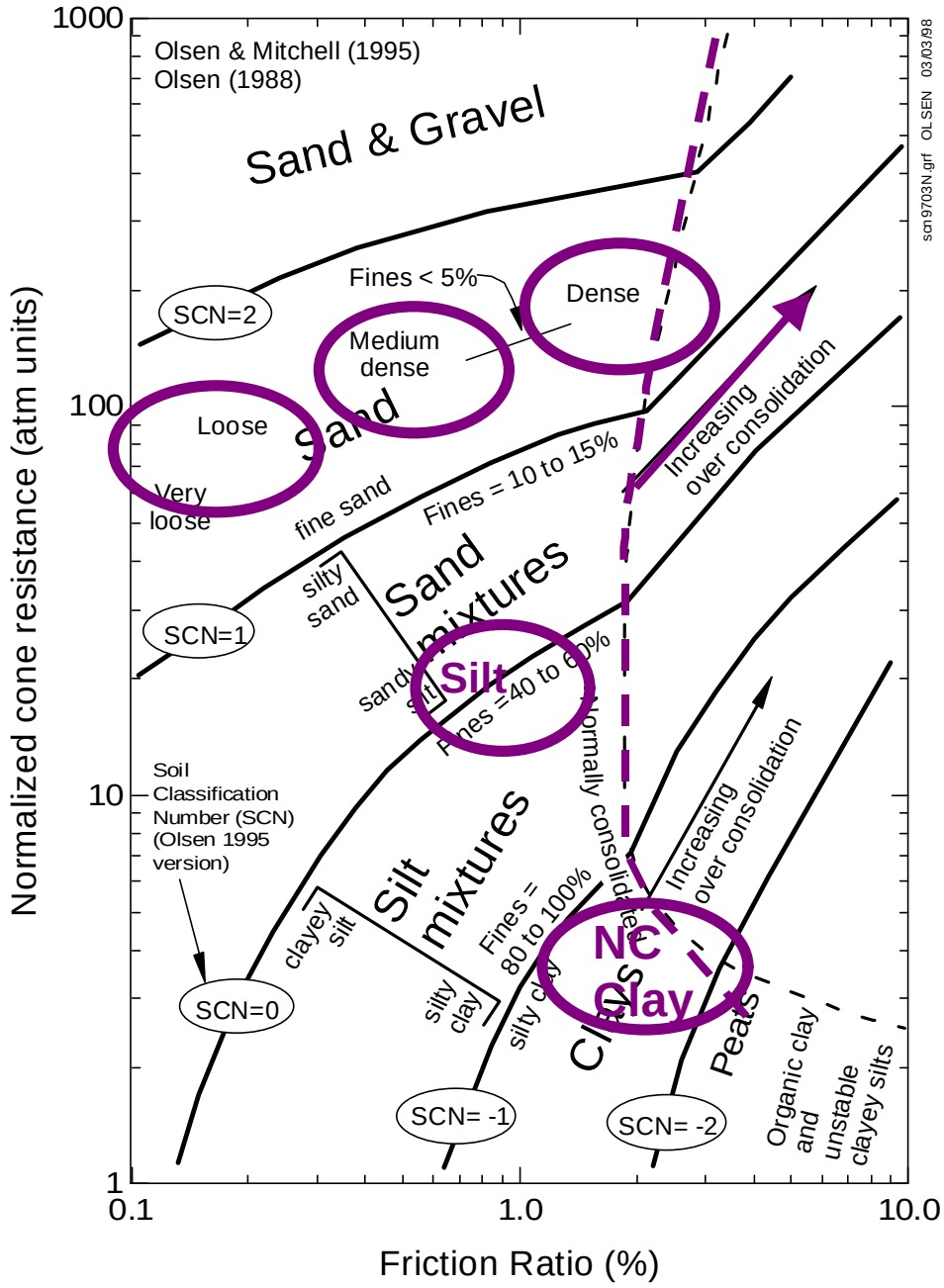


Comparison of Penetration Tests

Site Characterization: Penetration Testing

- CPT- Olsen, Material type, peak strength, residual strength, CRR1, N1,60, stress-focus theory

The CPT soil characterization chart (Olsen, 1984) provides the means for accurate estimation of soil properties and behavior trends

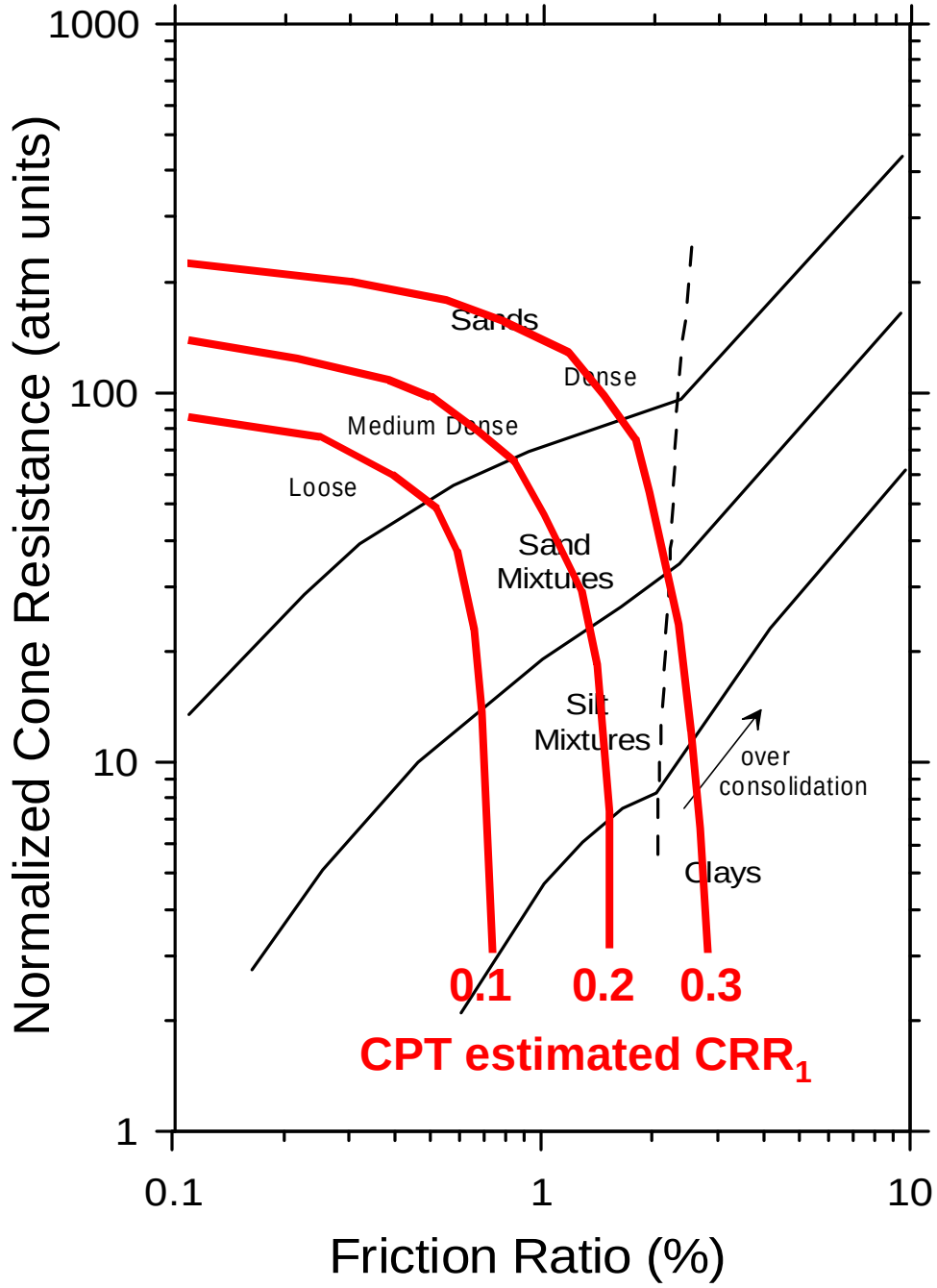


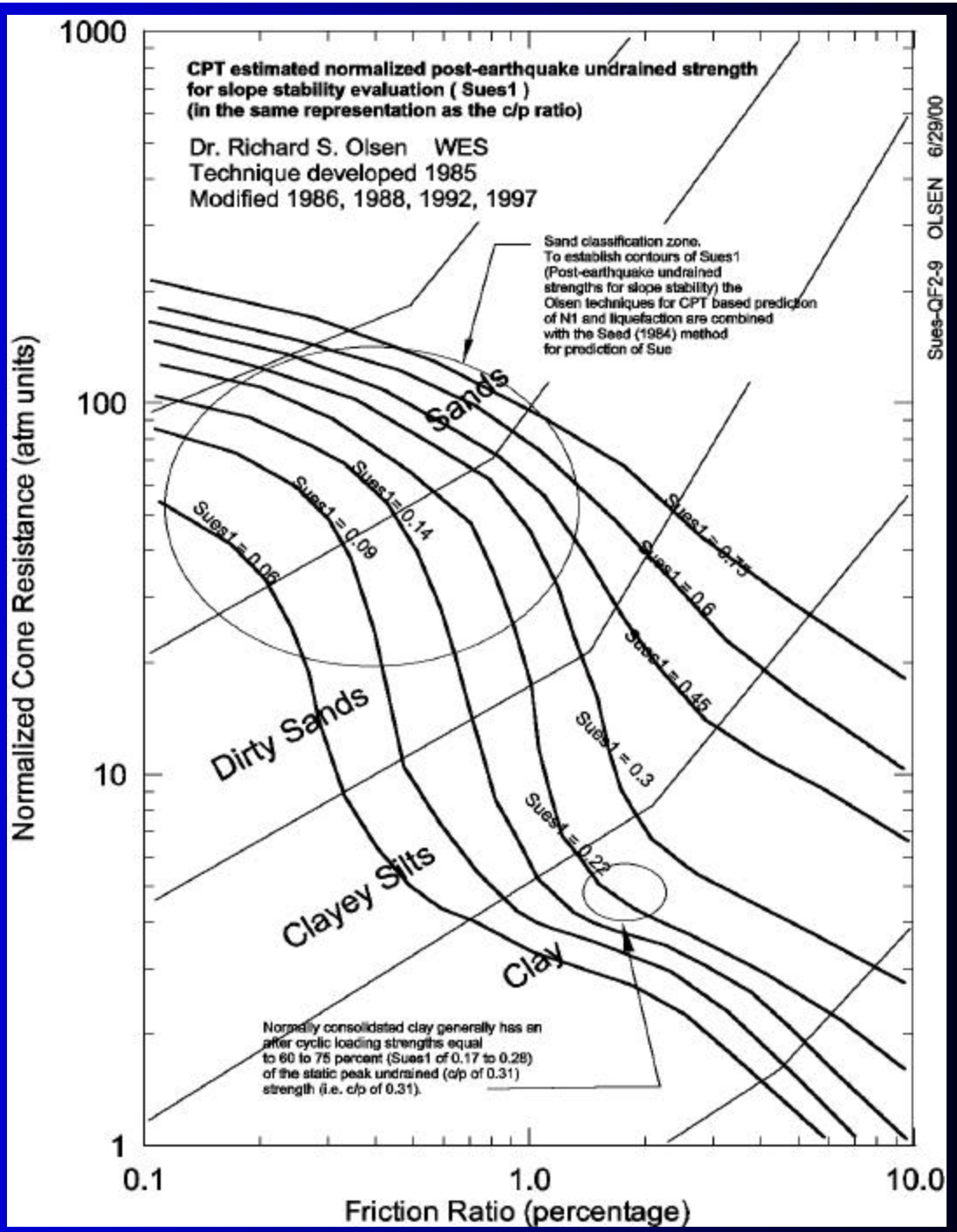
CPT estimation of liquefaction resistance (Olsen, 1984…1998)

The predicted liquefaction Cyclic Resistance Ratio (CRR) is defined as the liquefaction resistance divided by the vertical effective stress. The subscript "1" designates that this CRR_1 is for a condition at a vertical effective stress of 1 atm (approximately tsf)

NOTE: Liquefaction for this technique is assumed to represent 5% dynamic strain. Therefore, clays can experience "liquefaction like" dynamic strain levels at high shear stress levels.

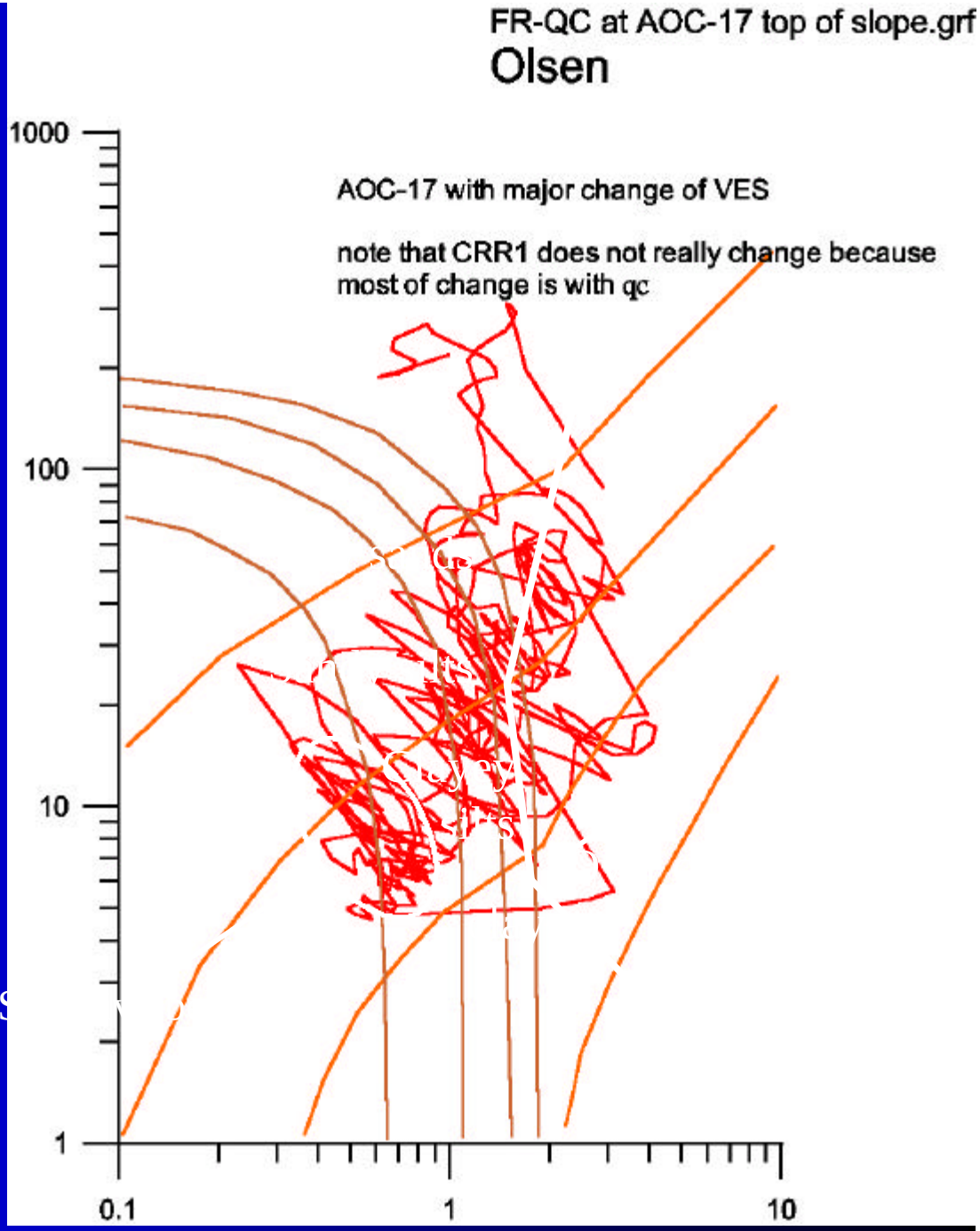
This technique used both CPT measurements to estimate liquefaction CRR_1 without the need for soil samples



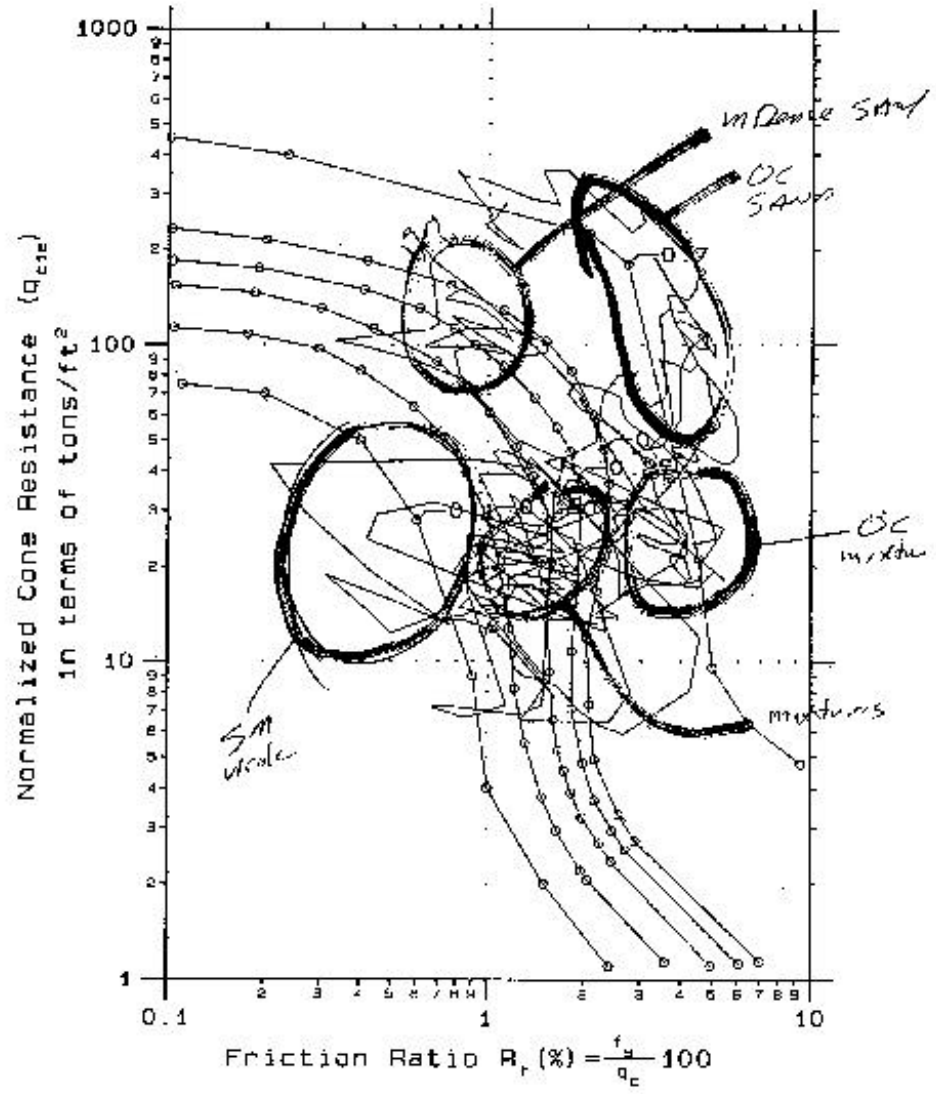

CPT estimated normalized post-earthquake undrained strength
for slope stability evaluation (Sues1)
(in the same representation as the c/p ratio)
Dr. Richard S. Olsen WES
Technique developed 1985
Modified 1986, 1988, 1992, 1997
Sand classification zone.
To establish contours of Sues1
(Post-earthquake undrained
strengths for slope stability) the
Olsen techniques for CPT based prediction
of N1 and liquefaction are combined
with the Seed (1984) method
for prediction of Sue
Sands
Dirty Sands
Clayey Silts
Clay
Sues1 = 0.06
Sues1 = 0.09
Sues1=0.14
Sues1 = 0.6
Sues1 = 0.45
Sues1 = 0.3
Sues1 = 0.22
Normally consolidated clay generally has an
after cyclic loading strengths equal
to 60 to 75 percent (Sues1 of 0.17 to 0.28)
of the static peak undrained (c/p of 0.31)
strength (i.e. c/p of 0.31).
Normalized Cone Resistance (atm units)
1000
100
10
1
0.1
1.0
10.0
Friction Ratio (percentage)
Sues-QF2-9 OLSEN 6/29/00

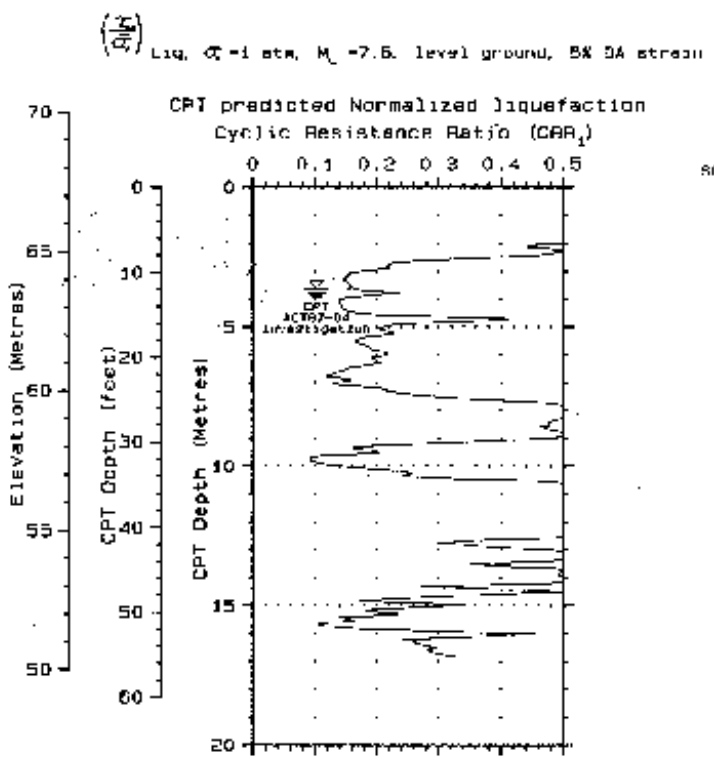
Another example of CPT tracing

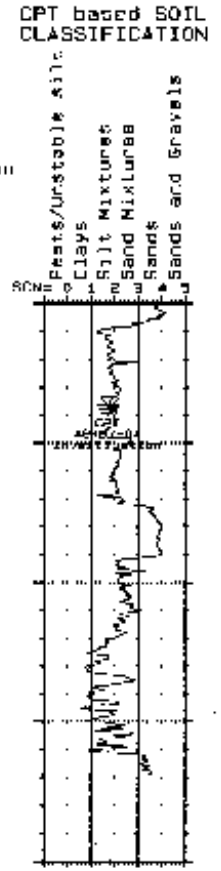
This trace is showing normally consolidated clayey silt to sand silt mixtures, of which some are sensitive



More examples of CPT tracing with corresponding depth plots

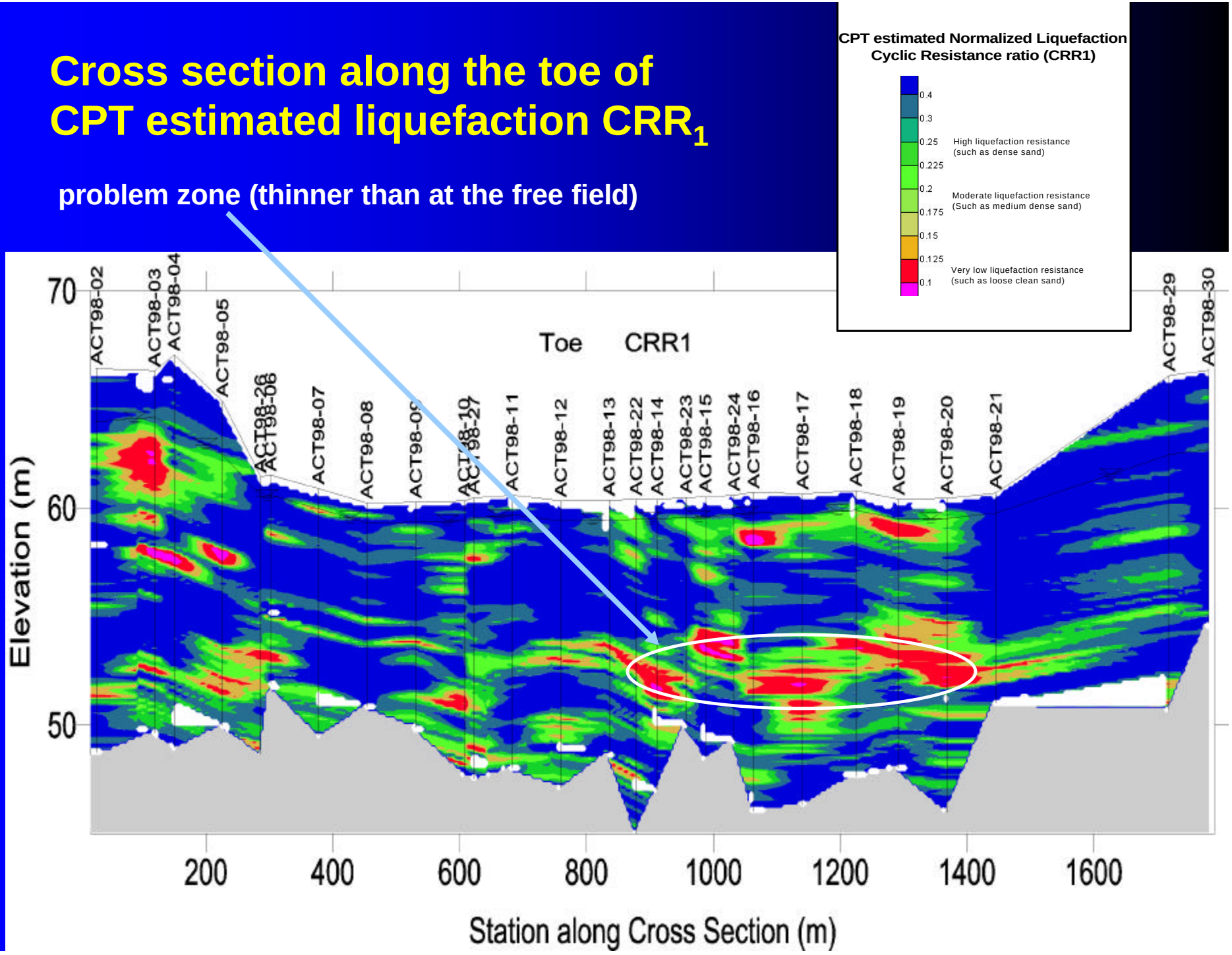






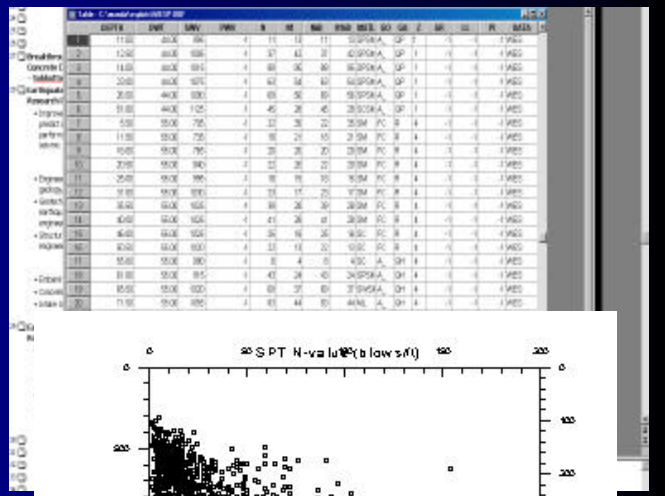
Cross section along the toe of CPT estimated liquefaction CRR_1

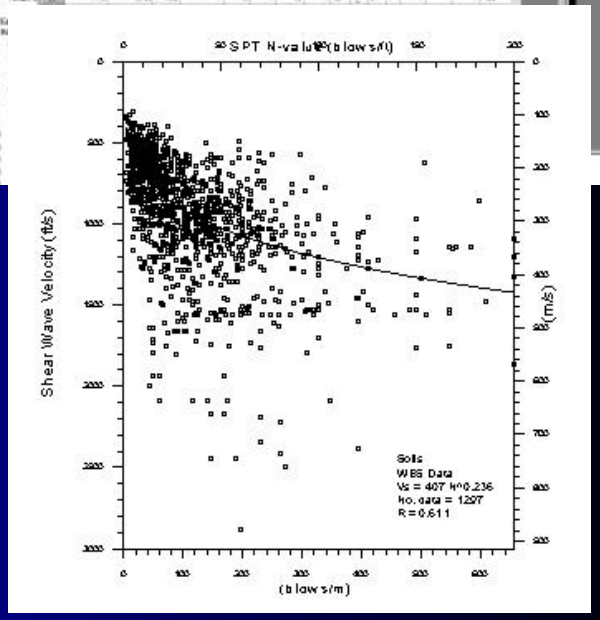
problem zone (thinner than at the free field)

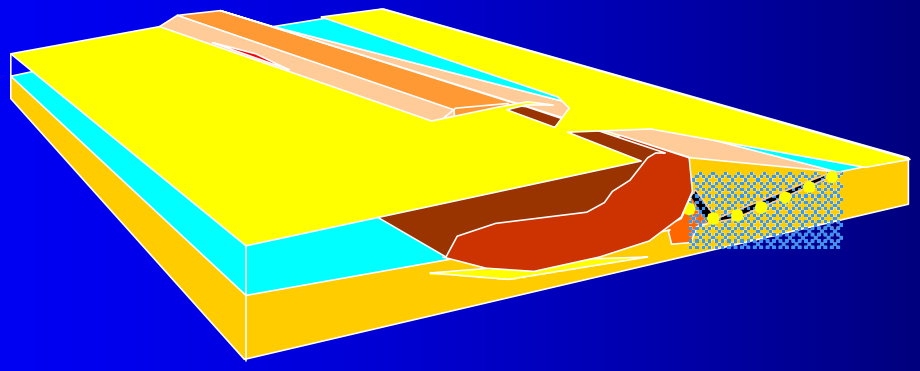


Earthquake Engineering Research Program

- Shear Wave Velocity Database - developed to support screening analysis, on web and GMAS
- Newmark Sliding Block Analysis – validated by compilation and investigation of >300 case histories, >130 dams
- Criteria for identifying liquefiable fine-grained soils - liquid limit off 3%



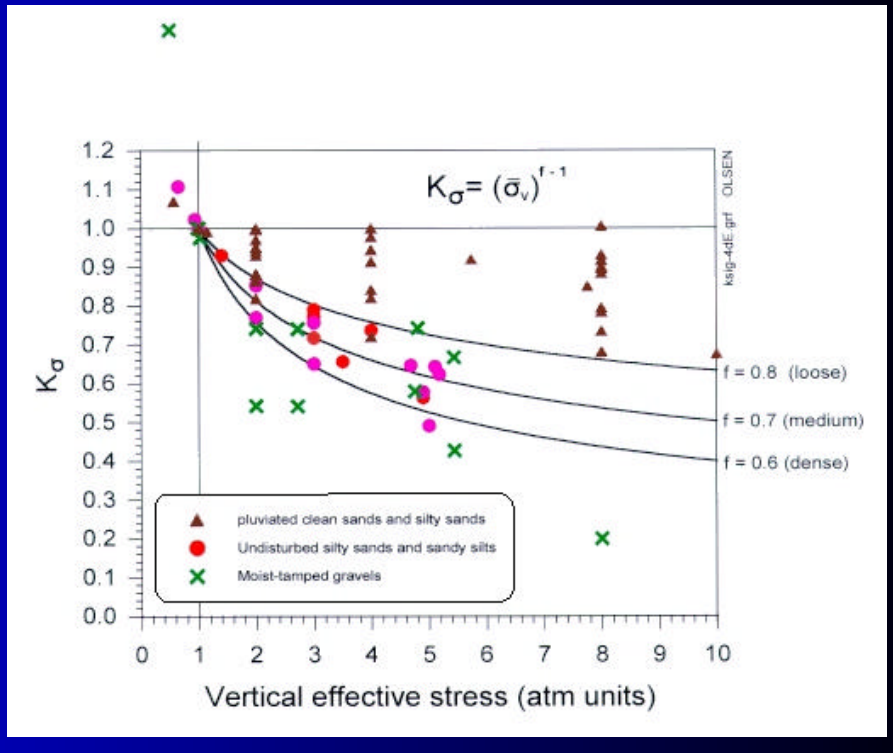




Earthquake Engineering Research Program

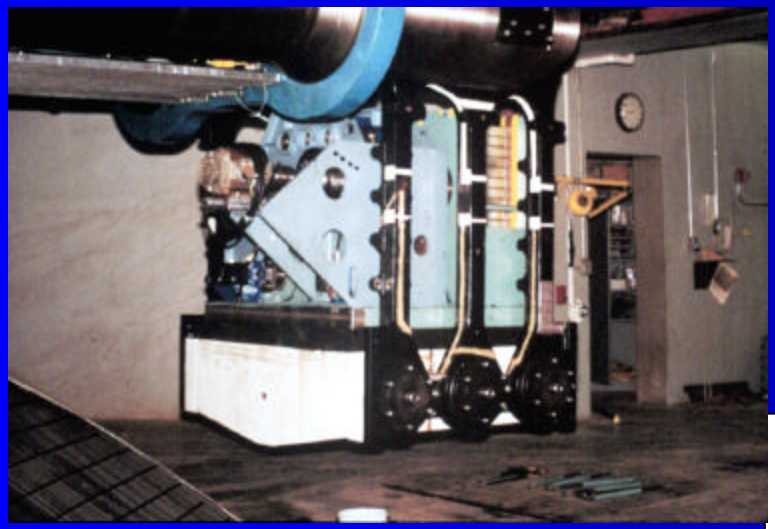
Liquefaction

- Problems with current practice
- Stress-strain behavior throughout liquefying process, not just trigger and jump to residual
- K-sigma, K-alpha
- lab vs. centrifuge, vs. field

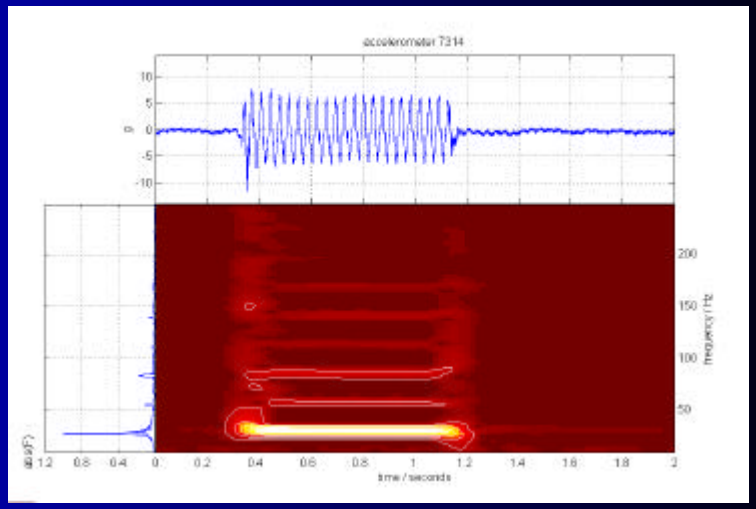


Earthquake Engineering Research Program

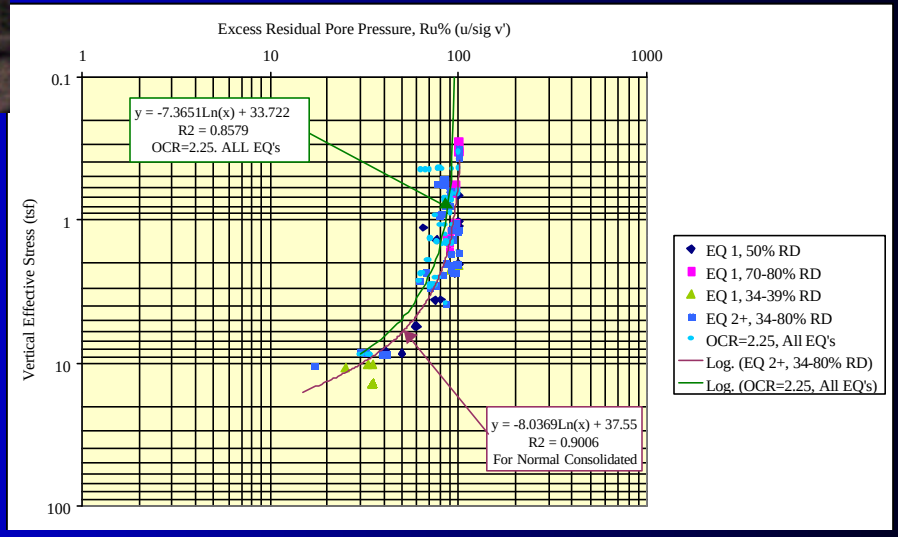
- Research into the behavior of liquefying soils



Earthquake shaker mounted on centrifuge arm



Wavelet analysis of soil response to earthquake loading response

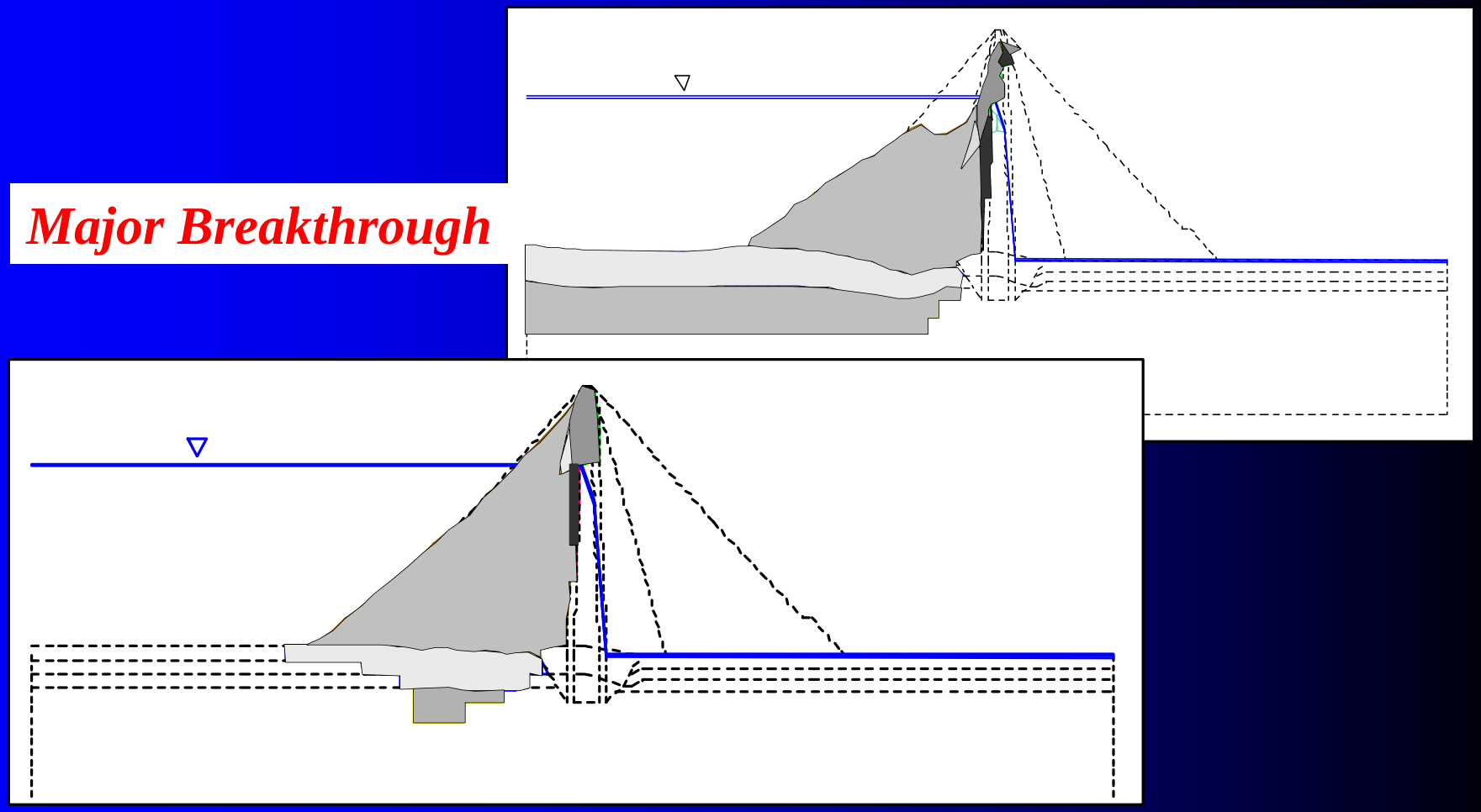


Dynamic Induced Residual Excess Pore Pressure Limit

Earthquake Engineering Research Program

- Liquefaction: Improve state-of-the-practice for determining confining stress effects

Major Breakthrough



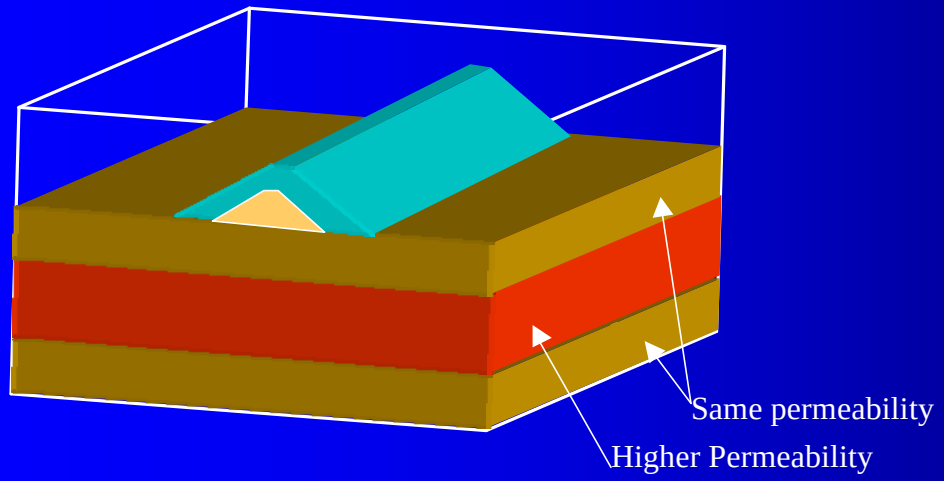
Effect of current findings on limiting depth of liquefaction, Success Dam, CA

Earthquake Engineering Research Program

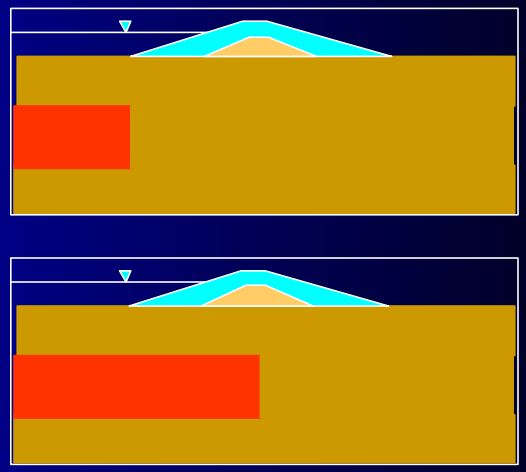
- **Failure Mechanisms and Damage:** Improve state-of-the-practice for determining performance of dams in response to liquefaction of soils

Slide in Lower San Fernando Dam - 1971

Centrifuge (physical) modeling



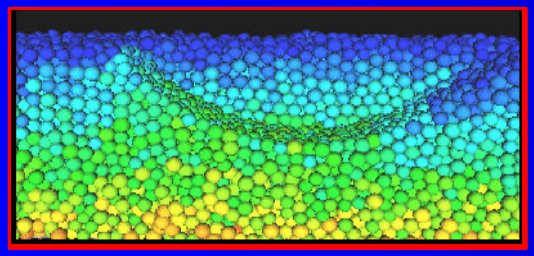
Effect of layer permeability



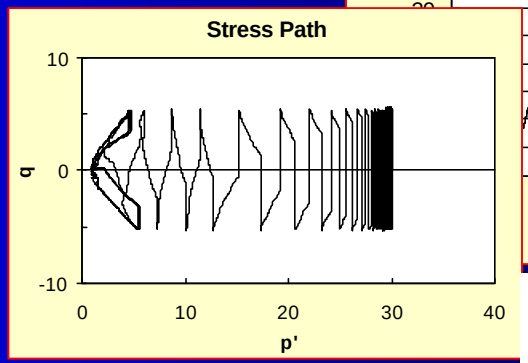
Extent of liquefiable layer

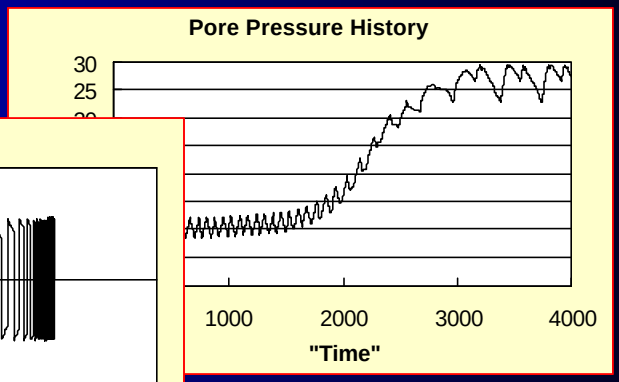
Earthquake Engineering Research Program

- **Seismic Stability and Deformations of Earth Structures and Foundations**
  - Use of numerical modeling to improve the estimation of post-earthquake deformation.
  - Fully coupled model, pore pressure generation with stress

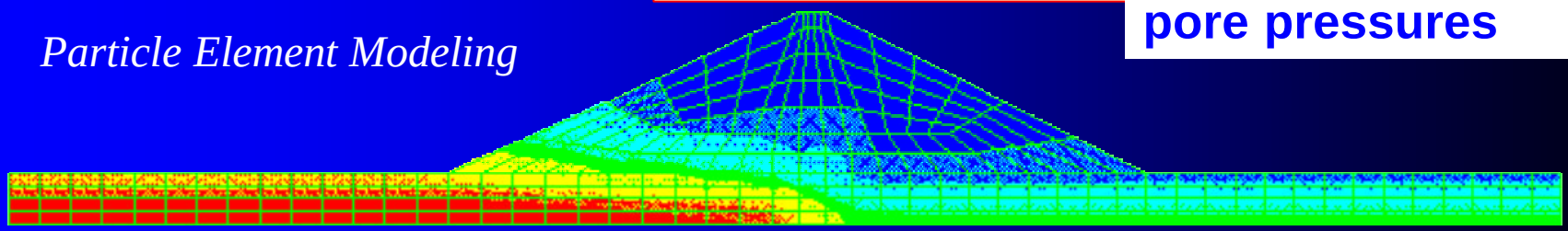


Particle Element Modeling





Coupled stress and pore pressures

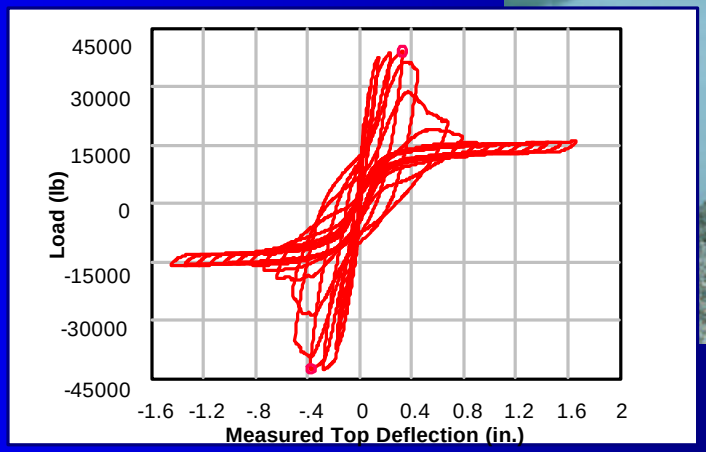


Idealized dam initial pore water pressure

Earthquake Engineering Research Program

Appurtenant Structures: Products & Accomplishments

- CSLIP – windows based program for computing seismically-induced deformations in retaining walls, for performance based designs
- Quantified ductility and analysis procedures
  - Rectangular Intake Towers
  - Complex Intake Towers
  - Outlet Works Gate Piers



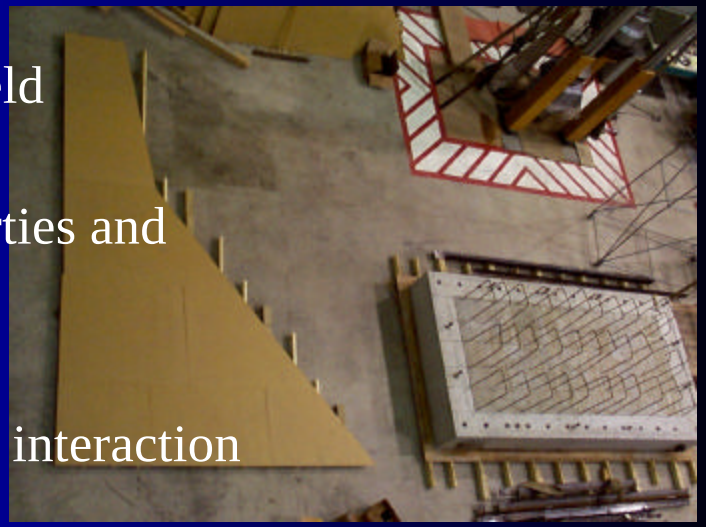
Cyclic loading response of intake tower model

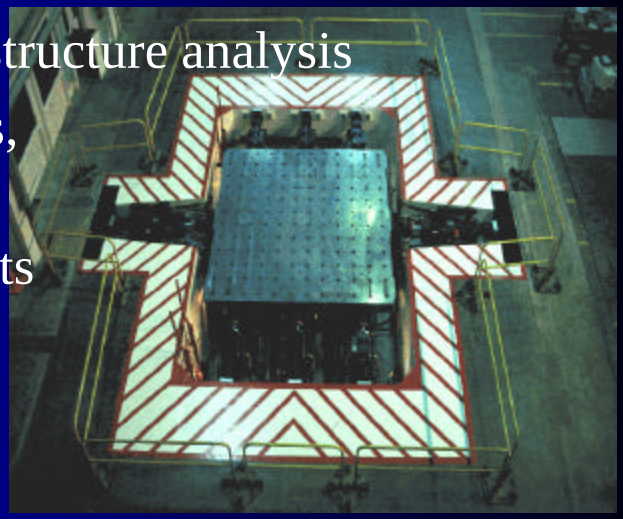
Gathright Tower

Earthquake Engineering Research Program

Concrete Dams - Summary

- Hydrodynamic loads on concrete dams – field procedures
- Roller-compacted concrete – seismic properties and construction procedures
- Nonlinear analysis code for cracking
- Nonlinear analysis for monolith to monolith interaction
- Nonlinear analysis for sliding on lift joints
- Comprehensive code for reservoir-foundation-structure analysis
- Software to translate FEM output into moments, shears, and thrusts
- Software to interpret time history analysis results



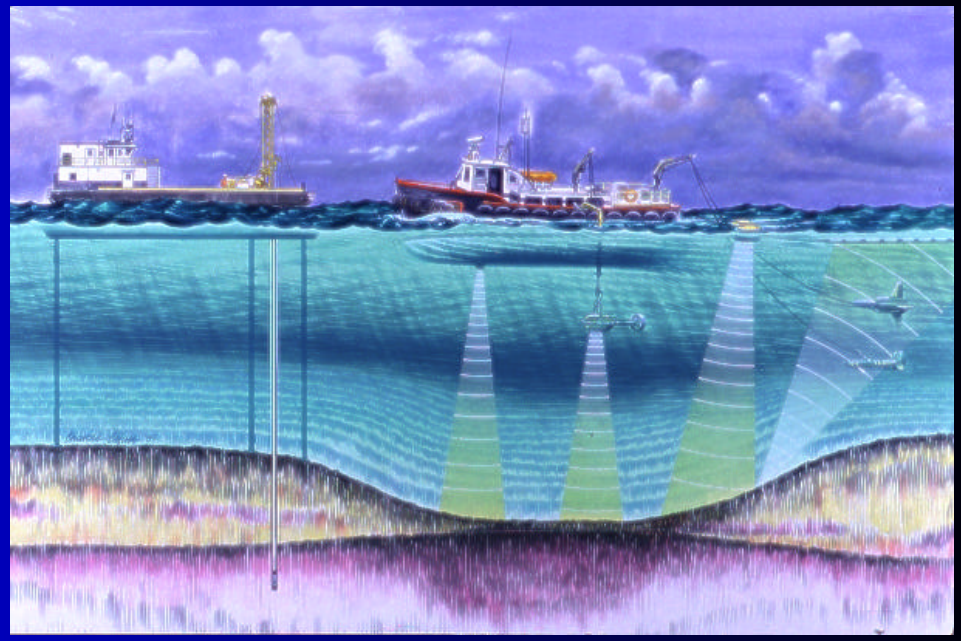


CERL Triaxial Earthquake Shock Simulator

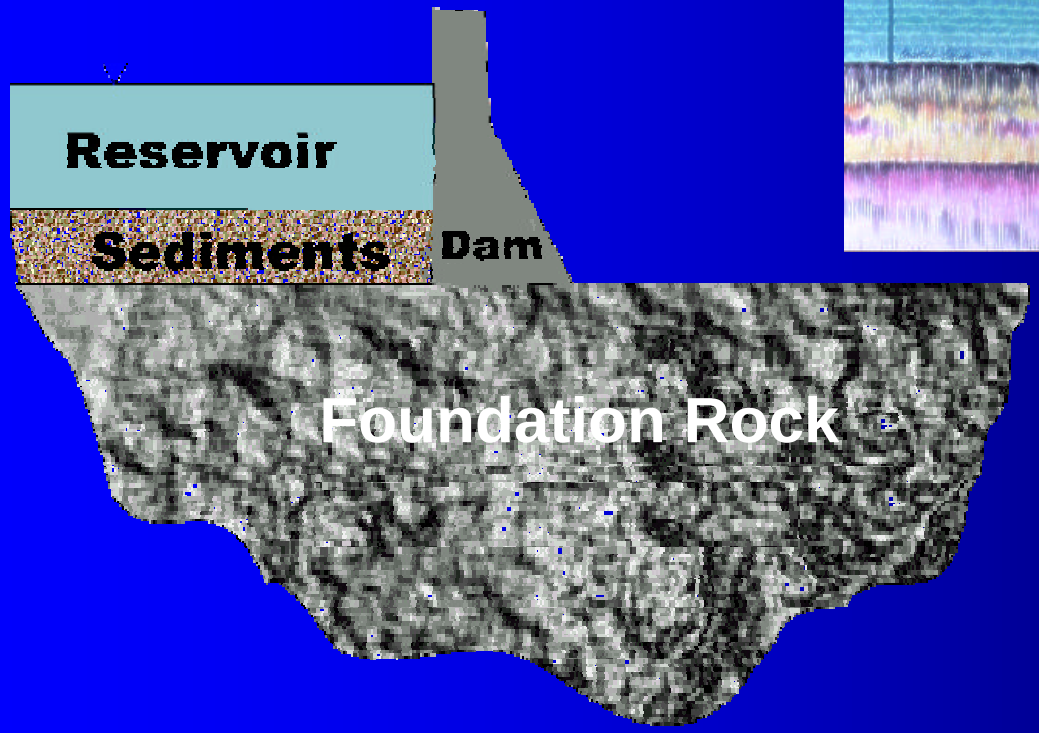
Folsom Dam, CA

Breakthrough in Concrete Dam Research

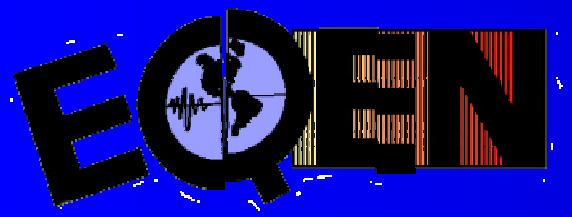
Subbottom Absorption

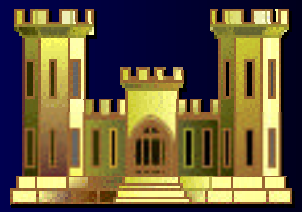


Subbottom Profiling System



Earthquake Engineering Research Program





Overview & Accomplishments

End