USACE Earthquake Research & Implementation Activities

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US Army Corps of Engineers
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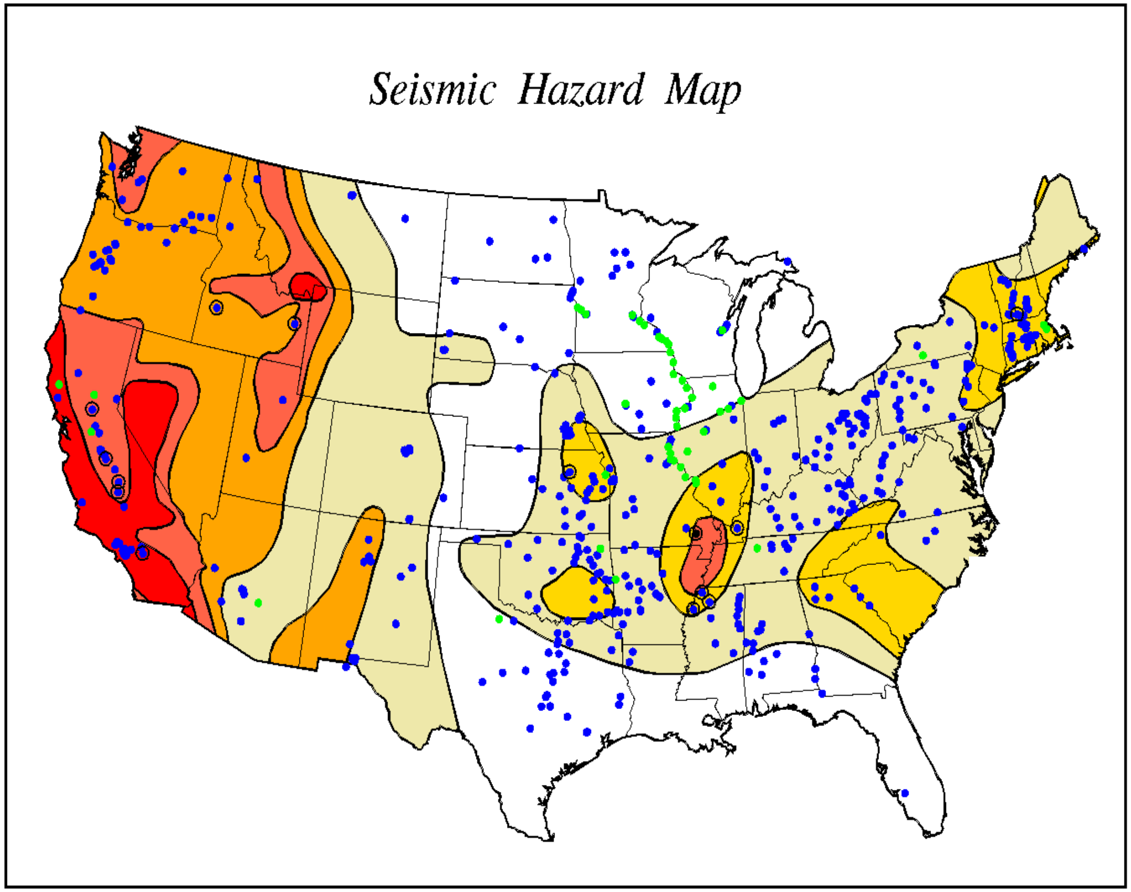
Earthquakes & Dams



- 162 COE dams in high seismic areas (2 and above) subject to damage
- Most built in 1940's and 1950's with no seismic design
- Seismic design for liquefaction came into practice in the late 1970's early 1980's

Earthquake Engineering

Near failure of Lower San Fernando Dam

San Fernando Earthquake - 1971

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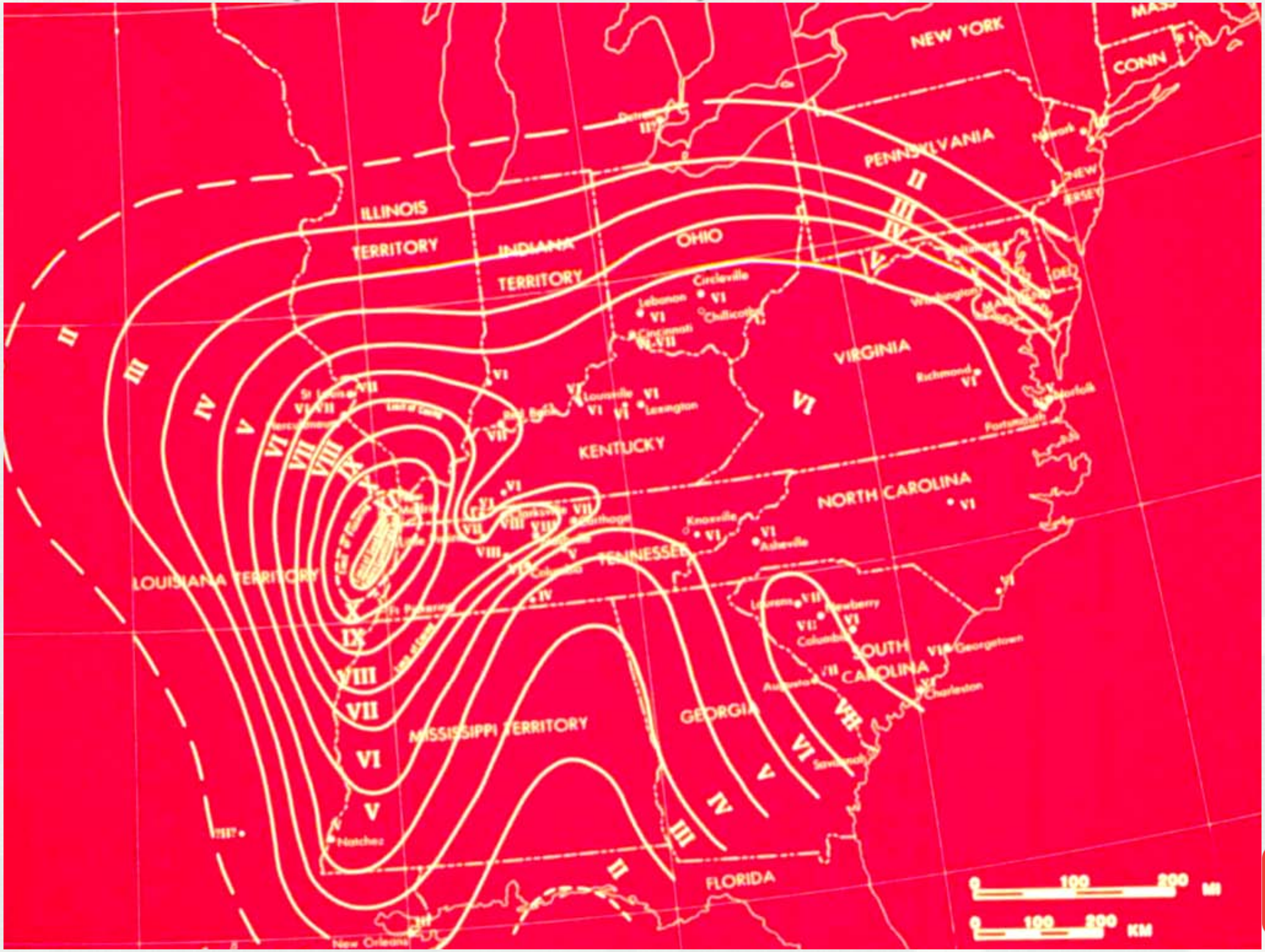
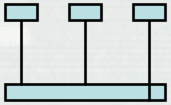
New Madrid Earthquakes, 1811-1812 (Isoseismals)



Earthquake Effects

- Transient loading or shaking
- Changes material properties
- Settlement
- Liquefaction
- Permanent ground displacement
- Dynamic response
  - Each *thing* has it own shaking response

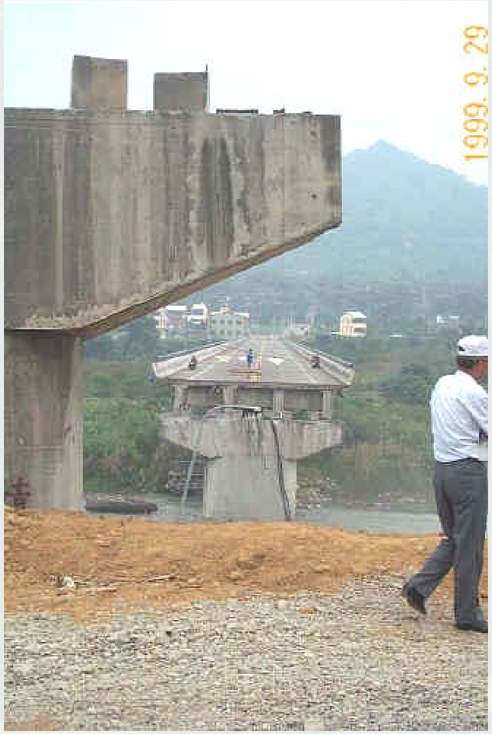


Earthquake Effects

- Liquefaction
  - ▶ Sand boils
  - ▶ Settlement
  - ▶ Slope failures

Earthquake Effects

- Permanent Ground Displacement



>15 ft of thrust faulting created this waterfall and destroyed bridge

What Levees Are

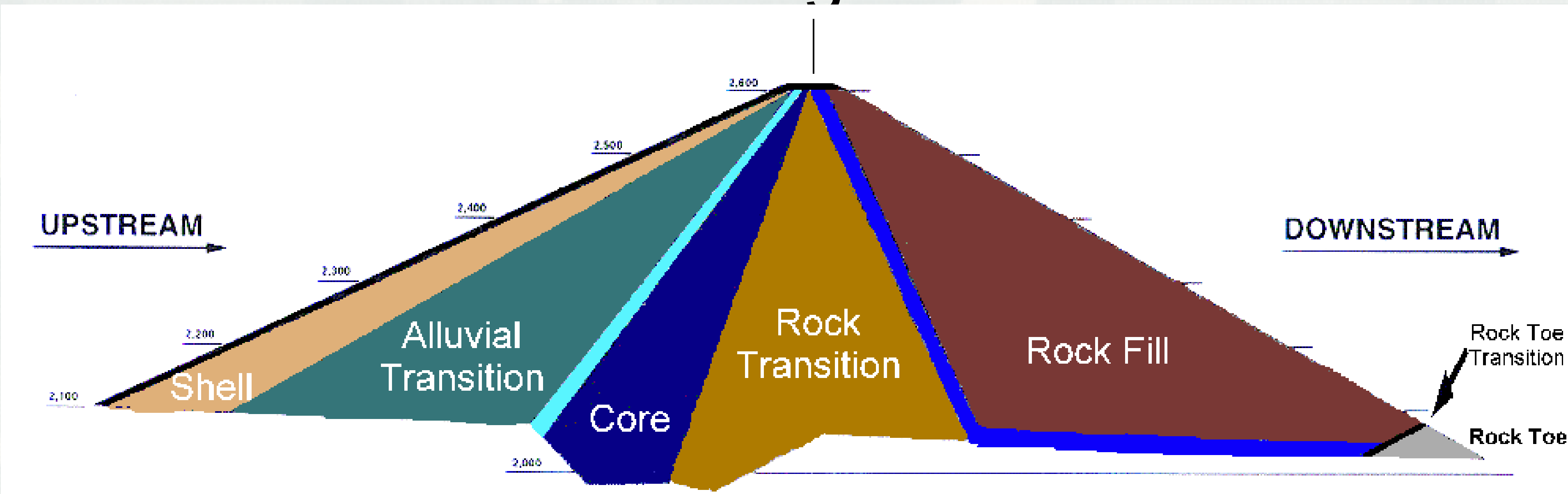
- Permanent structures (earthen, concrete/wood/steel walls, combination)
- Long
- Intended for ***temporary*** retention of streams during high water events
- Corps responsible for over 14,000 miles of levees

What Levees Are ***Not***

- Dams
  - They are not typically zoned to withstand long-term retention/seepage
  - They do not generally include deep seepage cut-off features
  - They are not typically built to withstand extreme, rare loading events (e.g., earthquakes, waves or surges)
  - They are very rarely designed to withstand overtopping flow

Levees are, however, expected to protect populations and property in the same manner as dams, for brief exposure time !

Seismic Considerations in Dam Design



▪ Freeboard	design pools, analysis -> design geometry
▪ Crack stoppers	filters, transition zones, drains, material properties
▪ Seepage & pore pressure control	relief well, weep holes
▪ Foundation stability	siting, in situ: replacement, improvement
▪ Embankment stability	deformation and dynamic material properties

Possible Earthquake Induced Modes of Failure

- Disruption of levee by fault movement in foundation
- Loss of freeboard due to settlement or differential tectonic ground movements
- Slope failures induced by ground motions
- Sliding of levee on weak foundation materials
- Piping failure through cracks induced by ground movements
- Overtopping of levee due to seiches in waterway
- Overtopping of levee due to slides or rockfalls into waterway

Vulnerability Assessment

- Seismic vulnerability of levees and dams are similar and are evaluated as such
  - ▸ Liquefaction triggering analysis
  - ▸ Seismic slope stability analysis
  - ▸ Post-earthquake stability analysis
  - ▸ Deformation analysis, if warranted

Seismic Vulnerability Classes for Levees

From CA Dept of Water Resources Draft Guidance Document for Urban Levees (in Review)

Table 6-2. Seismic Vulnerability Classes.

Amount of Deformation	Significant Damage to Internal Structures (e.g. Cutoff Walls)	Remaining Freeboard for Post Seismic Flood Evaluation (2-Year Flood Water Surface Elevation)	Post Seismic Flood Protection Ability
<1'	No	>1'	Probably Uncompromised
1' to 3'	Possibly	>1'	Possibly Compromised
3' to 10'	Likely if existing	None	Likely Compromised
Unlimited (flow side condition)	Yes	None	Compromised

Current Guidance

- **ER 1110-2-1806** (Earthquake Design and Evaluation for Civil Works Projects, July 1995 - under revision)
- **ER 1110-2-1156** (Safety of Dams - Policy and Procedures – in final review)
- **EM 1110-2-6000** (Selection of Design Earthquakes and Associated Ground Motions – in final review)
- **EM 110-2-6001** (Seismic Analysis of Embankment Dams – incl. levees – ongoing)
- **EM 1110-2-1913** (Design and Construction of Levees)

http://www.usace.army.mil/publications/

Design Earthquakes and Ground Motions

Motions selected on performance criteria

Performance criteria :

- Safety, loss of life **MDE = MCE**
- Economic considerations
  - Catastrophic failure **MDE < MCE**
  - Little or no damage **OBE**

Inspection After Earthquake

- Guidance similar to that for dams

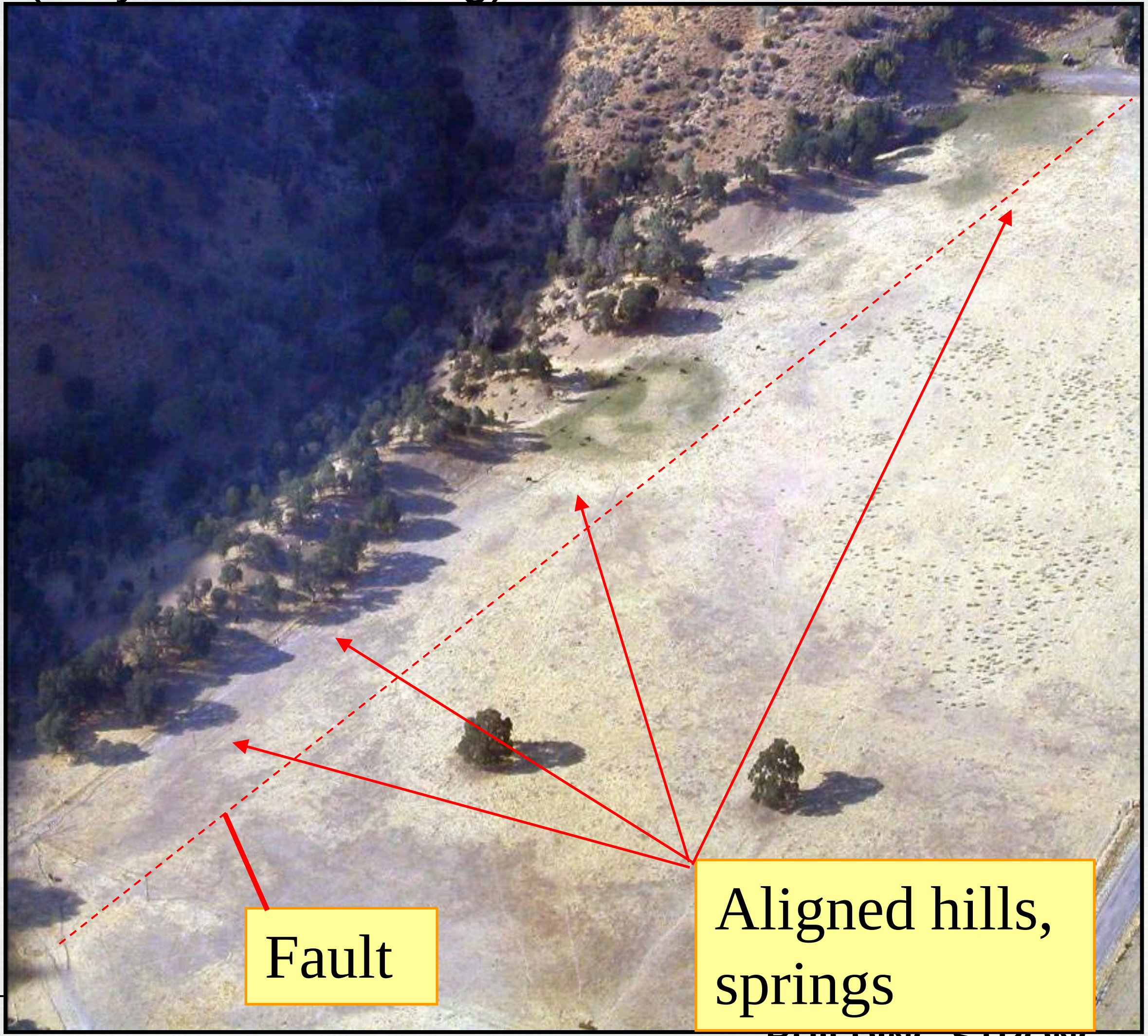
(paraphrased from USSD Guidelines for Inspection of Dams After Earthquakes, 2003)

- If an earthquake is felt at or near the dam (levee), or has been reported to occur, with:
  - M ≥ 4.0 w/in 25 miles,
  - M ≥ 5.0 w/in 50 miles,
  - M ≥ 6.0 w/in 75 miles,
  - M ≥ 7.0 w/in 125 miles, or
  - M ≥ 8.0 w/in 200 miles, …immediate inspection is indicated.

Isabella Dam

Seismic investigation began before sPRA (very limited funding)

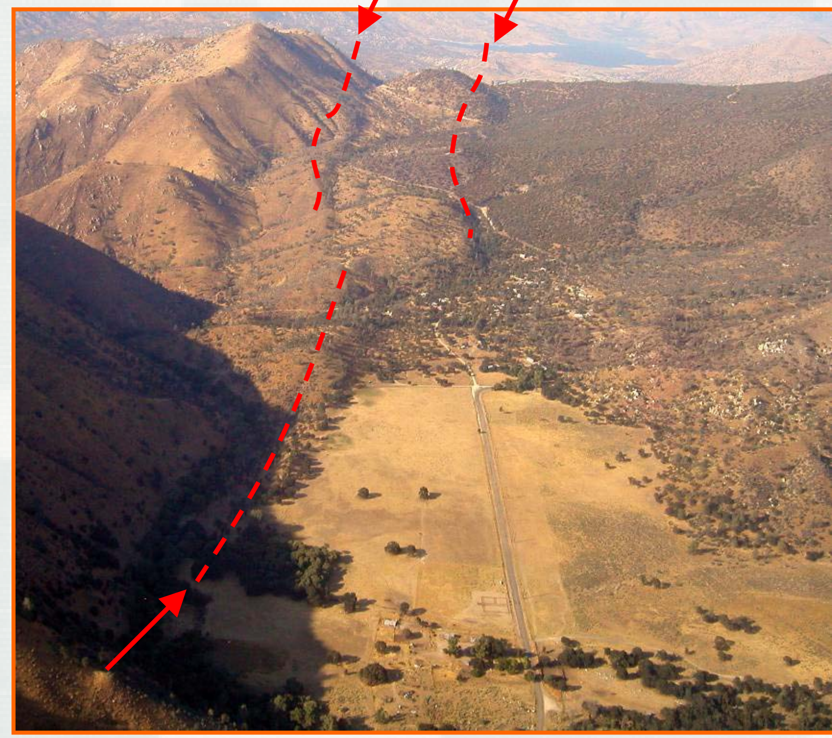
Initial site visit observed features apparently inconsistent with previous belief of inactivity of KCF



Isabella Dam

Kern Canyon Fault - initial site visits

North of dam

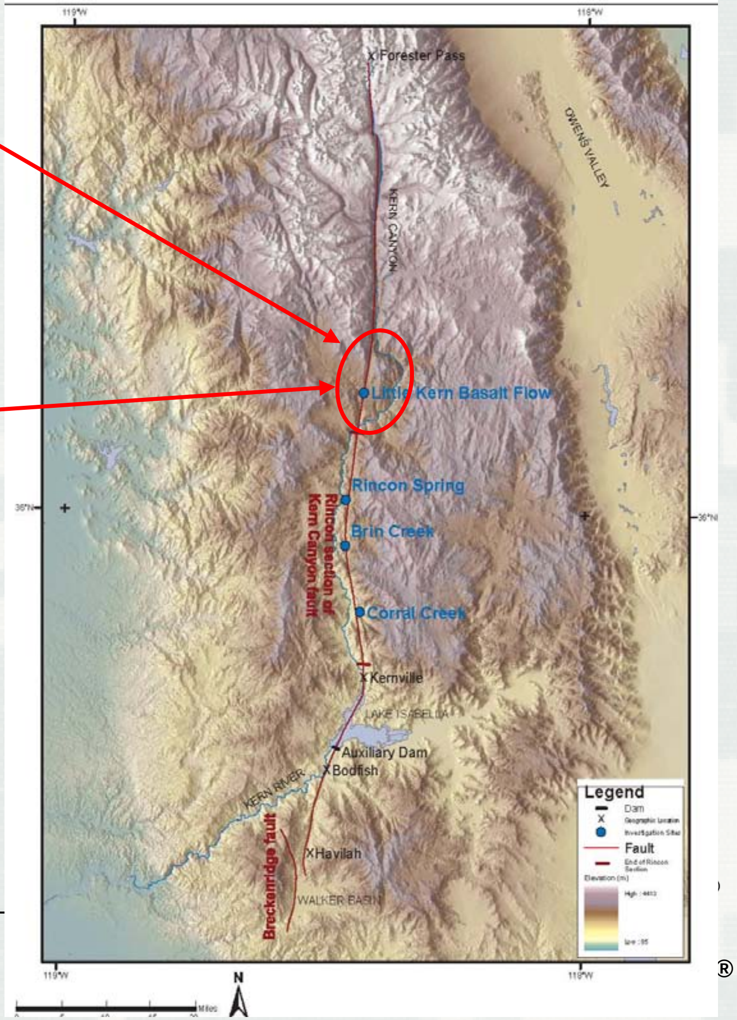


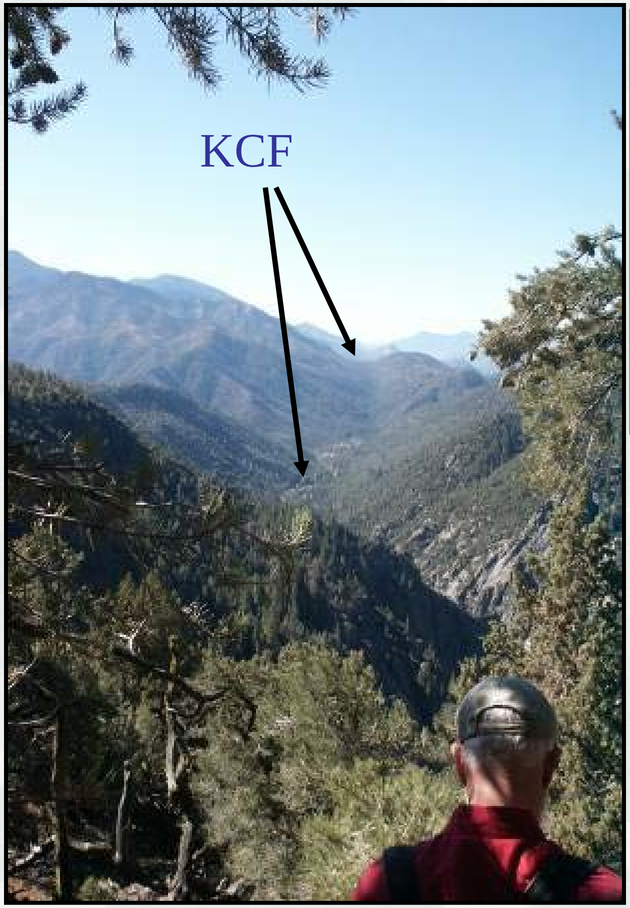
South of dam

Recent offset?

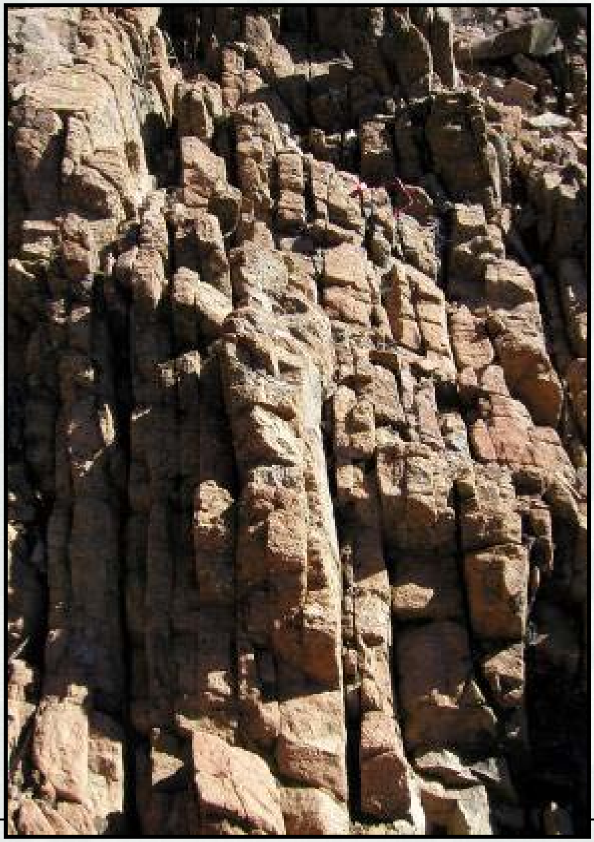
Isabella Dam

3.5 ma lava flow that was "unfaulted"(?)





- Lava *is* faulted, sheared
- This established that the previous primary evidence of non-activity is invalid

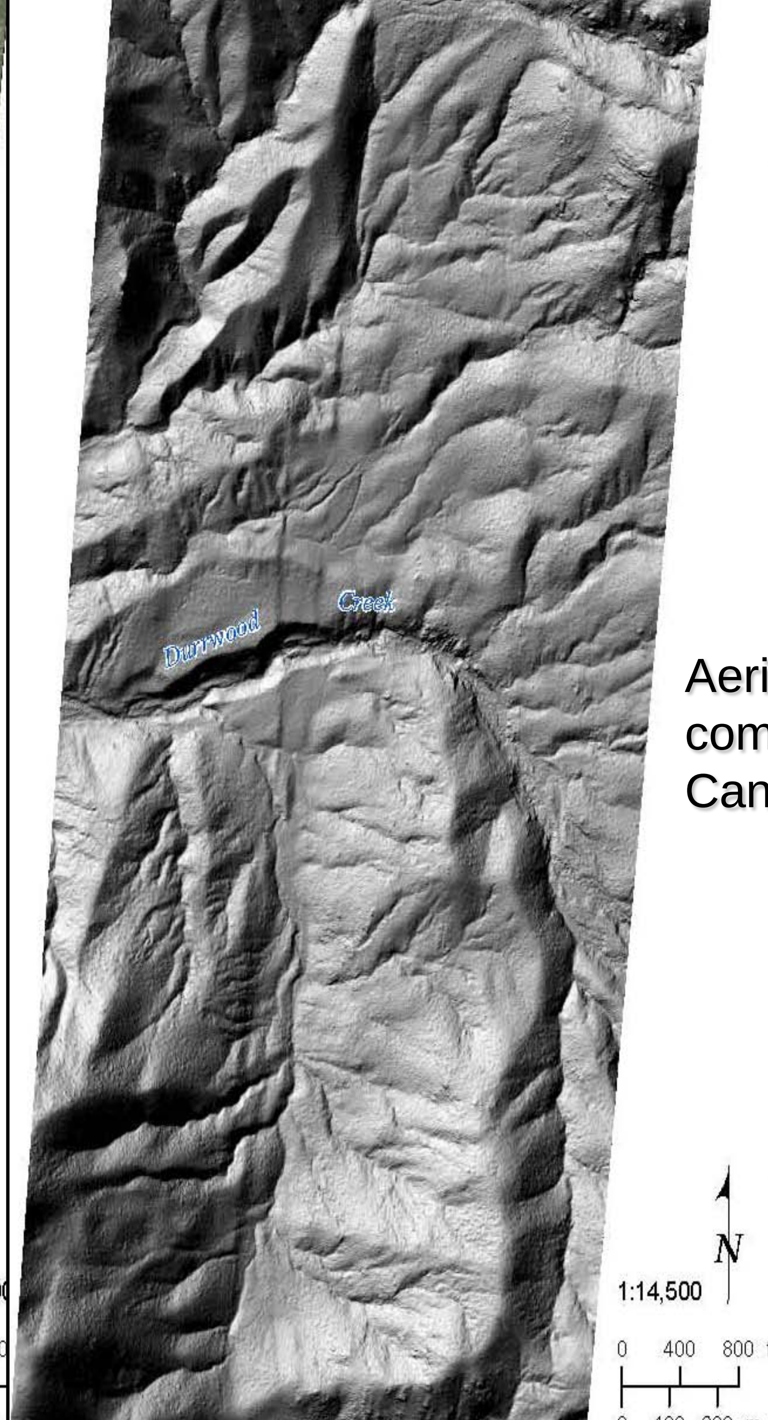


View South

Isabella Dam

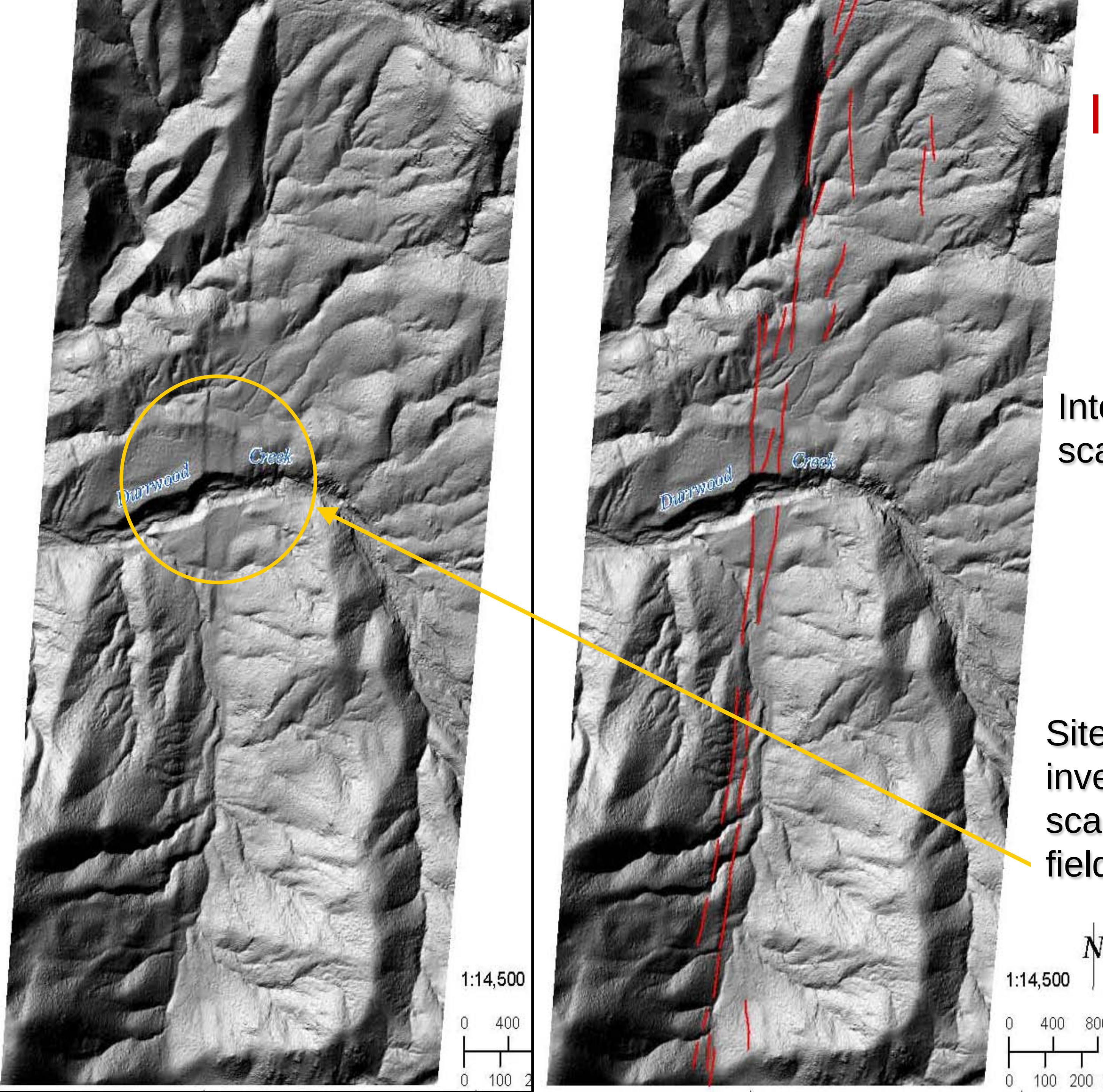
Established active since 3 ma, but how recently?

Isabella Dam



Aerial Photo/ LiDAR comparison – Kern Canyon Fault

Isabela Dam



Interpreted LiDAR (fault scarps)

Site had been investigated, but several scarps not seen even in field

NG®

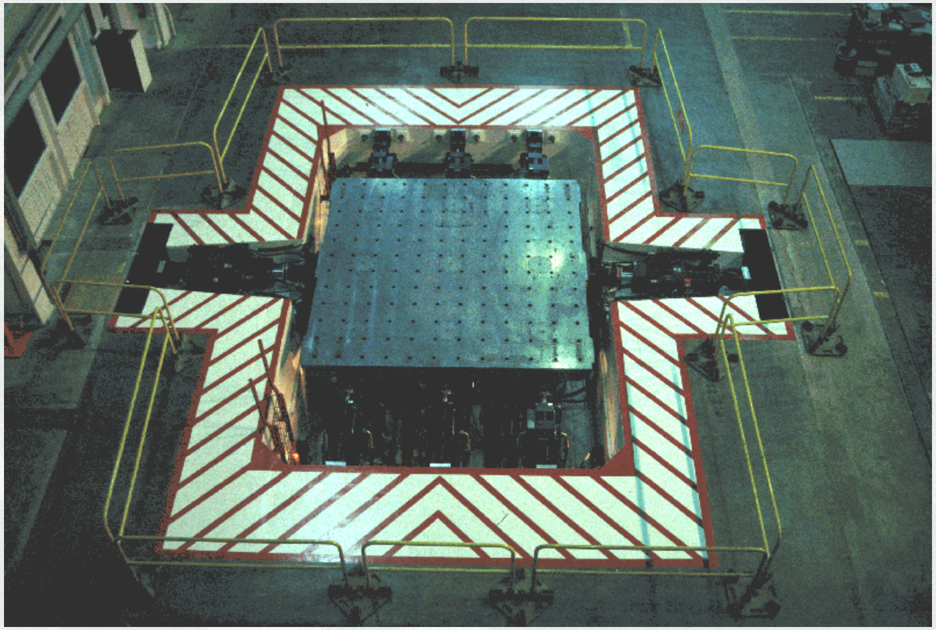
Capable Fault

- **USNRC** – Exhibits one or more of the following characteristics (10 CFR 100 Appendix A) :
  - ► Movement at or near the ground surface at least once within the past 35,000 years or movement of a recurring nature within the past 500,000 years; or
  - ► Macroseismicity instrumentally determined with records of sufficient precision to demonstrate a direct relationship with the fault; or
  - ► A structural relationship to a capable fault according to characterizes (1) or (2) above, such that movement on one could be reasonably expected to be accompanied by movement on the other
- **California Division of Mines and Geology**
  - ► Surface displacement within *Holocene* time (about the last 10,000 years)

Capable Fault

- **USBR**
  - Relative displacement within the past 100,000 years
- **USACE** (ETL 1110-2-301 26 Aug 1983)
  - Movement at or near the ground surface at least once within the past 35,000 years
  - Macroseismicity ($\geq$3.5 magnitude) instrumentally determined with records of sufficient precision to demonstrate a direct relationship with the fault
  - A structural relationship to a capable fault such that movement on one could be reasonably expected to be accompanied by movement on the other
  - Established patterns of microseismicity that define a fault and historic macroseismicity that can be reasonably associated with that fault

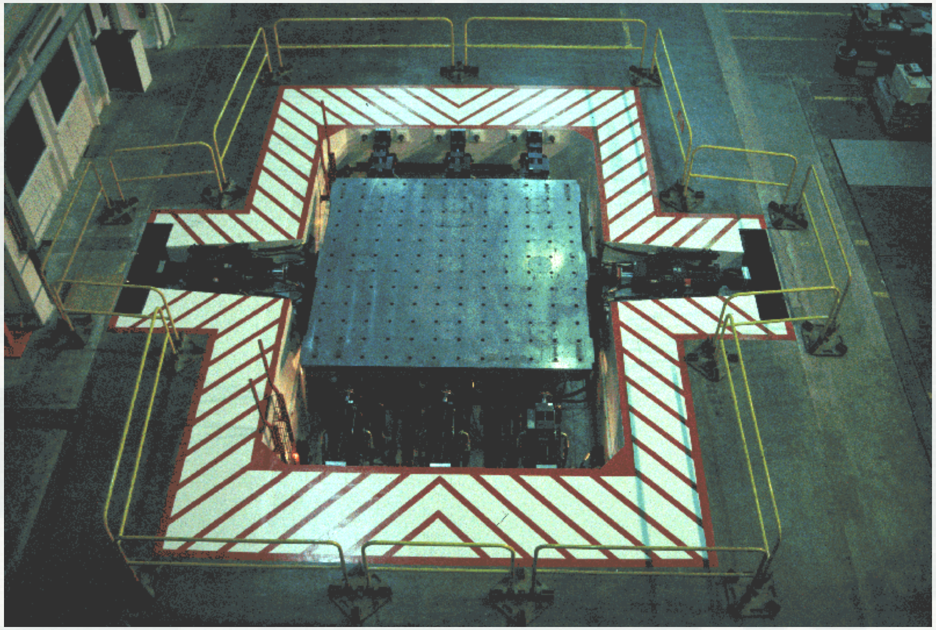
Triaxial Earthquake and Shock Simulator



- TESS can simulate a wide variety of controlled, realistic motion environments
- Time and frequency domain defined tests
- Controlled six degree of freedom motion
- High-frequency, high-amplitude motion, with large payloads
- Ideal for seismic, random and shock-induced vibration testing

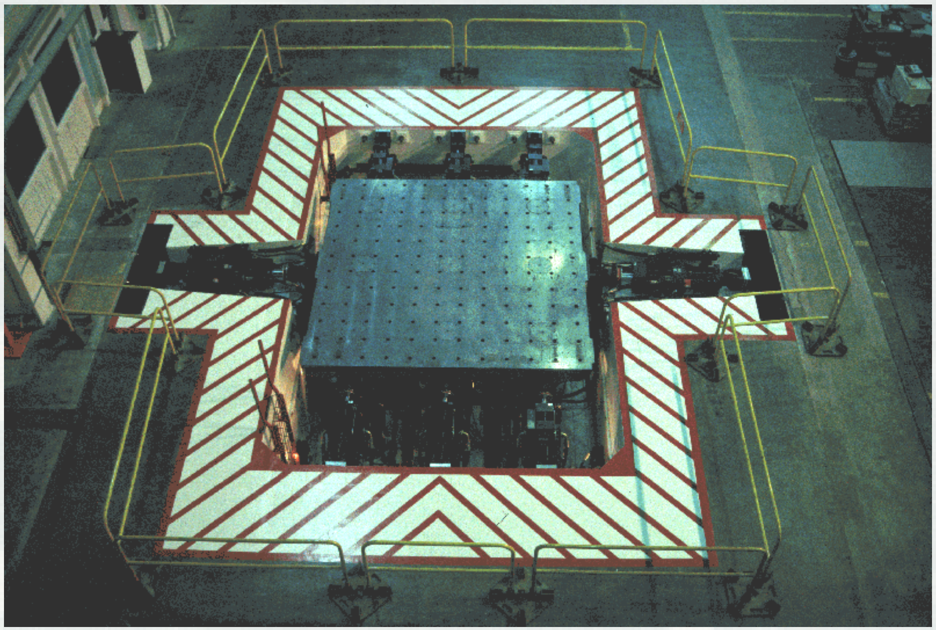
- **Technical Personnel**
  - **Ghassan Al-Chaar: Structural Engineer w/experimental experience**
  - **Steve Sweeney: Structural Engineer w/experimental experience**
  - **Jonathan Trovillion: Materials Engineer who operates the TESS**
  - **Jim Wilcoski: Structural Engineer w/shock & vibration experience**

Triaxial Earthquake and Shock Simulator



- TESS Platform Dimensions
  - 12 ft square
  - Large test fixtures have extended this surface
- Force:
  - X-axis: 450,000 lb
  - Y-axis: 150,000 lb
  - Z-axis: 810,000 lb
- Table Accelerations w/15 kip Payload:
  - X-axis: 15 g
  - Y-axis: 4 g
  - Z-axis: 30 g
- Displacements:
  - X-axis: 2.75 in. (5.5 in. p-p)
  - Y-axis: 6.00 in. (12 in. p-p)
  - Z-axis: 1.375 in. (2.75 in. p-p)

Tests That Illustrate TESS Capabilities

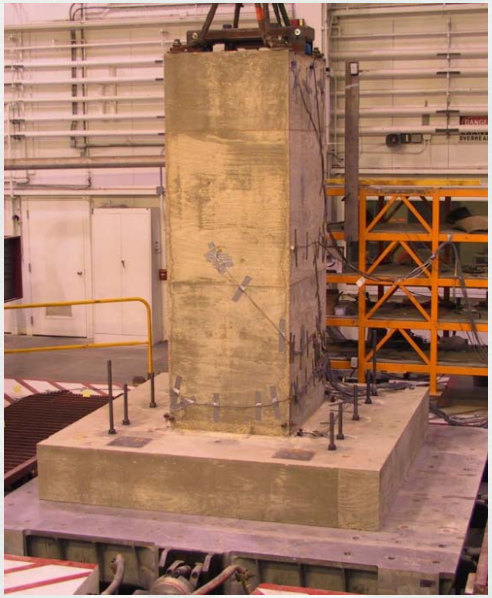


- Koyna Dam
- Intake Tower
- Bridge Abutment
- Cold-Formed Steel
- High-Voltage Switch
- IBM Mainframe Server
- Navy Crane Pod
- Power Transformer Bushing

Seismic Testing of a 1/20 Scale Model of Koyna Dam

- Customer: ERDC-GSL
- Objective: Cast and test with sinusoidal motions a 1/20 scale model of the Koyna dam.
- Results:
  - ▸ 200 psi mix design presented unique challenges for formwork
  - ▸ Unique formwork design
  - ▸ Cast on the TESS

Seismic Testing of 1/8th Scale Model of an Intake Tower

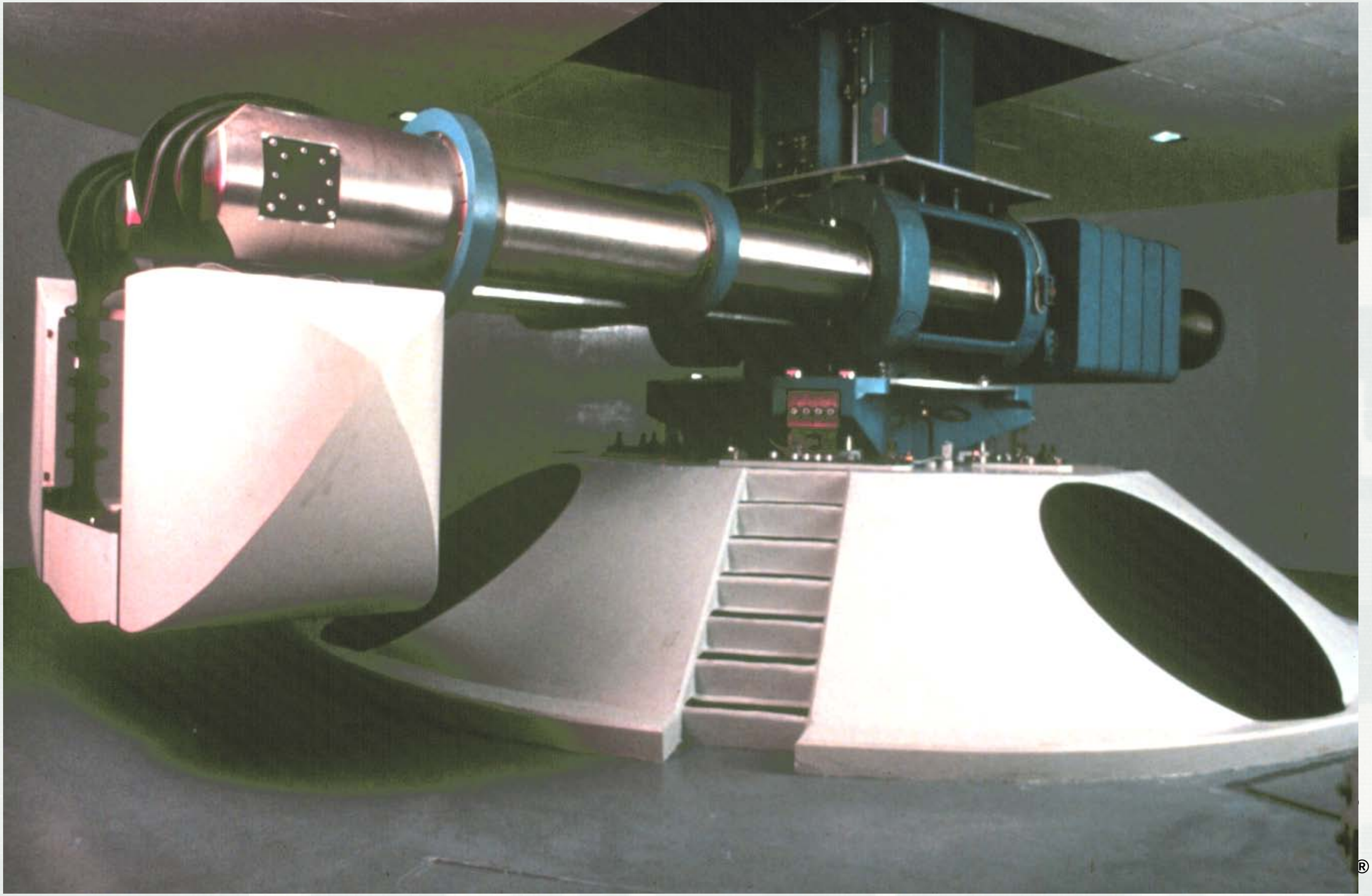


- Customer: ERDC-GSL
- Objective: Define Failure Mode and Progression along cold-joint
- Results:
  - Scaling relations required large vertical load for gravity effects
  - 12 g, 16 Hz sinusoidal motion for failure progression
  - Documented failure development and progression along cold-joint

Seismic Testing of Block Wall & Geotextile Bridge Abutment System

- Customer: U of WM
- Objective: Define the Failure Mode and Amplitude of Failure to Compare with Analytical Models
- Results:
  - Largest model tested on the TESS at 250,000 lb
  - Good control of the TESS
  - Sinusoidal motion at 1.5 and 3.0 Hz
  - Model performed well with resonant response at bearings and failure of wall
  - Measured, pressures, strains, accelerations & deformations

CENTRIFUGE



THEORY

$$F = ma$$
$$(a = g)$$

g (gravity)

$$F = ma$$
$$(a = Ng)$$

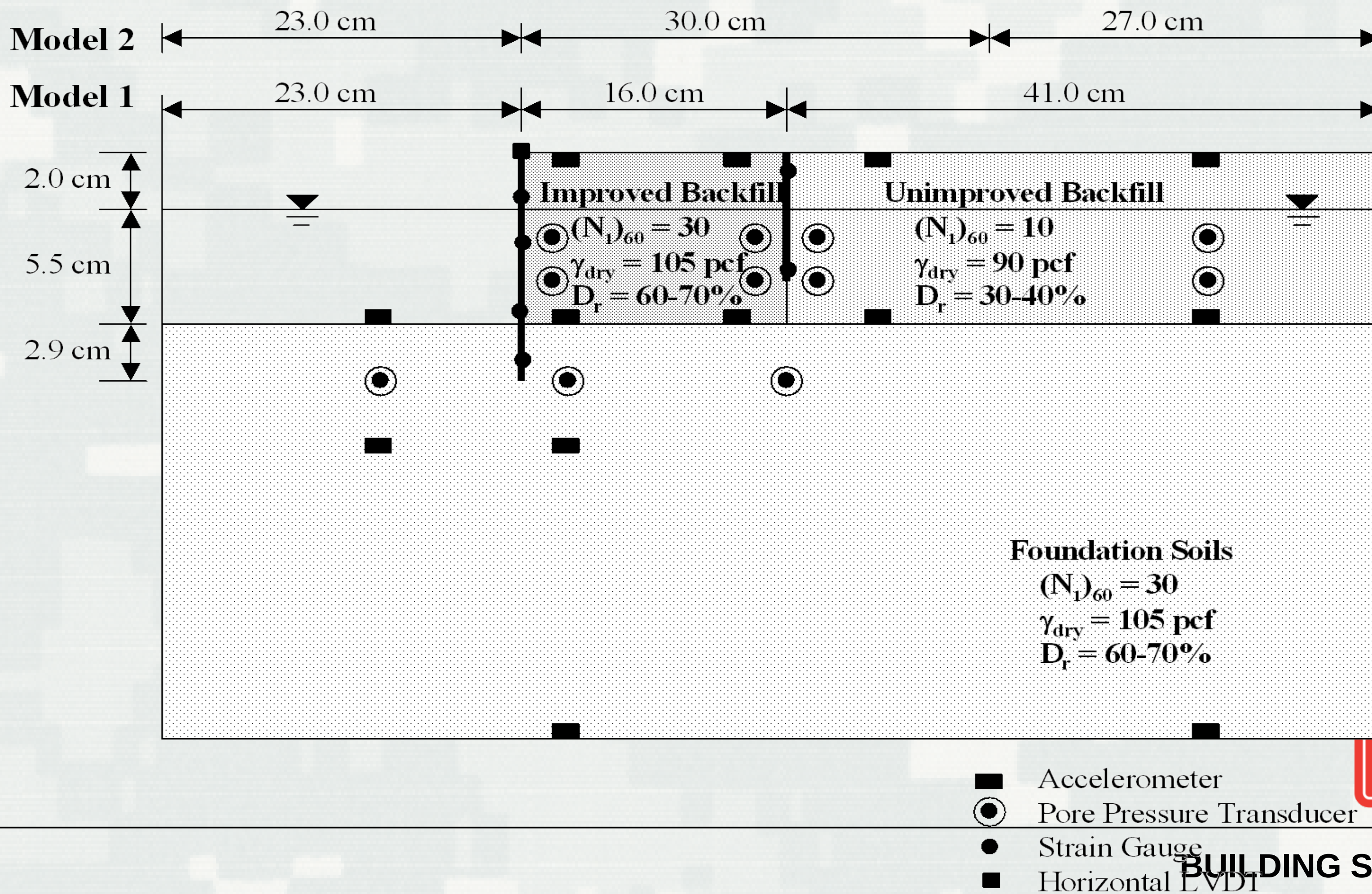
Ng (N times gravity)

<u>Similitude</u>

(or, Scaling Relationships - derived from dimensional analysis)

Quantity	Full Scale (Prototype)	Centrifugal Model at N x g
Linear dimension	1	1/N
Stress (force/area)	1	1
Strain (displacement/unit length)	1	1
Density	1	1
Force	1	$1/N^2$
Energy	1	$1/N^3$
Displacement (distance)	1	1/N
Velocity (distance/time)	1	1
Acceleration (distance/time^2)	1	N
Time		
Dynamic problems	1	1/N
Diffusion problems	1	$1/N^2$
Viscous flow problems	1	1
Frequency		
Dynamic problems	1	N

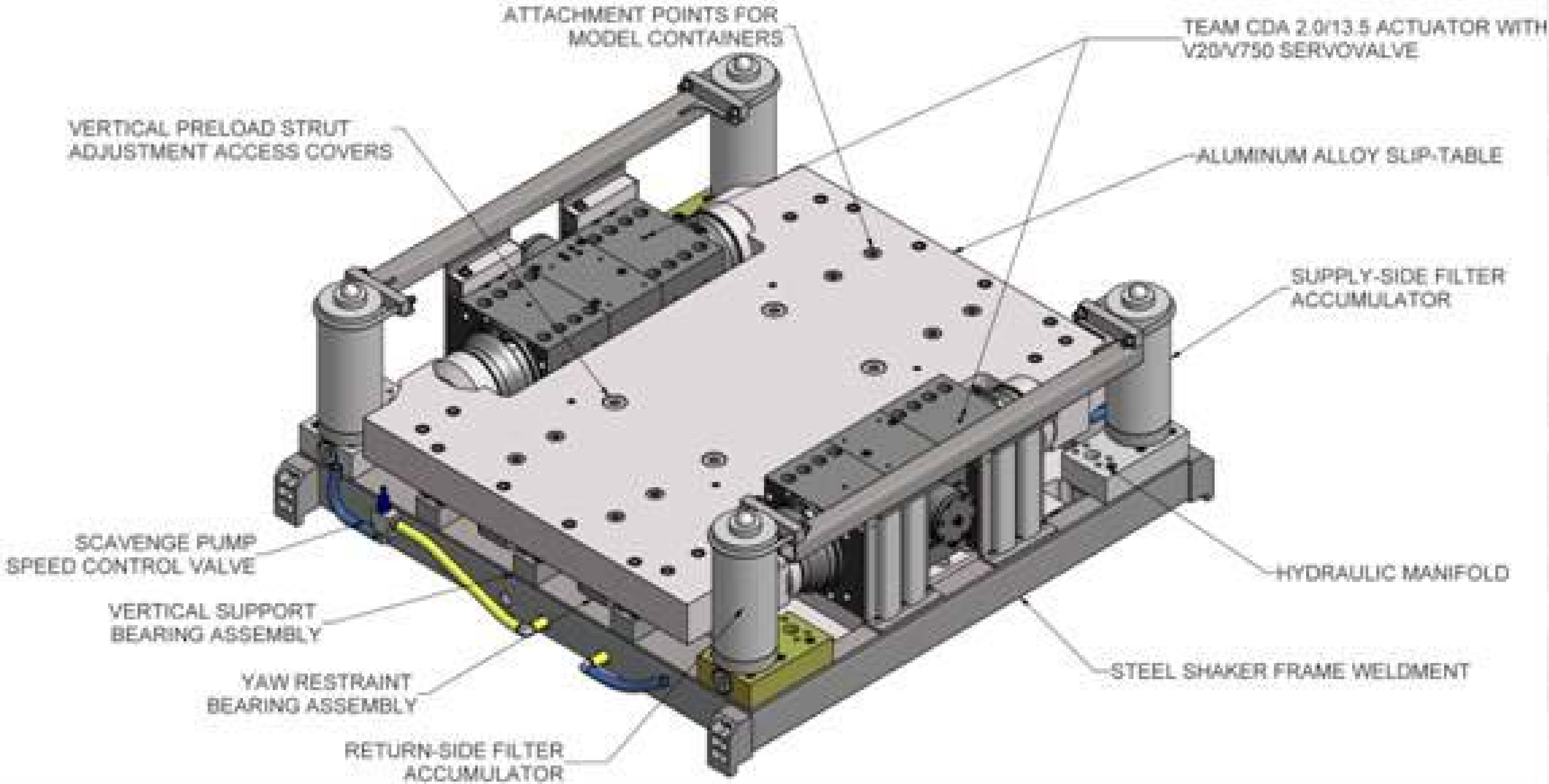
Schematic of Retaining Wall Model



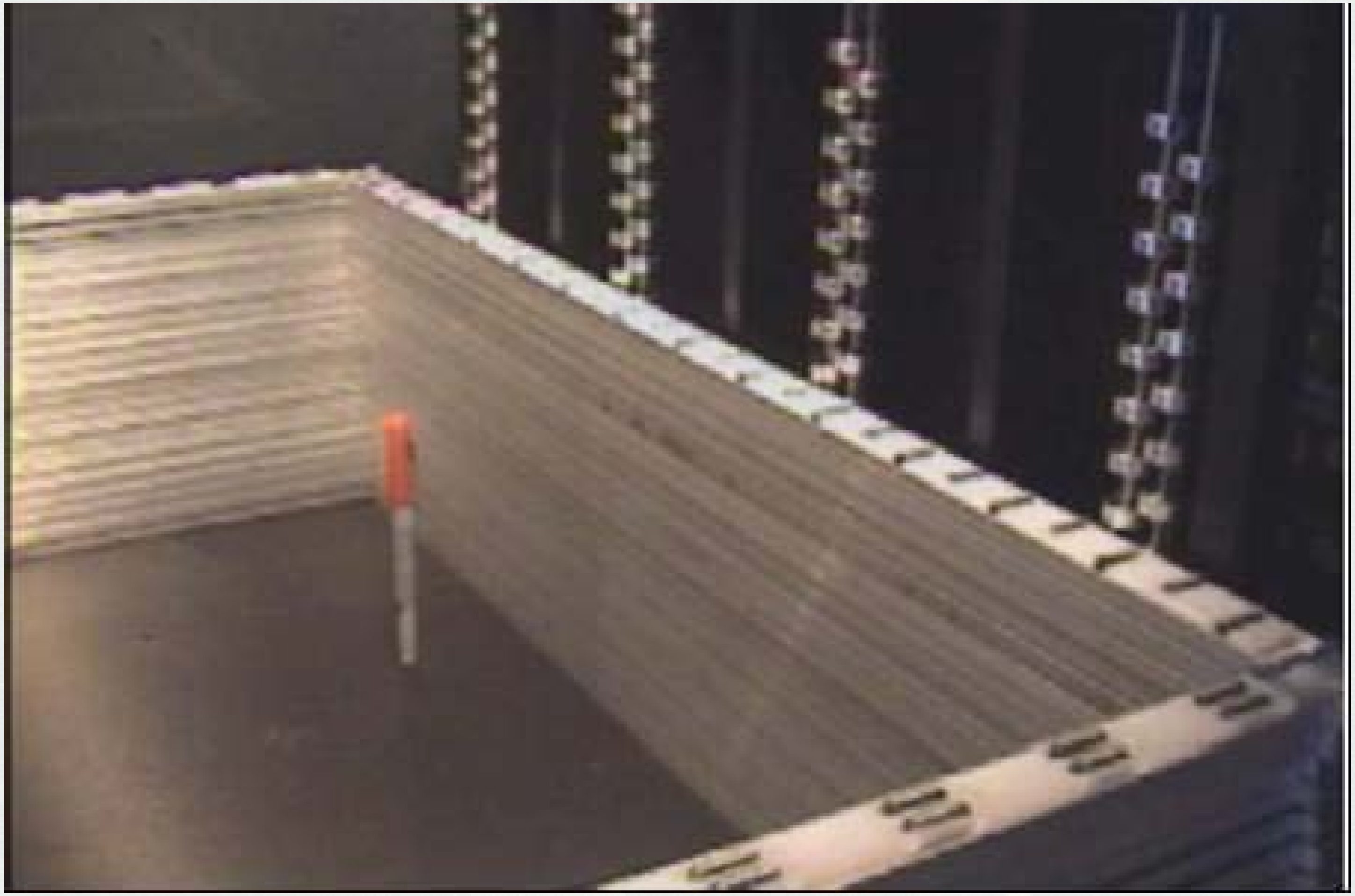
ES-80 Performance Specifications

- **Method:** ***Servo-hydraulic multi-actuator system***
- **Shaking Type:** ***Periodic or random***
- **Shaking Direction:** ***One-directional***
- **Nominal Shaking Force:** ***80 kips peak dynamic force***
- **Max. Displacement:** ***0.5 inch***
- **Max. Velocity:** ***50 in./s***
- **Max. Payload Dimensions:** ***25 in. W x 49 in. L x 23 in. H (Laminar Box***
- **Max. Centrifugal Acceleration:** ***150 g***

ES – 80 Shaker Components



Stacked rings and bearing arrangement for laminar box



Summary

- Stresses in a centrifuge model equal those in the prototype
- Earthquakes and other dynamic loads may be replicated on models
- The ES-80 shaker provides controllable dynamic loads on the world’s most powerful centrifuge platform