Understanding and Coping with Risks of

Living in Earthquake Country

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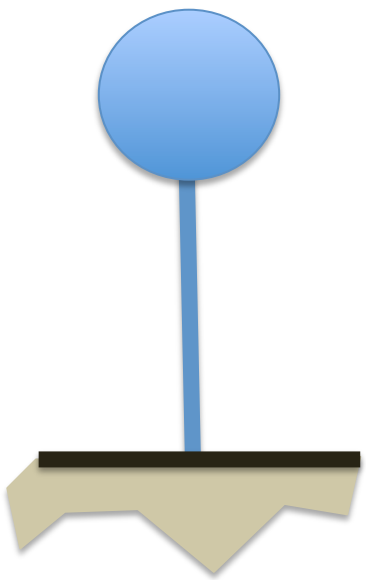
Department of Civil Engineering

STAT/CS 79: Societal Risk and Law

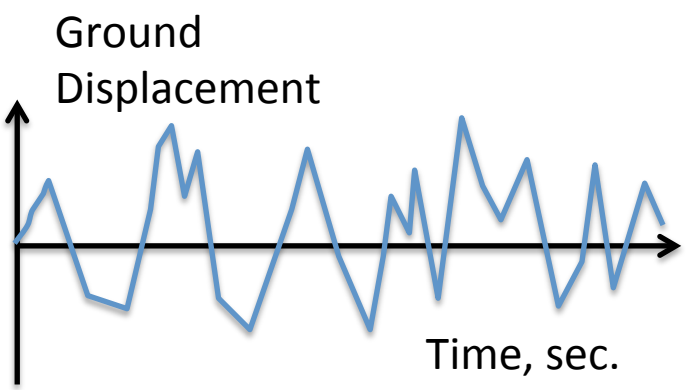
Spring 2013

Primer

- Earthquakes are Newtonian



Force = Mass x Acceleration

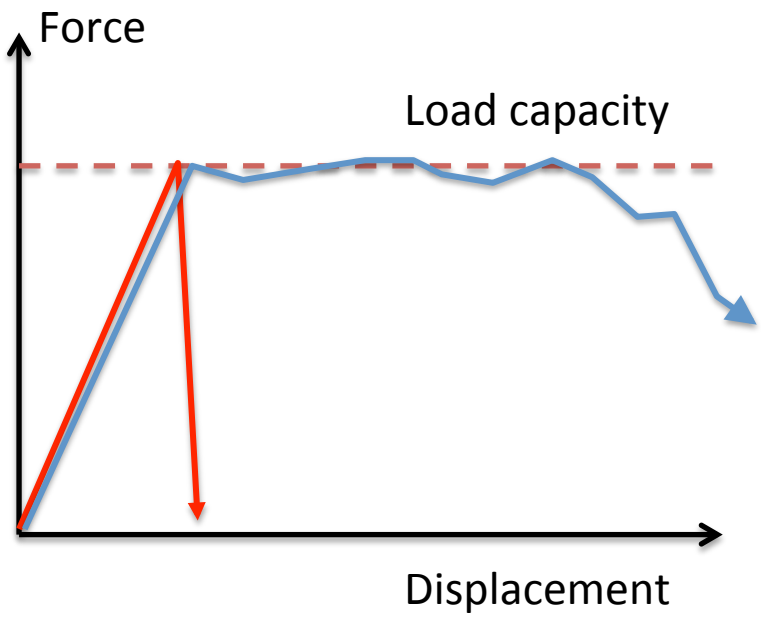


- Structures can resist only so much force

Demand < Capacity

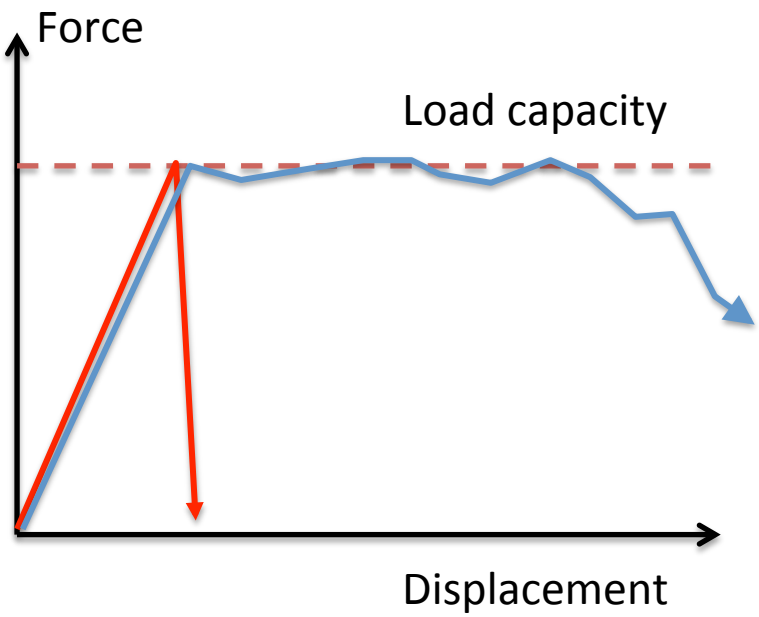
Primer

Capacity > demand?

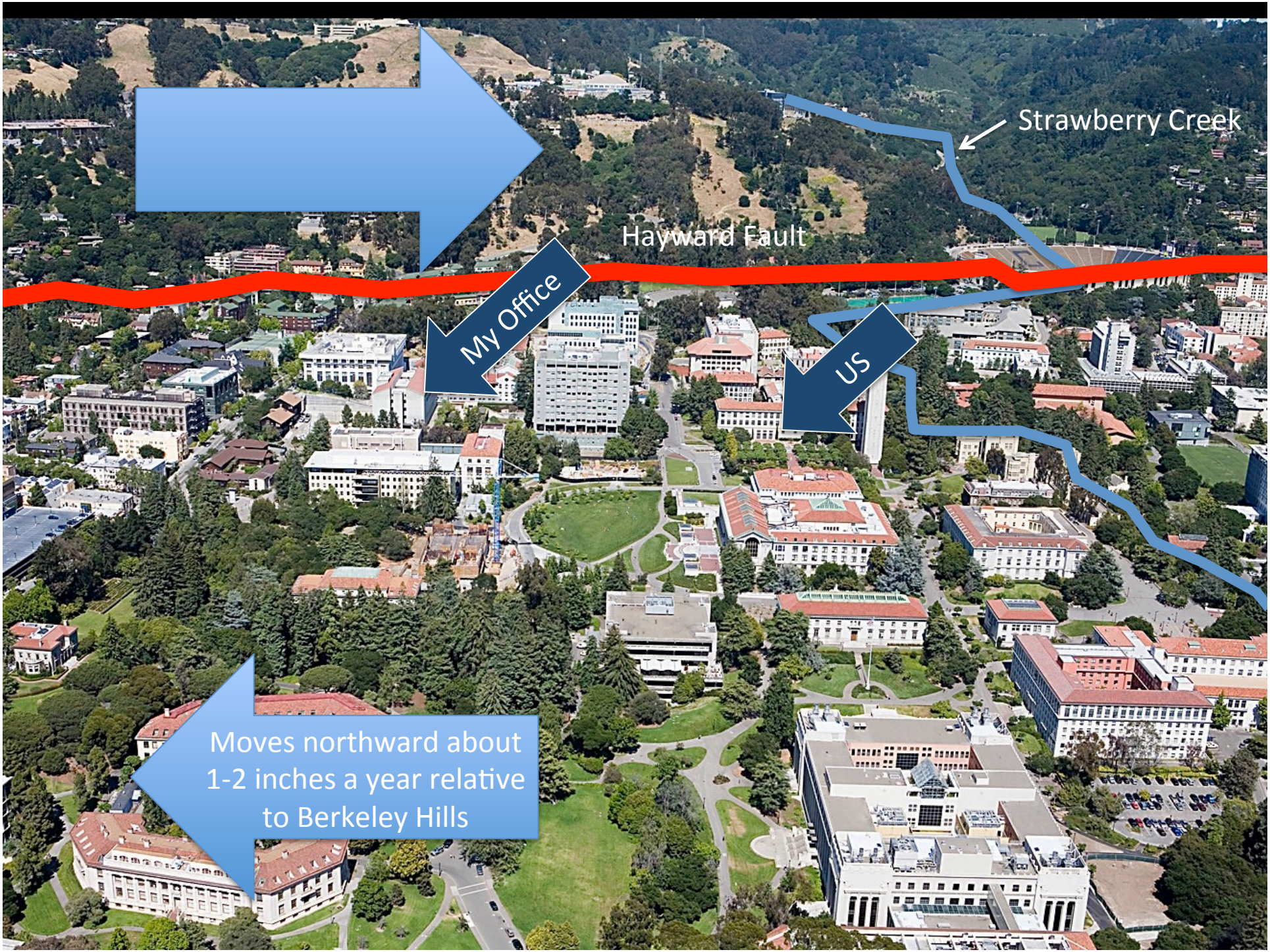


Primer

Capacity > demand?



SHOULD WE WORRY?


Strawberry Creek
Hayward Fault
My Office
US
Moves northward about 1-2 inches a year relative to Berkeley Hills

SHOULD WE WORRY?

San Francisco 1906

SHOULD WE WORRY?

Warning: I am an engineer

$$\lambda(DV) = \int\int\int G(DV \mid DM)\, dG(DM \mid EDP)\, dG(EDP \mid IM)\, d\lambda(IM)$$

RISK = PROBABILITY x HARM

Risk Assessment Depends on Context

Risk Assessment Depends on Context

Informed individual acceptance of risk

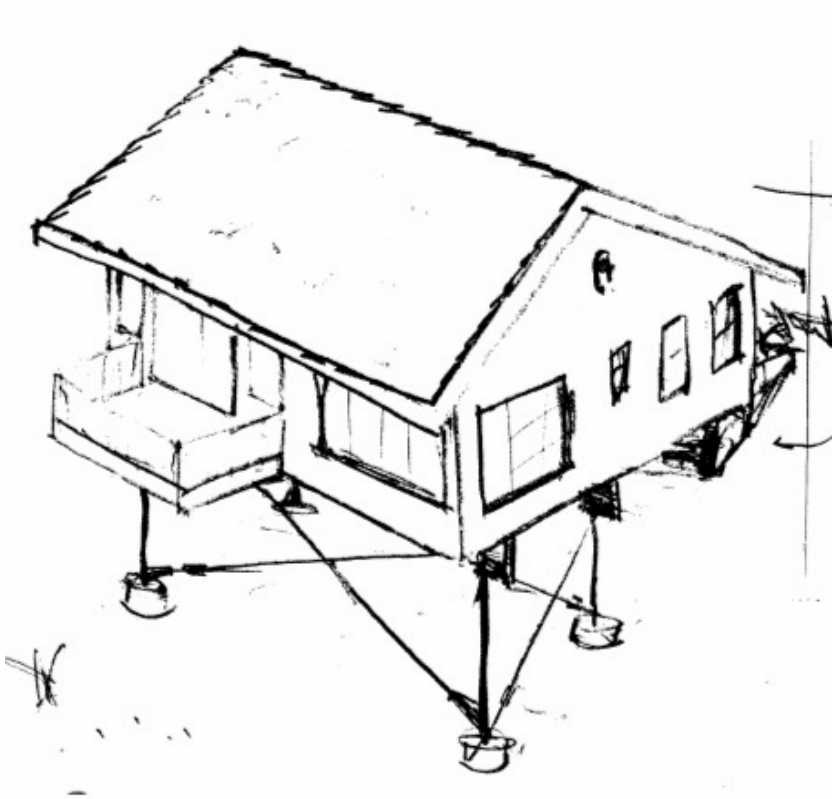
Risk Assessment Depends on Context

Presumptive Freedom from Public Risks

Risk Assessment Depends on Context

Presumptive Freedom from Public Risks

Acceptable Risks



Perspective Differs Amongst:

- Owners
- Engineers
- Government Agencies
- Insurance and Finance

Managing Risk

- Accept / Ignore
- Transfer
- Reduce Probability of Occurrence
- Reduce Vulnerability
- Reduce Exposure

RISK = PROBABILITY x HARM

For probabilistic seismic risk assessment

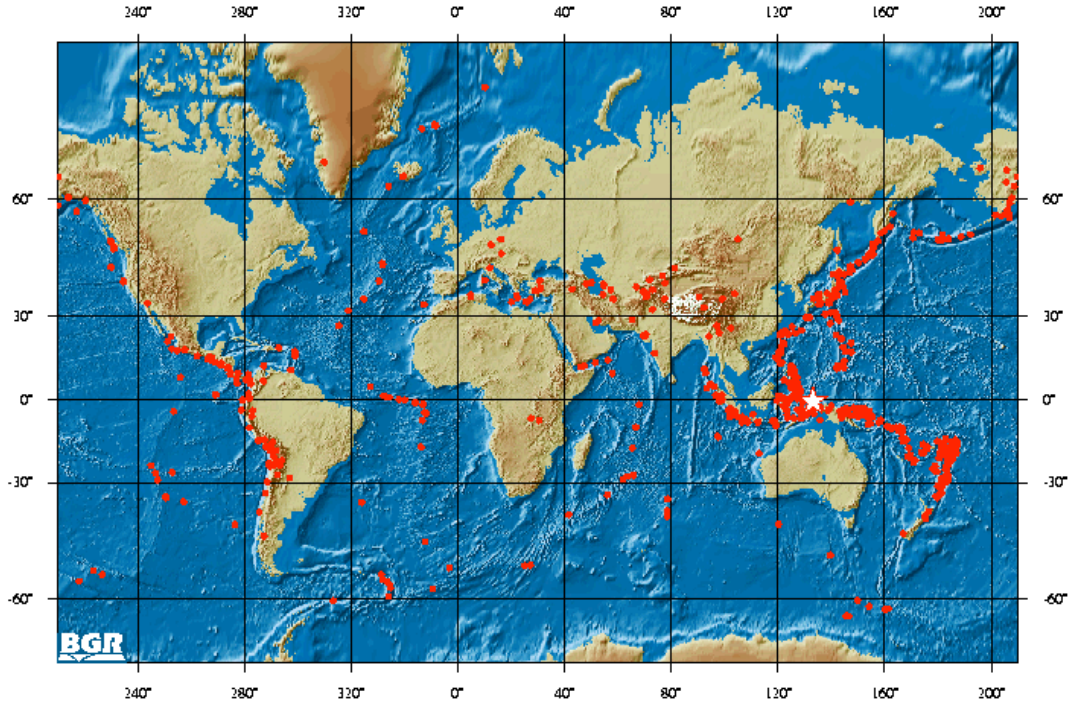
SEISMIC RISK =

HAZARD X VULNERABILITY X EXPOSURE

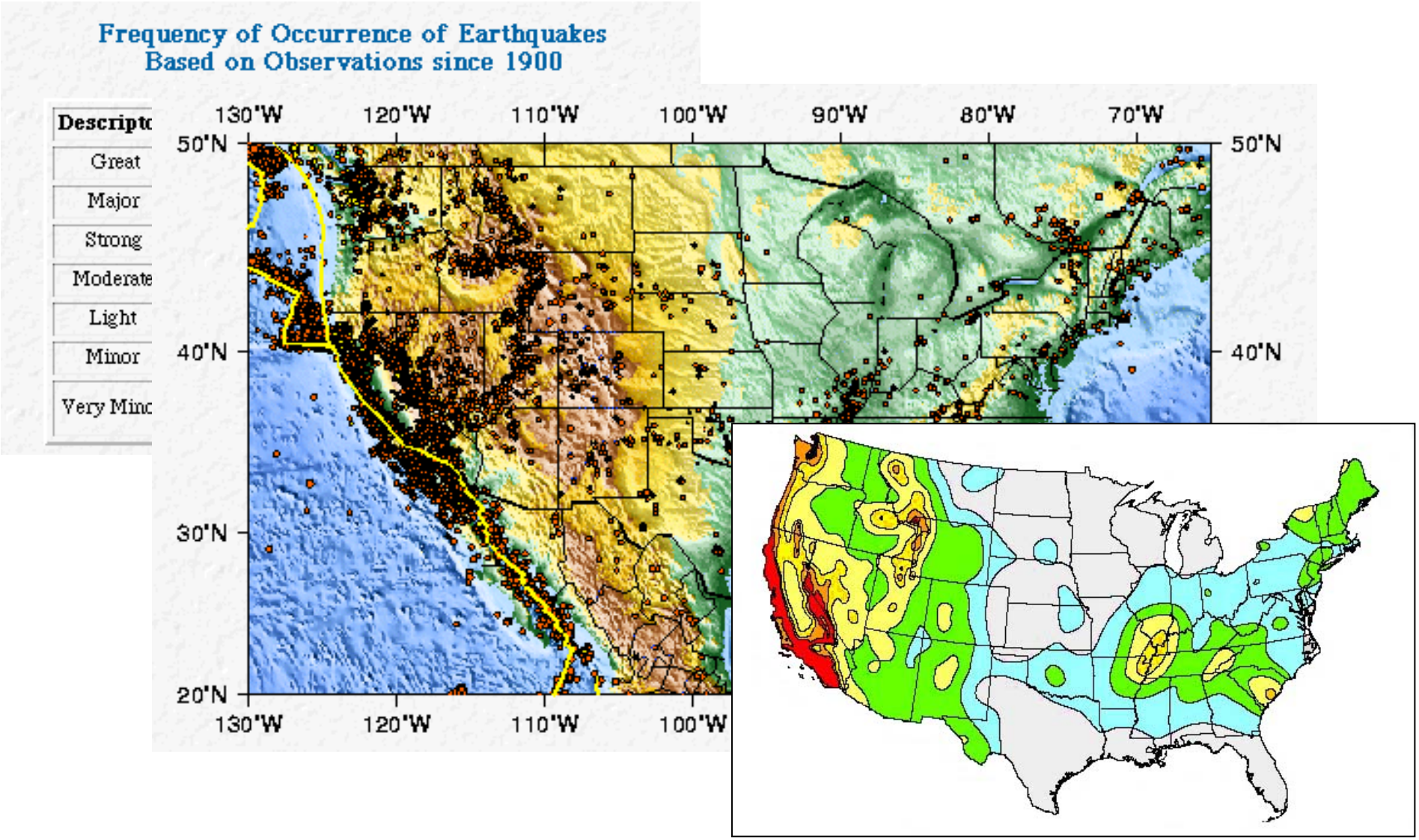
Earthquakes

<u>Sources</u>

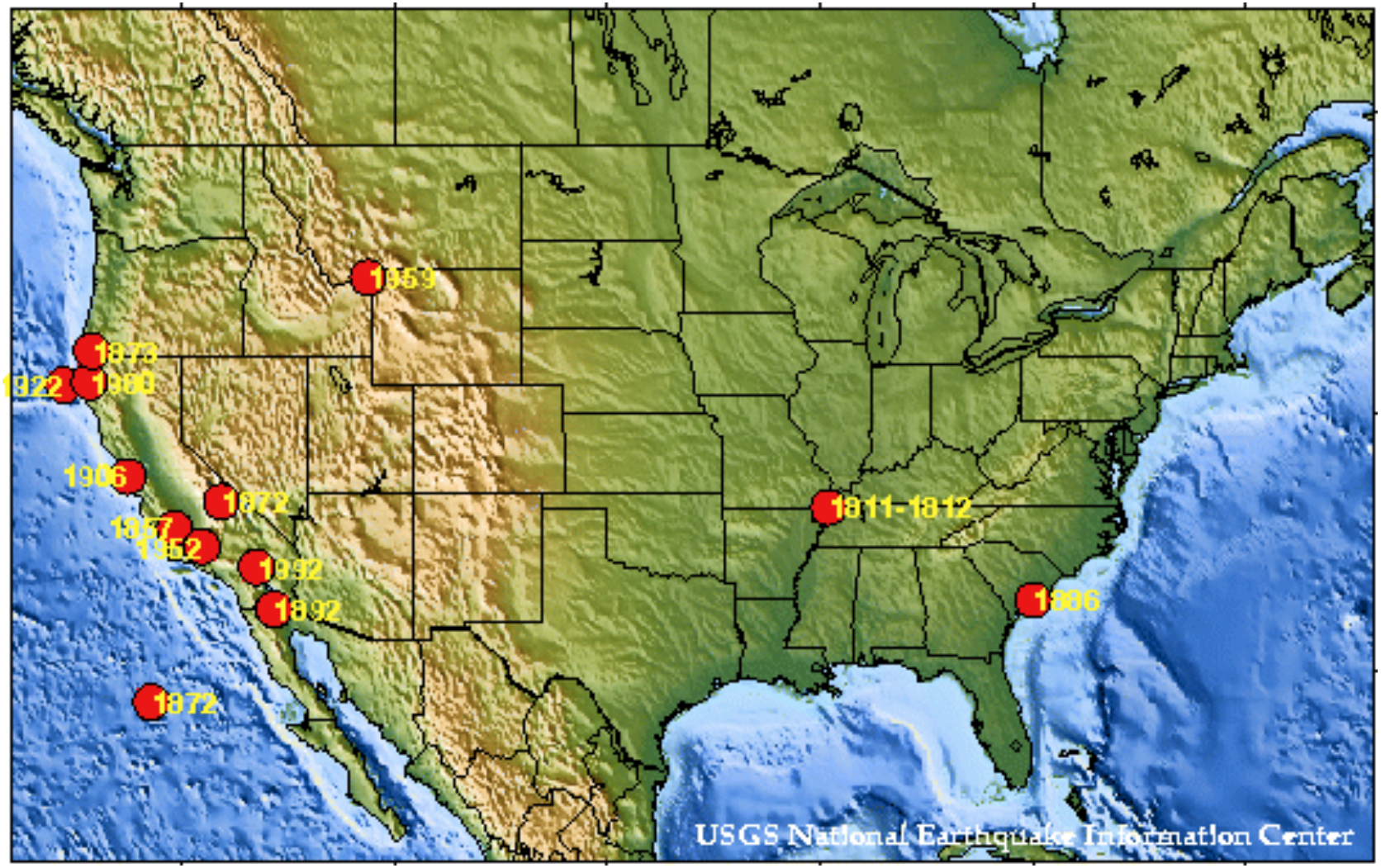
- Meteor Impact
- Volcanoes
- Reservoir Induced
- Well Injection
- Tectonic
  - Associated with continental drift
    - at edges of continental plates
    - mid-continent
    - mid-ocean ridges



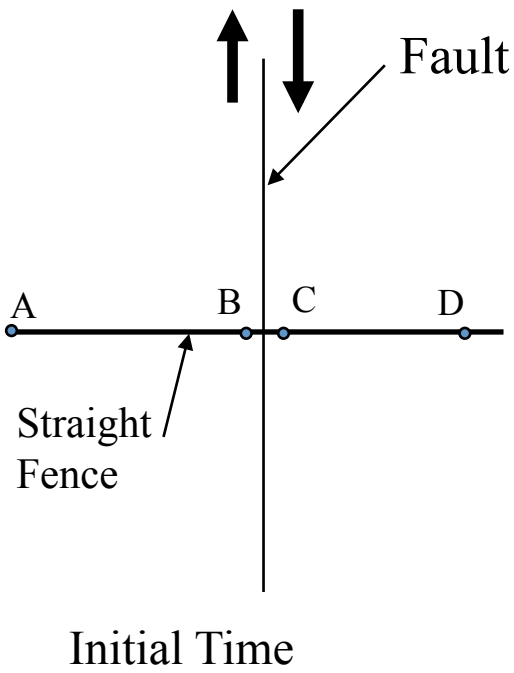
Rate of Occurrence

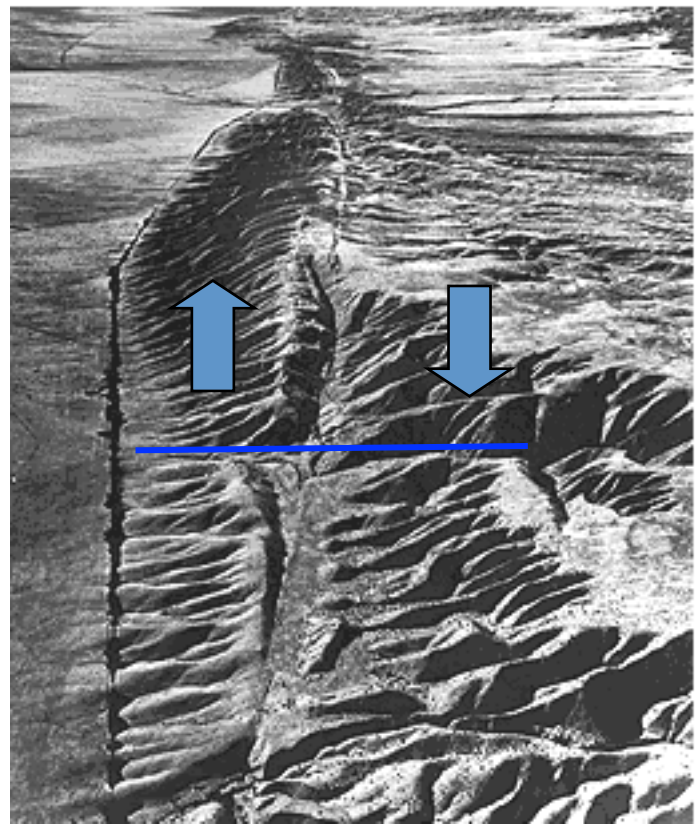


Largest Earthquakes in US



Elastic Rebound Theory





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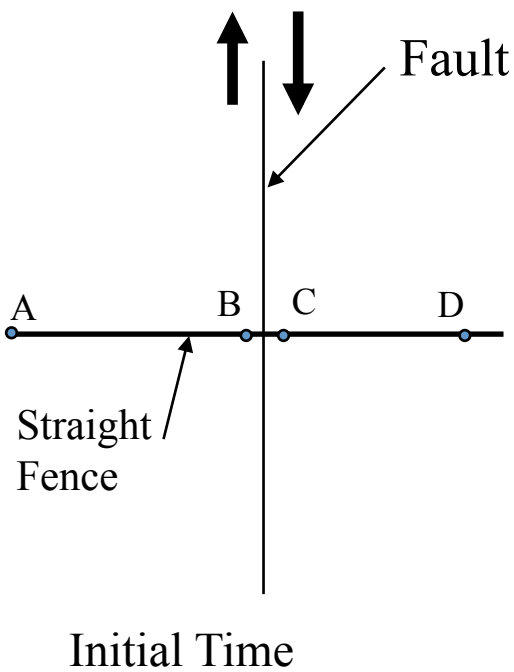

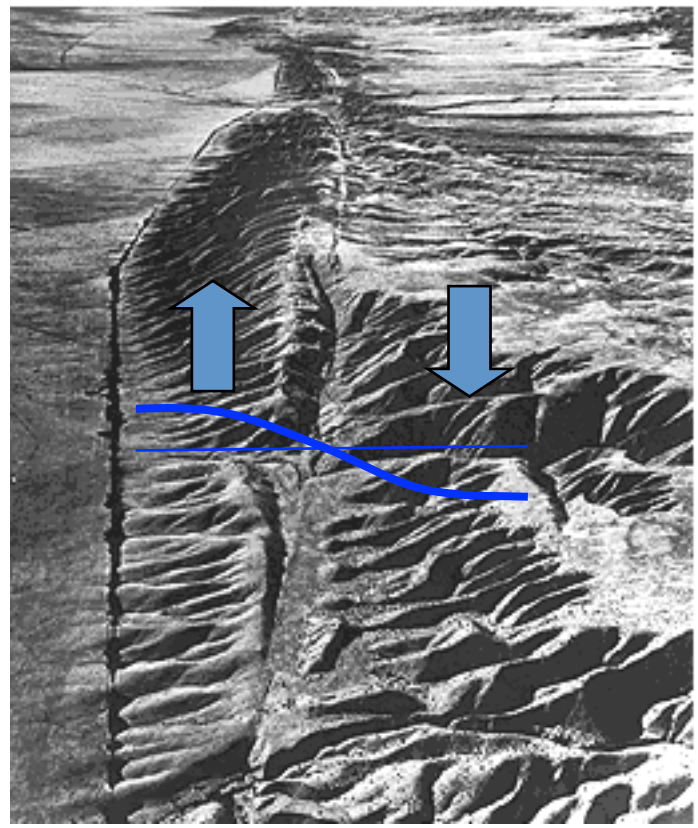

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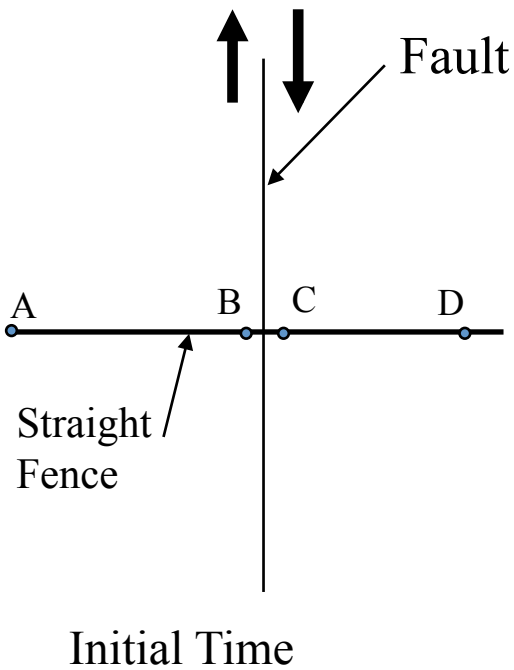

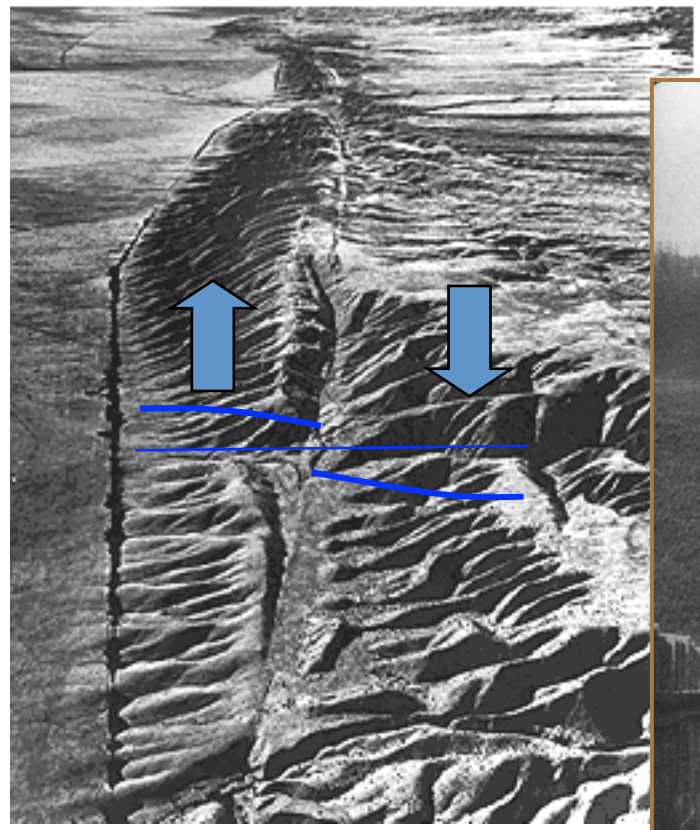

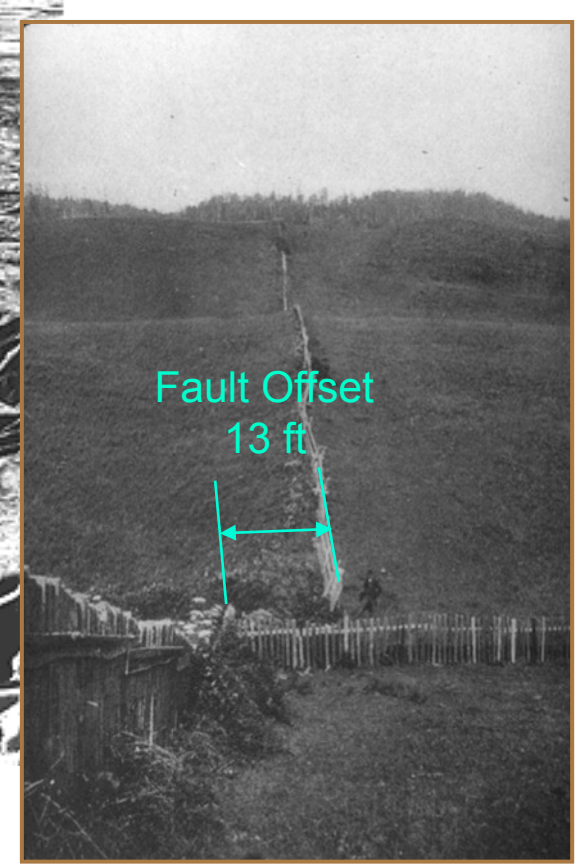

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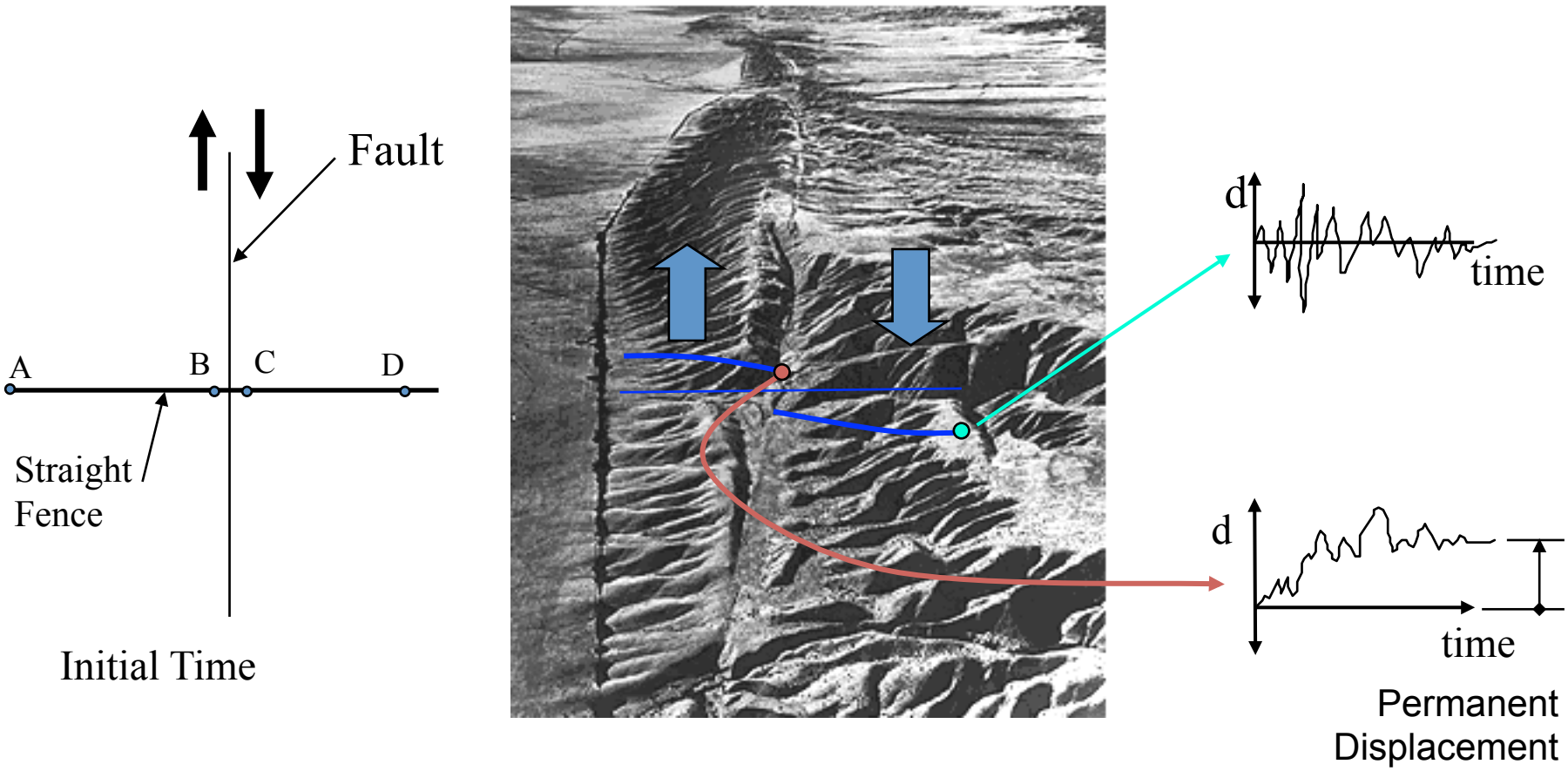
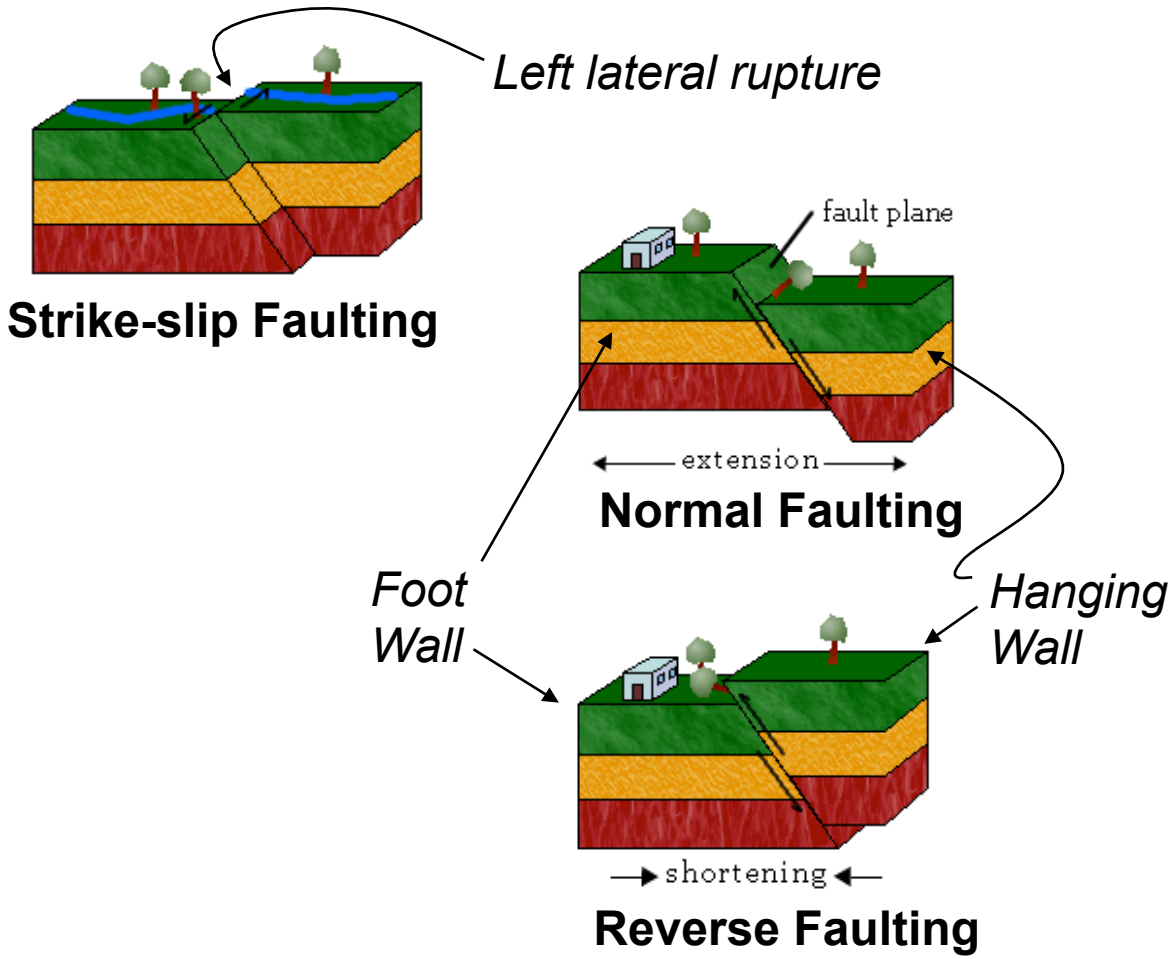
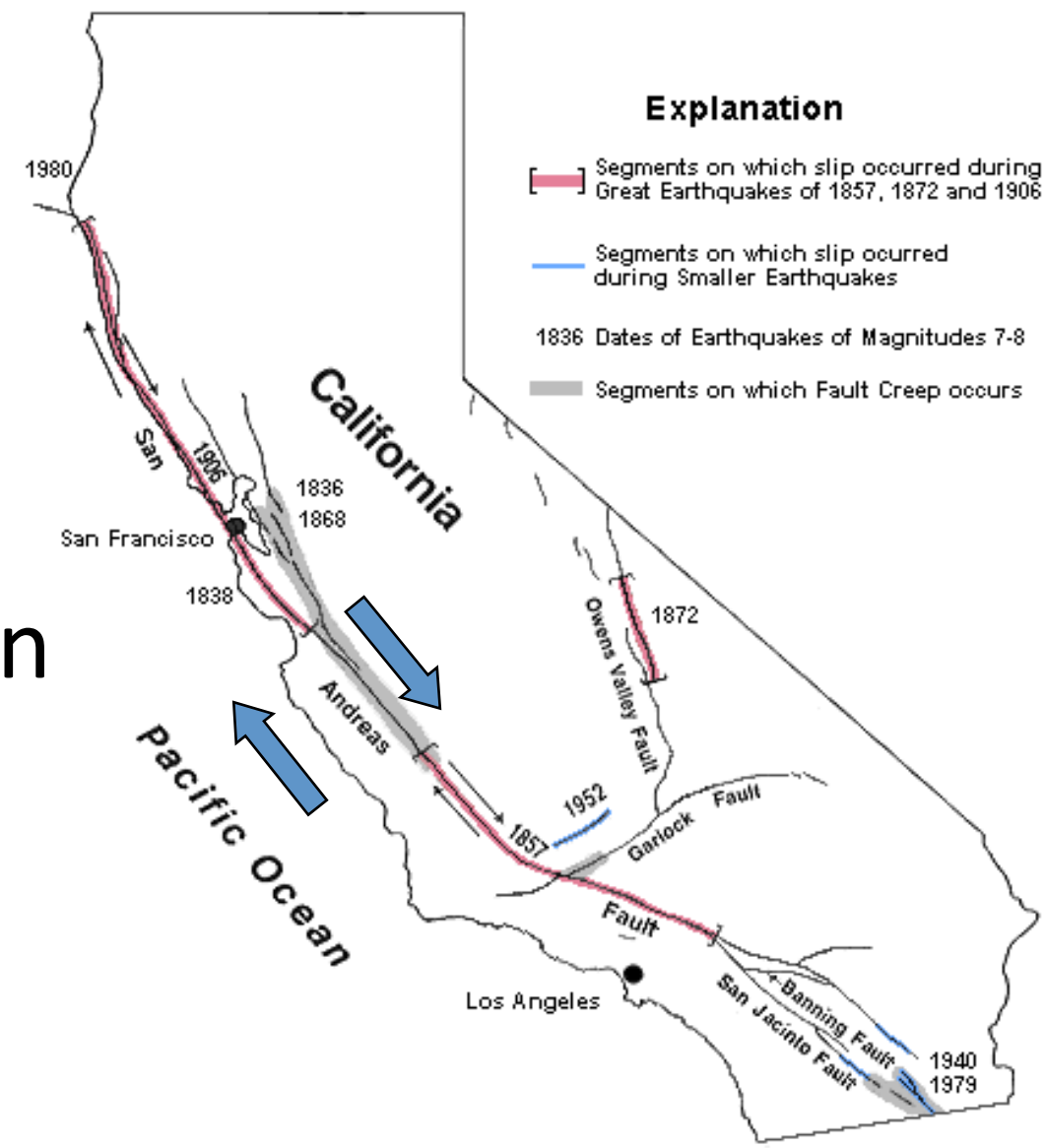


Basic Types of Faulting

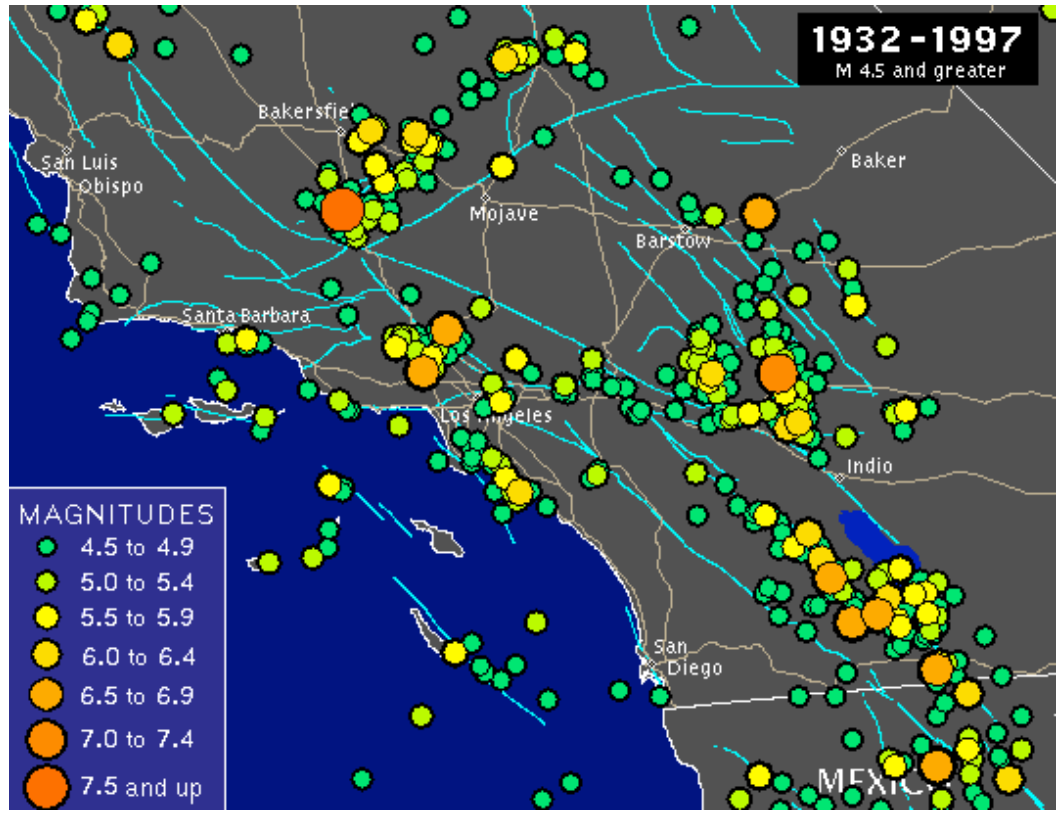
- Surface Faulting
  - Strike-slip
  - Dip slip/thrust
  - Combinations



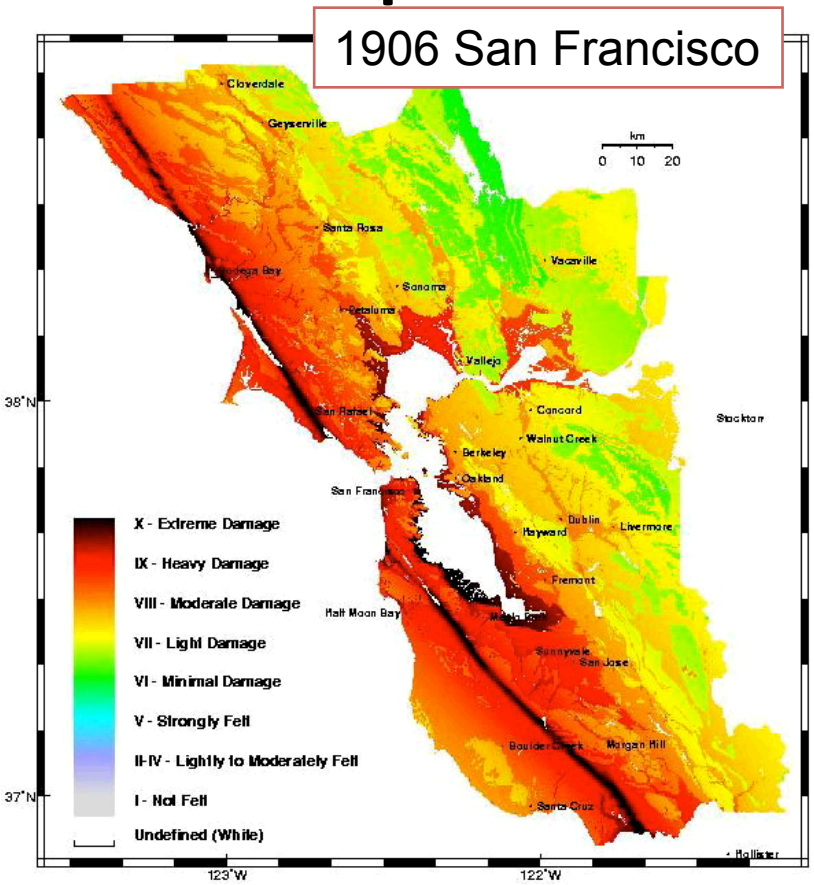
Major Faults in California

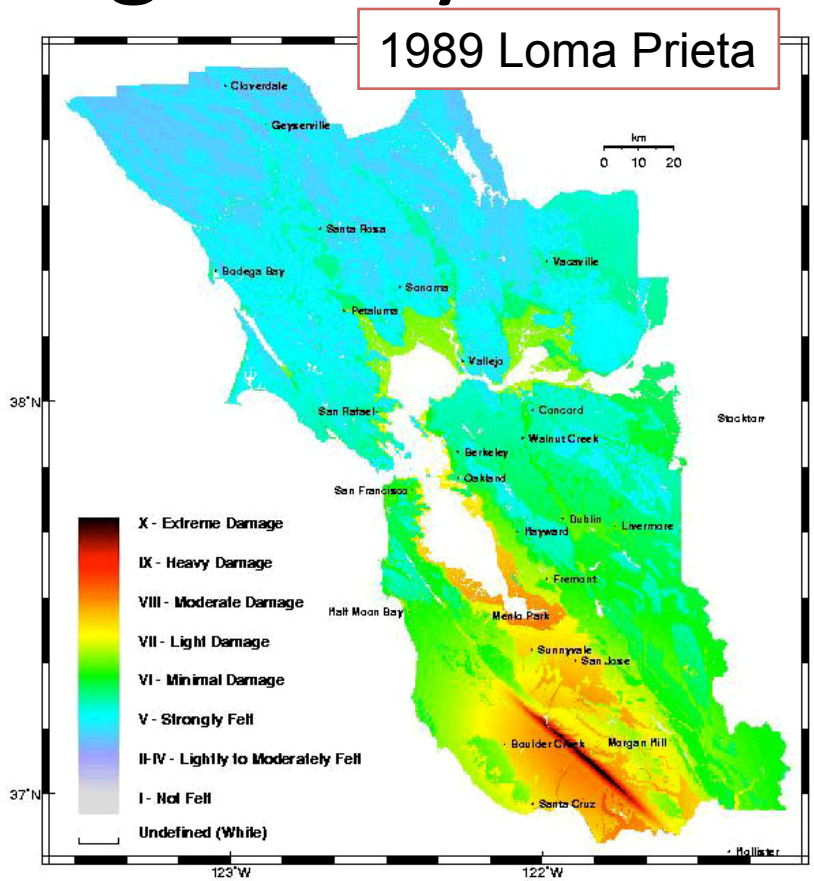


Faulting in Northern and Southern CA



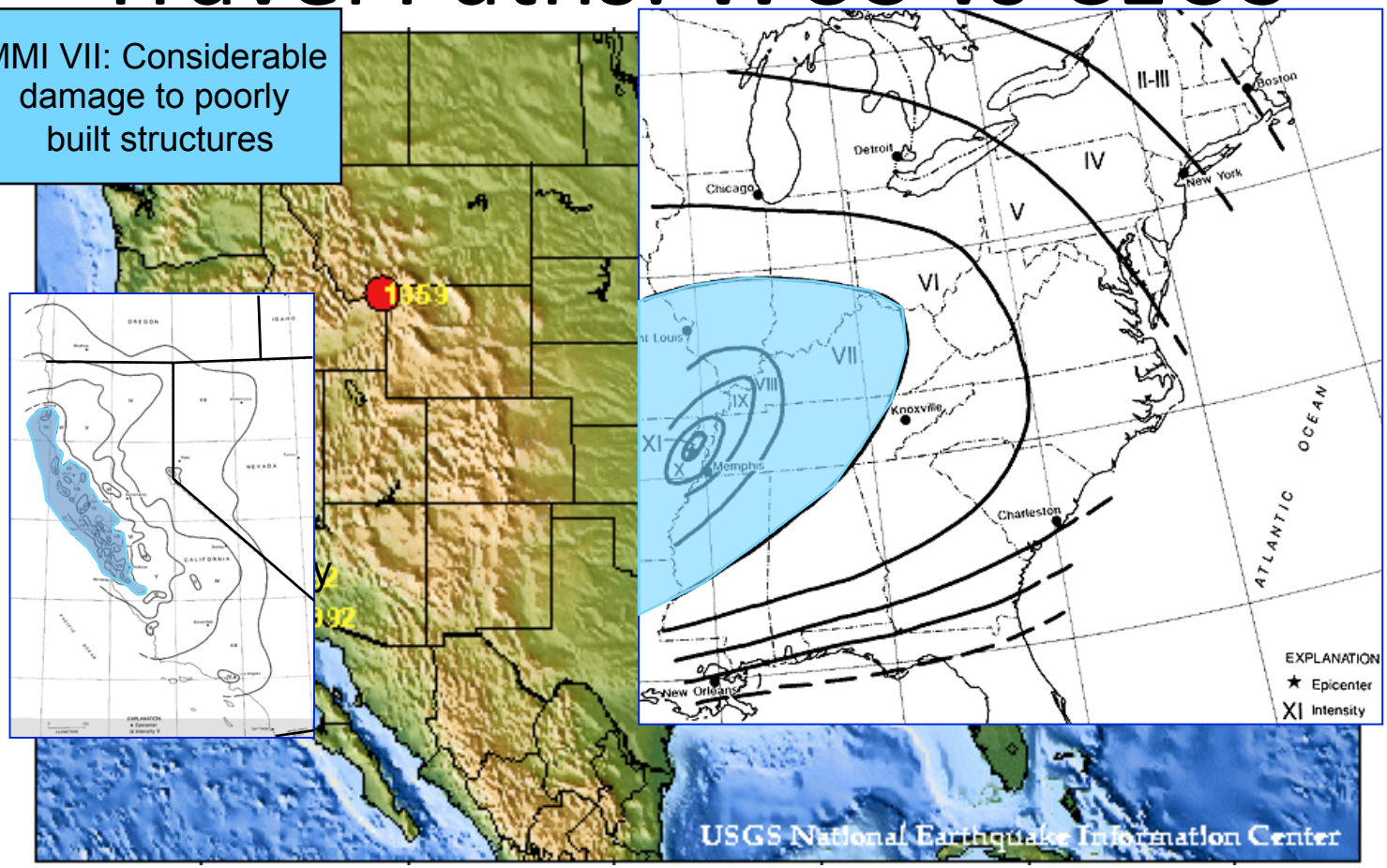
Earthquake Shaking in Bay Area





Travel Paths: WUS vs CEUS

MMI VII: Considerable damage to poorly built structures



Sources of Damage

Damage caused by:

- Ground shaking
- Fault rupturing
- Liquefaction and soil movement
- Slope instability and landslides
- Tsunami and seiche
- Fire
- Flooding
- Interaction with adjacent structures (pounding)

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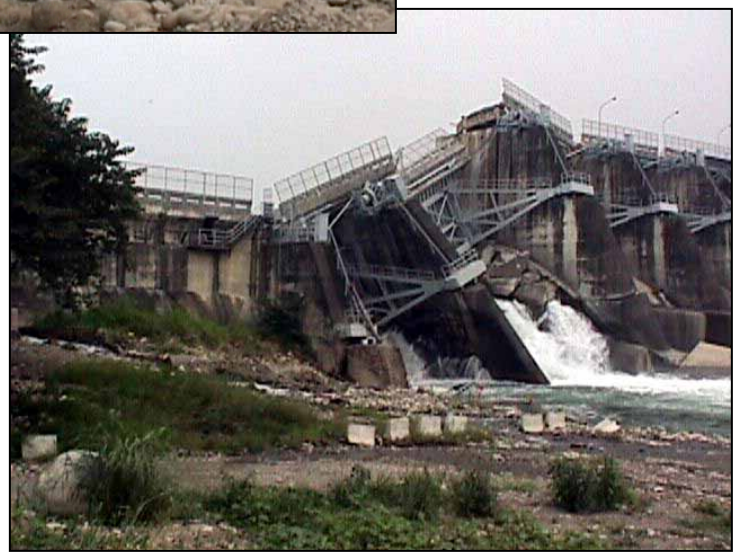

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Sources of Damage

Crescent City 11/15/06

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Hilo, Hawaii following 1960 M 9.5 Chilean Earthquake (61 fatalities)

14-meter tall tsunami in 1946 resulting from M 7.8 Alaskan Earthquake caused 159 fatalities

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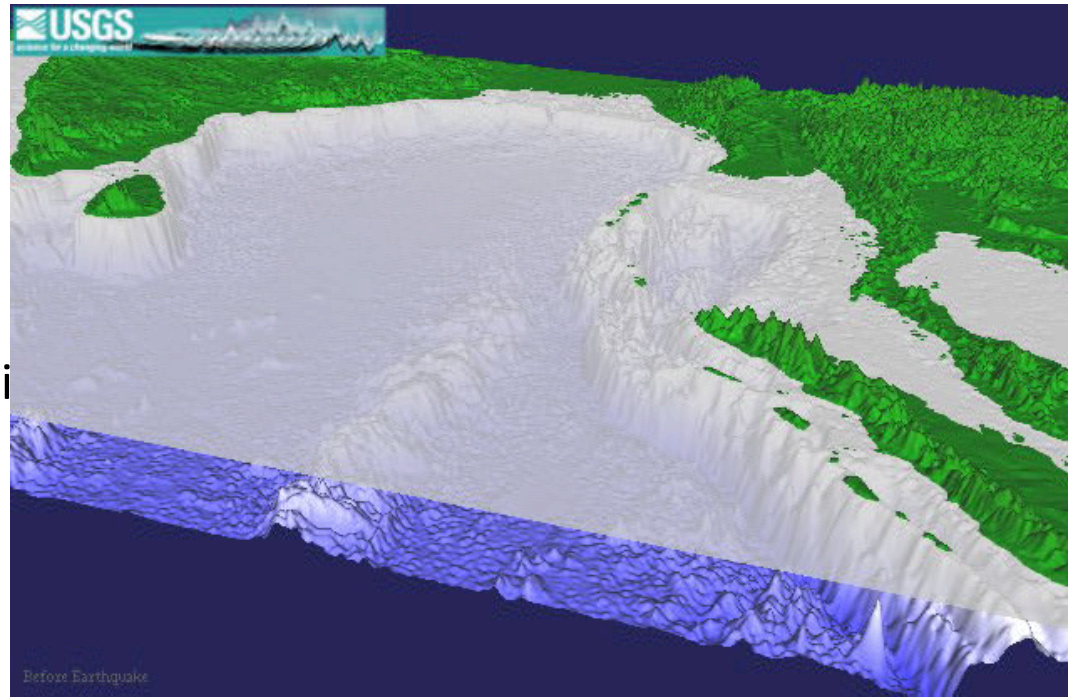

December 2004 Sumatra Earthquake

Tsunami Videos (see:http://www.asiantsunamivideos.com/)

Dec. 26, 2005 Banda Aceh, Indonesia

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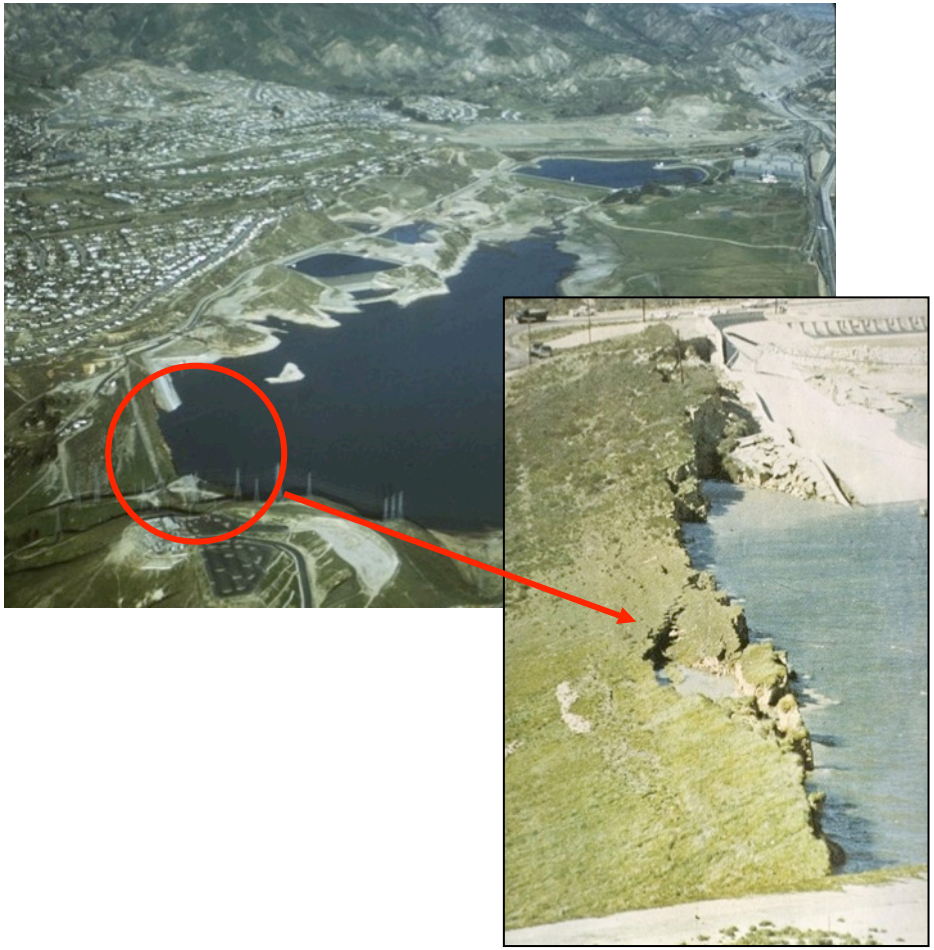

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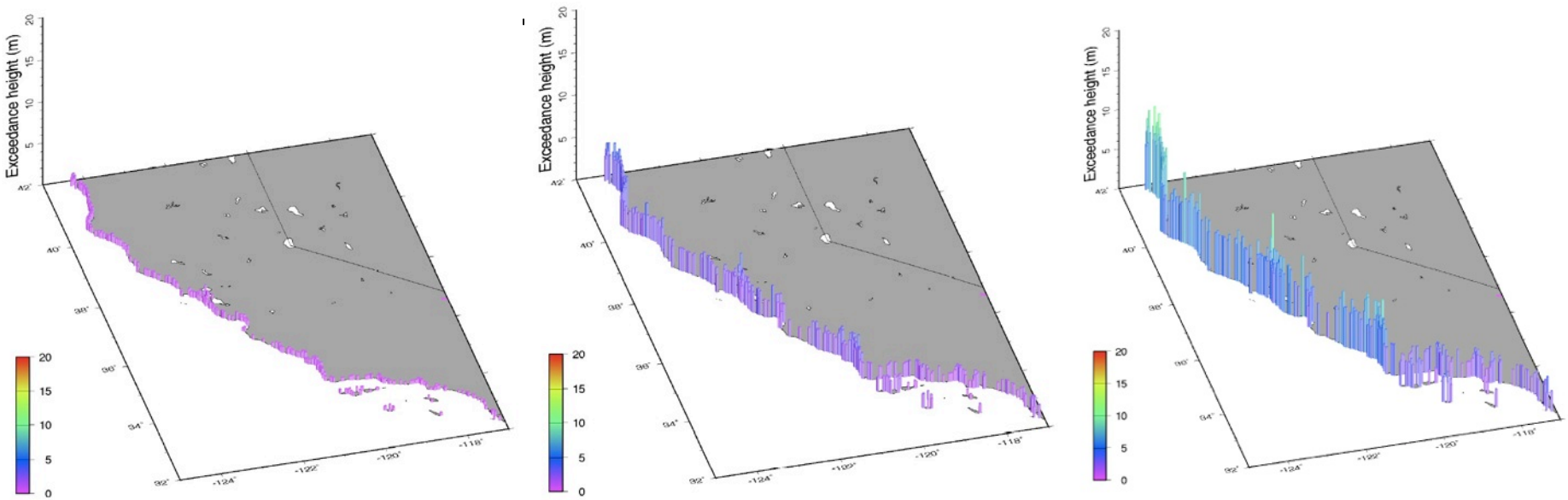
Earthquake-Related Hazards:
Tsunami Engineering

- Probabilistic hazards in a form consistent with ground motion

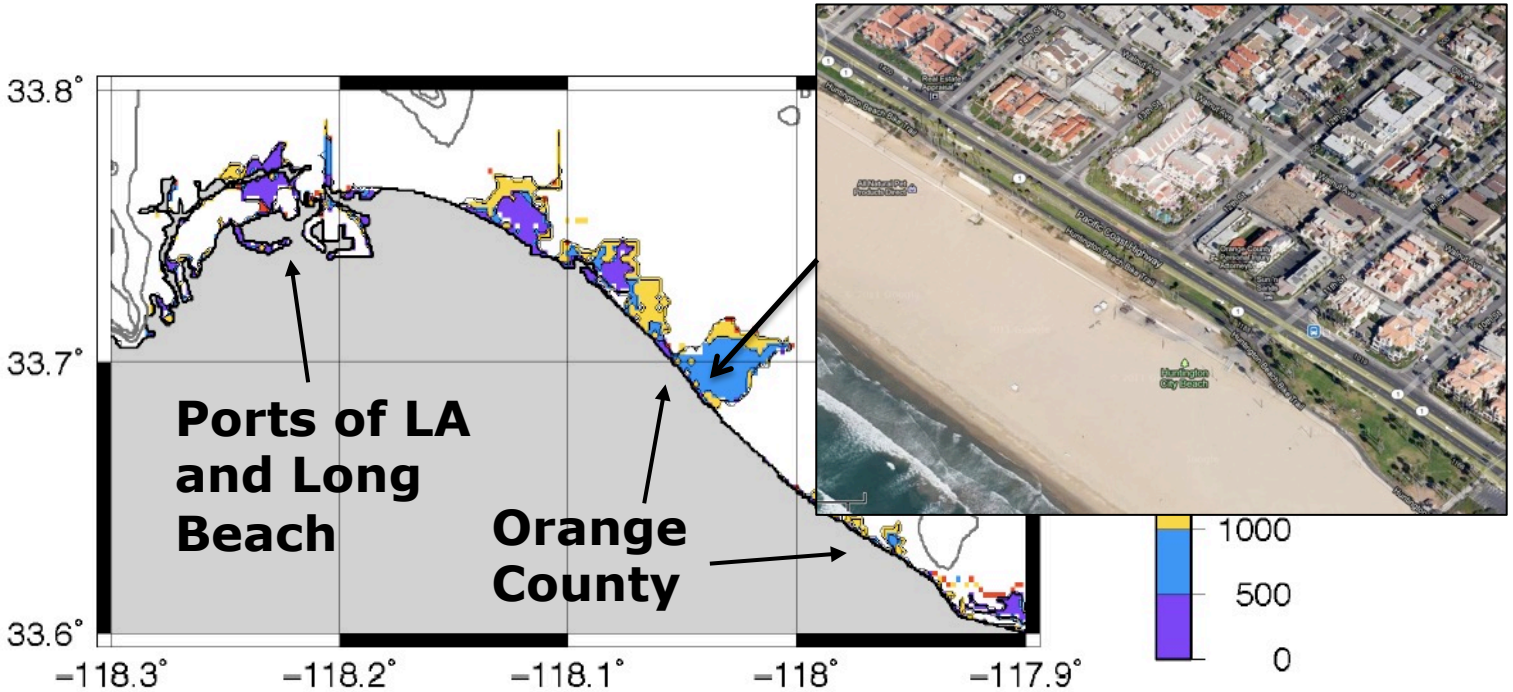


72 year **475 year** **2500 years**

Probabilistic Wave Height and Velocity Estimates

Probabilistic Tsunami Hazard Analysis

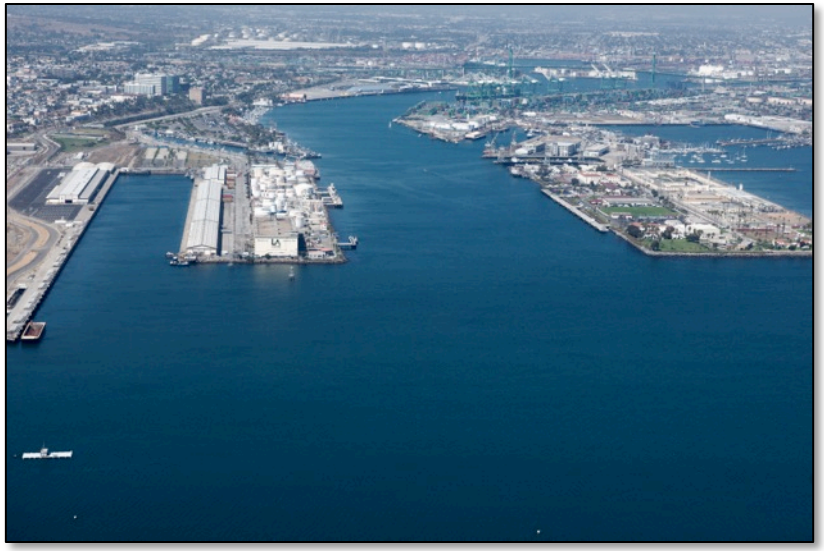
- Probabilistic hazards in a form consistent with ground motion hazard estimates



Probabilistic Inundation Maps
(plus wave height and velocity maps)

Tsunami Engineering

Risk Assessment and Mitigation



Other Earthquake Related Hazards:

Fire Following Earthquakes

Aging infrastructure can trigger fires

Will resources be available to fight urban fires?

Will earthquake damage prevent effective fire suppression in tall buildings?

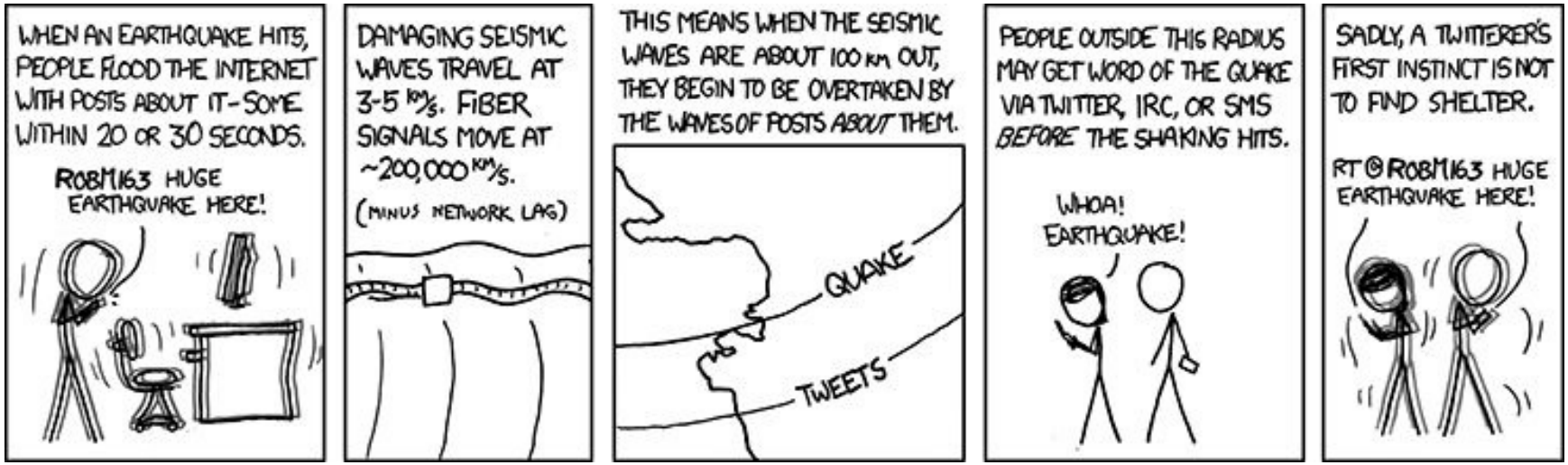
New research initiatives on:

- Vulnerability of fuel and water supply systems to earthquakes
- Case studies of fires in tall buildings following earthquakes

Predicting Earthquake Hazards

Predicting Earthquake Hazards

We can predict an earthquake a few to several seconds before it gets to you.



This can be useful for critical facilities and certain occupancies

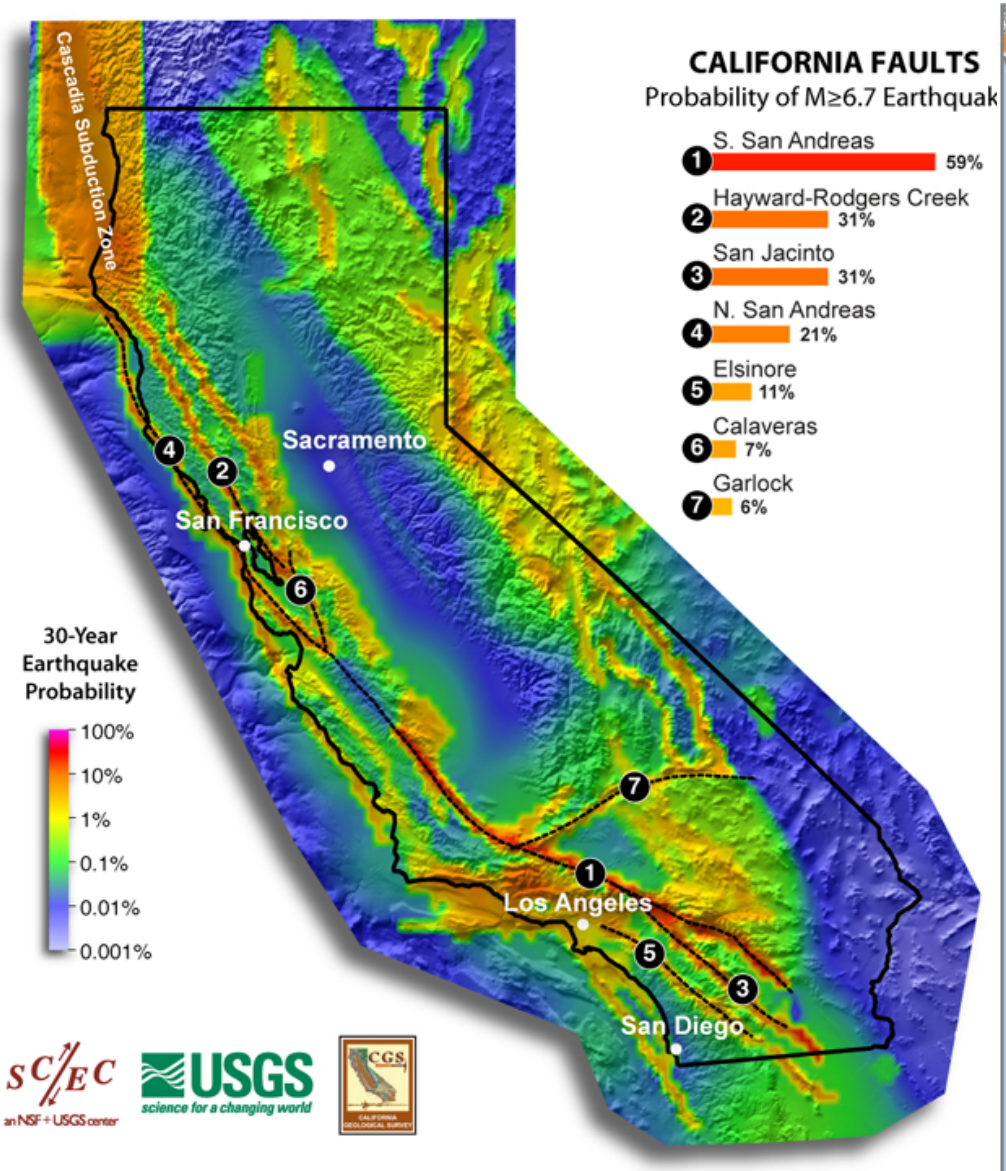
Large project on this at Berkeley in EPS

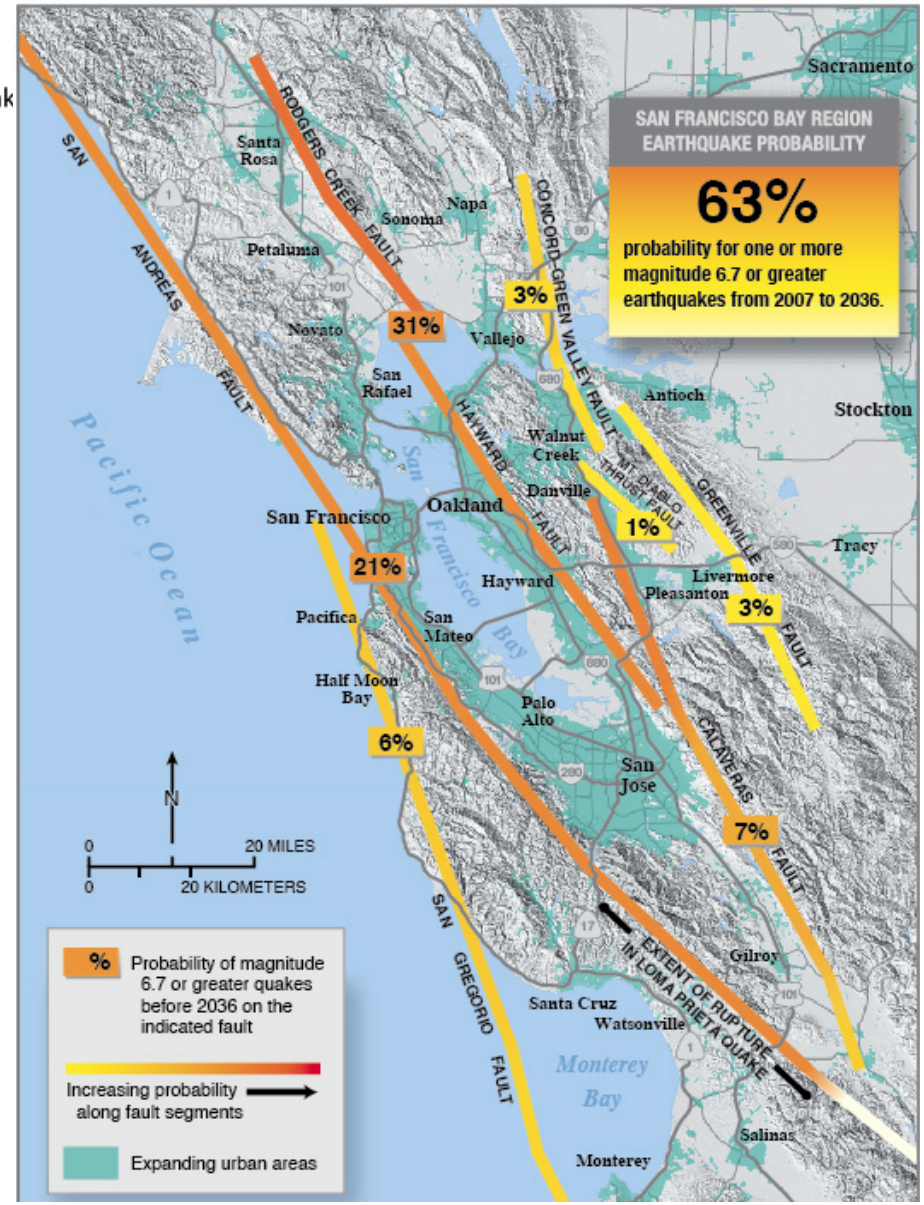
Estimating Earthquake Hazards

Seismic source characterization

- Locate faults or source regions
- Characterize fault (strength of materials, slip rate, when were last events, how big were past events, etc.)
- Examine catalogs of similar past earthquakes to estimate max. size earthquake possible
- Estimate time between quakes of different size

Estimating Earthquake Hazards

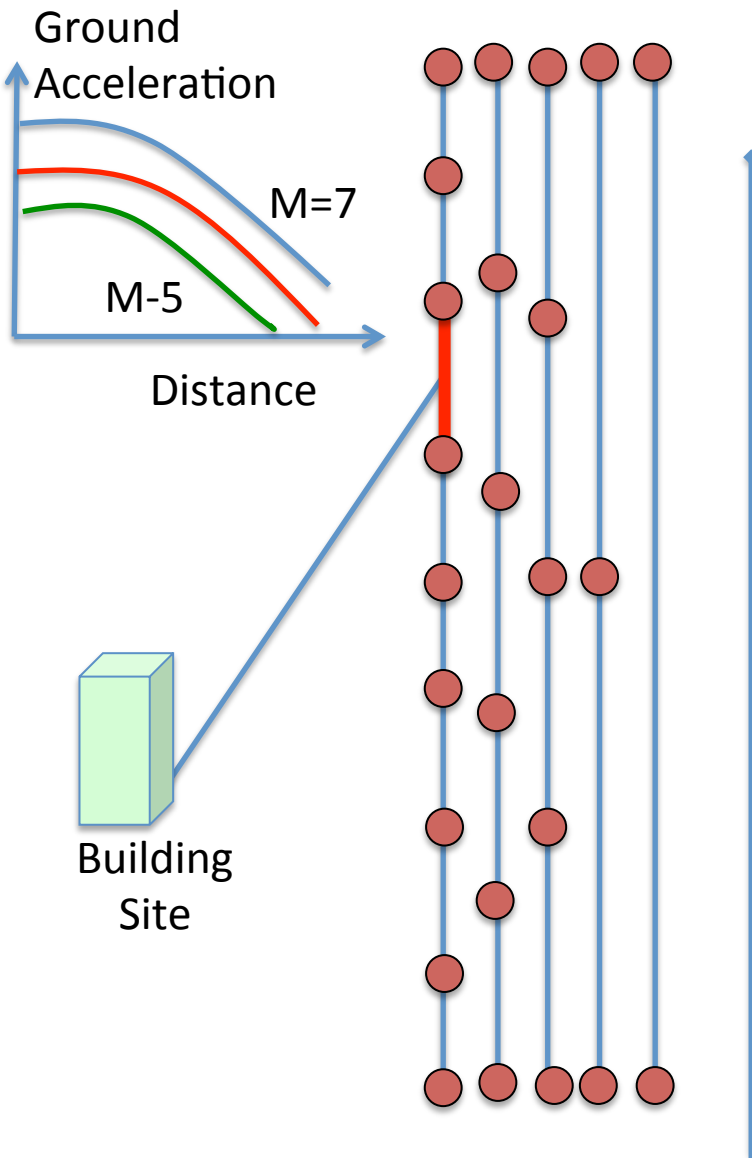




Estimating Earthquake Hazards

Seismic Wave Travel Path

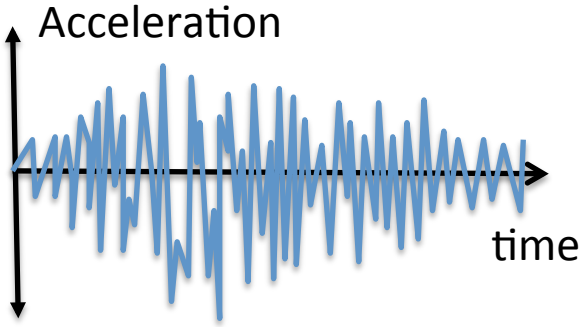
- Divide fault(s) up in to possible segments that could rupture
- Estimate probability (frequencies) of each segment rupturing
- From catalogs, determine probable size of event from each segment
- For that size and distance to each segment, estimate ground shaking characteristics at site
- Compute probable characteristics of shaking at a site resulting from all possible earthquakes



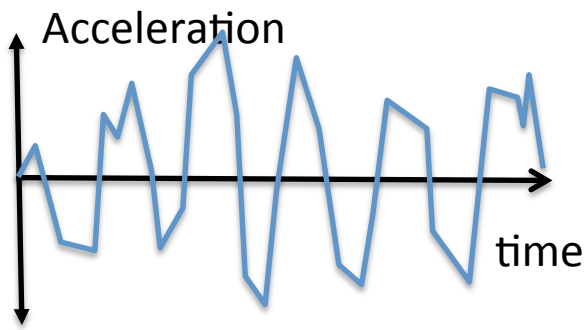
Estimating Earthquake Hazards

Account for Local Soil Effects

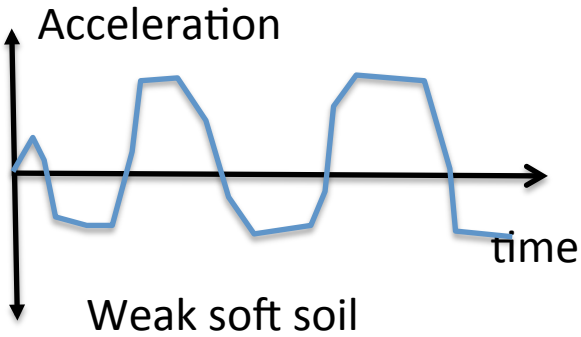
- Compute stiffness and strength of soil
- Estimate effects of soil on ground motions



Thus, different soils will damage different buildings



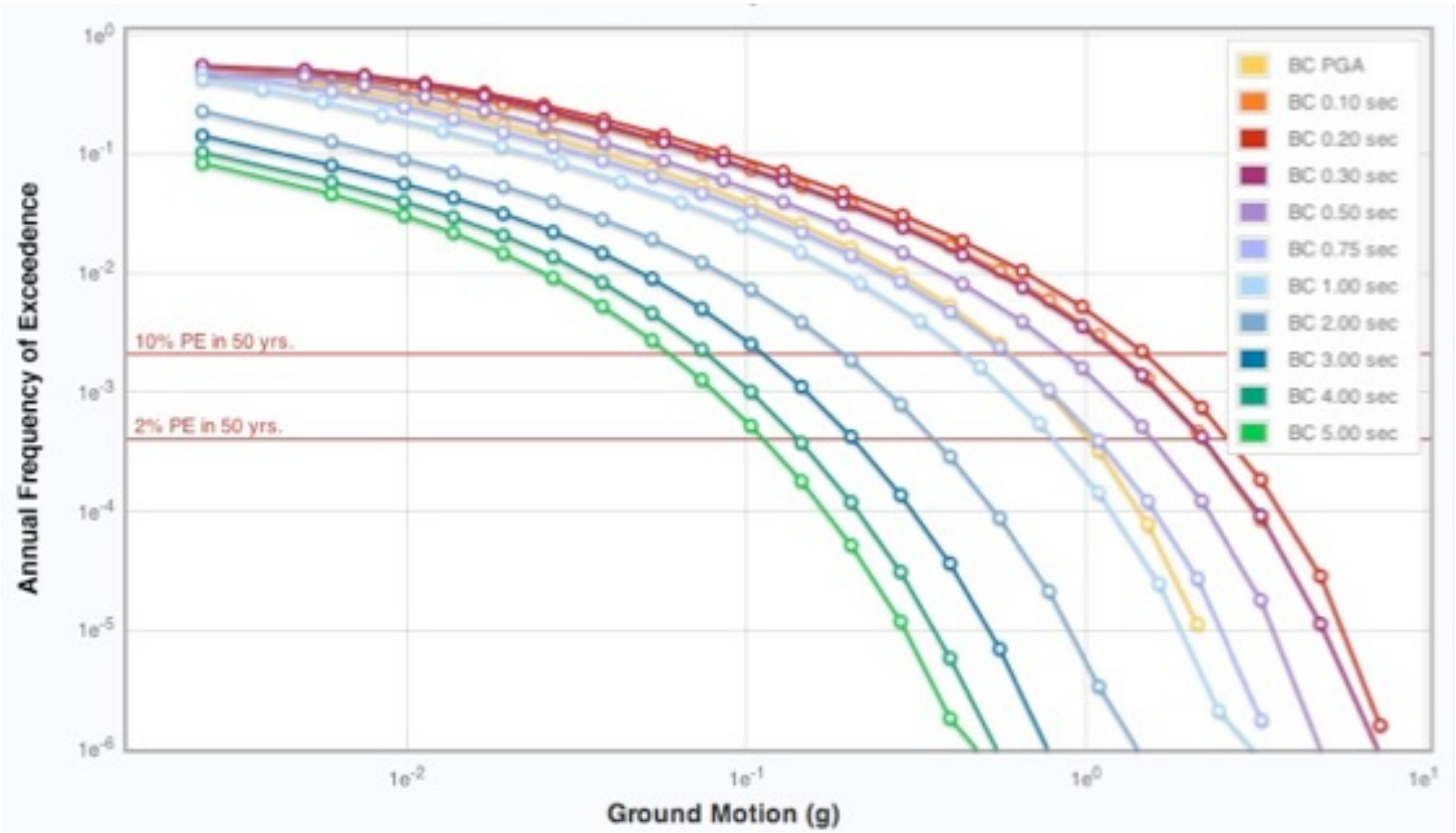
Small earthquake on soft but strong soil



Weak soft soil

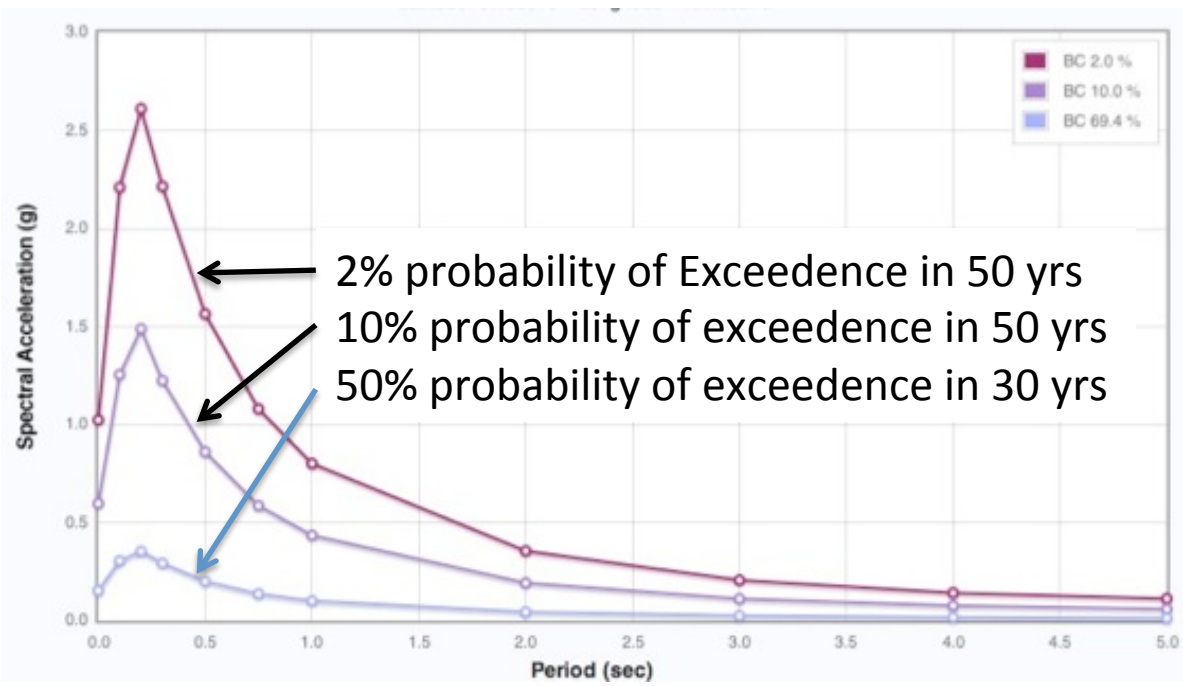
Estimating Earthquake Hazards

Net result

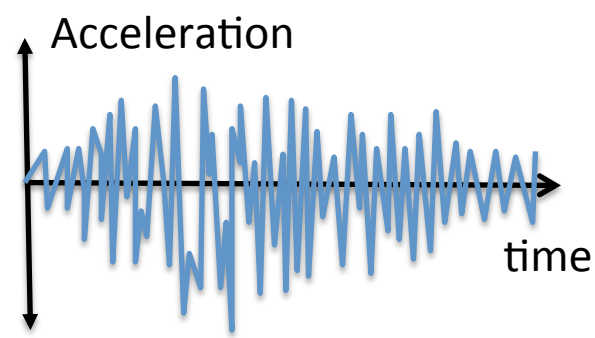
- 

Estimating Earthquake Hazards

For Design:

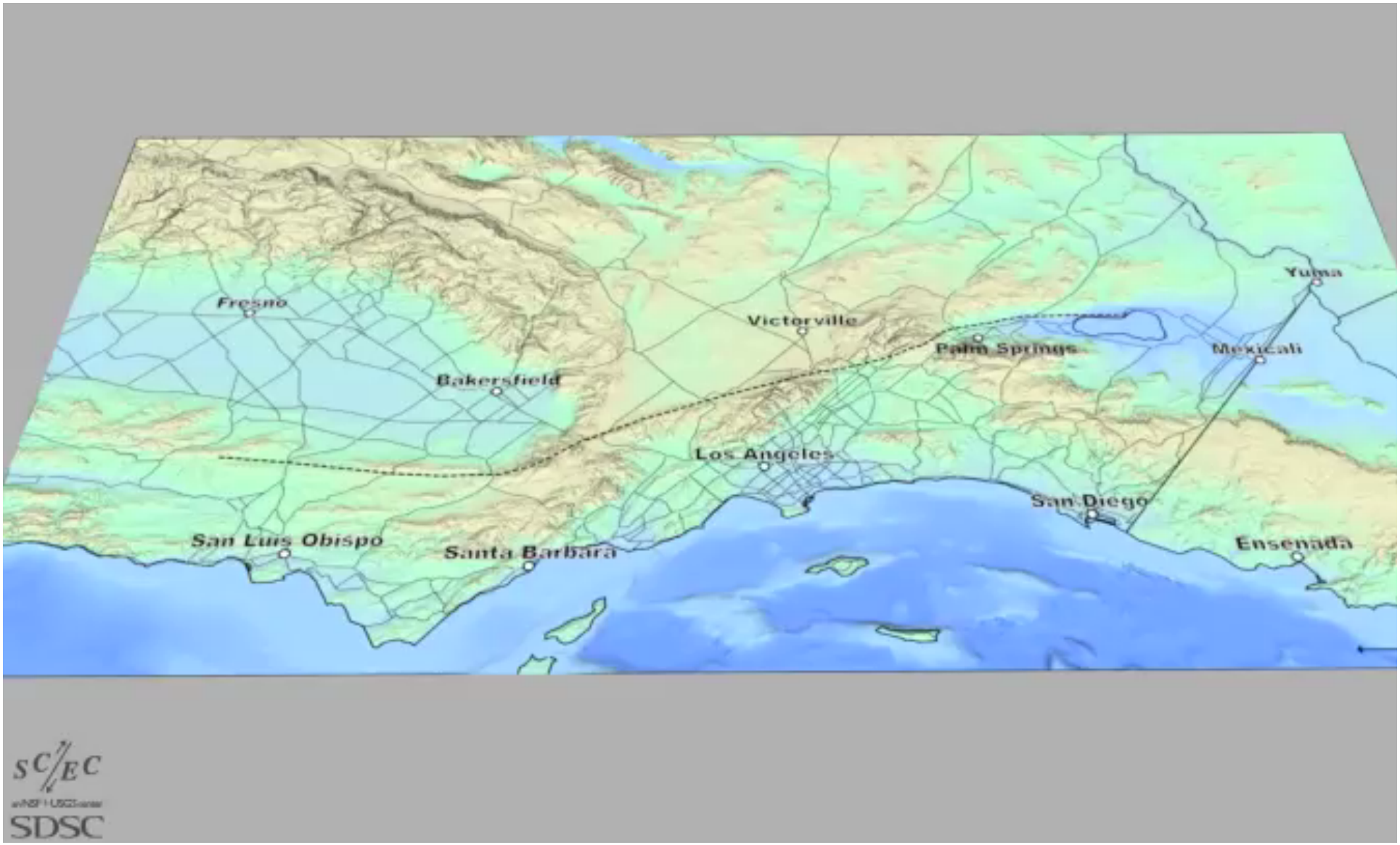


Uniform Hazard Response Spectrum



Time histories from databases, synthetic ground motions, or finite fault models

Computer models to predict motions



All of this is highly uncertain

- The past is no guarantee of future events
- Engineers and public often take median expectations as deterministic predictions
  - Large coefficients of variation
  - Actual outcome can be far far worse, or better.
- Statistical and numerical methods suspect
  - Short history of events
  - Heterogeneous data sets
  - Epistemic uncertainties
  - Statistical distributions not bounded by theory

Risks of Conveying Risk to Public

2009 L'Aquila Earthquake

- Seven Scientists and Engineers (one a Berkeley grad) sentenced to six years in prison for manslaughter
- Members of Government Panel: National Commission for the Forecast and Prevention of Major Risks

Risks of Conveying Risk to Public

2009 L'Aquila Earthquake

- Commission gave advice in a meeting 6 days before the earthquake, and a day after the strongest in an ongoing swarm of small earthquakes that shaken the area around L'Aquila.
- The prosecutor accused them of convincing some of the town's residents to stay indoors on the night of the quake instead of seeking shelter outside, as they were used to doing when tremors happened.
- Judge said they had analyzed the risk of a major quake in a "superficial, approximate and generic" way and that they were willing participants in a "media operation" to reassure the public.
- The judge said the scientists were not convicted for failing to predict an earthquake, something he says was impossible to do, but for their complete failure to properly analyze, and to explain, the threat posed by the swarm.
- They have appealed their conviction.

Engineering Challenge

Design structures that are:

- Safe
- Robust such that they will behave well in spite of great uncertainties in ground motions (and computer modeling and actual behavior)
- Resilient
- Sustainable
- Affordable

RISK = PROBABILITY x HARM

For probabilistic seismic risk assessment

SEISMIC RISK =

HAZARD X VULNERABILITY X EXPOSURE

What are earthquake engineers in US trying to accomplish?

Preserve Life Safety and Prevent Collapse!

Building codes are minimum standards for public safety

- Stated purpose:
  - Provide minimum provisions for design and construction of structures to resist effects of seismic ground motions
  - "…to safeguard against major structural failures and loss of life, not to limit damage or maintain function."

Designed to protect life in extreme event, but damage is expected

Building codes do not provide earthquake proof structures

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Building codes do not provide earthquake proof structures

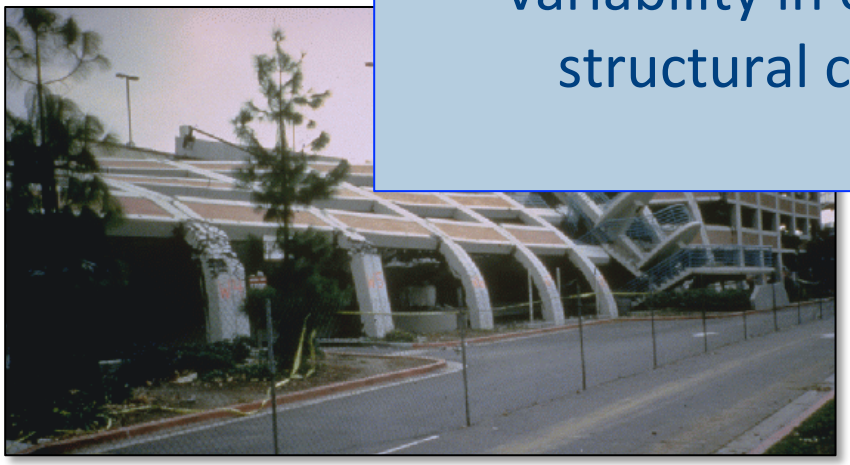
Most building codes are INDIRECT

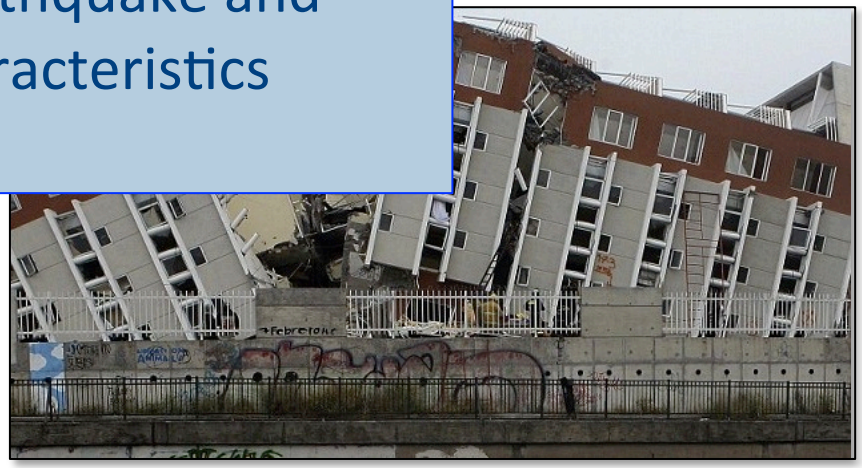
- Numerous provisions:
  - If satisfied, provide assurance that structure is safe
  - Are not directly related to outcomes
- Wide variation in seismic performance expected for similar structures

Intended 90% confidence of preventing collapse in earthquake with 2% frequency of being exceeded in 50 years.

Wide variety of building and ground motion characteristics

Robust structures and systems needed to account for great variability in earthquake and structural characteristics



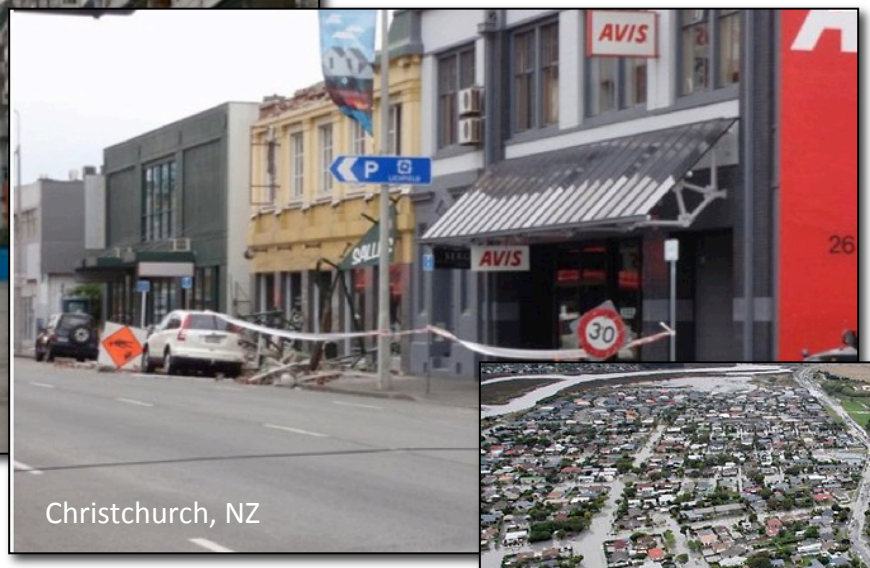


Nonstructural Elements: Life Safety and Economic Concerns

Structures Should Not Be Considered in Isolation: Disaster vs Catastrophe

Natural disasters cause wide-spread moderate to severe damage that may strain ability of a community to respond and recover


Wenchuan Earthquake



Christchurch, NZ


Christchurch, NZ

Widespread damage can have substantial long-lasting social, economic and cultural impact on the well-being and vitality of a city and nation

Resilient Communities

- Provide citizens, organizations and businesses the ability at a minimum to "shelter in place" following earthquakes
  - Without this, recovery is slow and impact large
- Communities need at least:
  - Basic infrastructure and lifelines
  - Key public/government services
  - Housing
  - Business continuity for employment and services
  - Schools
  - Food

Next challenge for engineers: Earthquake-Resilient Structures

In *Earthquake Engineering*, our future challenge is to develop new or improved structures and infrastructure systems that:

- ✓ protect public safety, and are
- ✓ economical,

but that

- ✓ can be constructed quickly with minimal disruption to the public and to the environment, and
- ✓ **can withstand strong earthquake ground shaking (and other hazards) safely, with little disruption or cost associated with post-earthquake inspections and repairs.**

Common Characteristics of Disaster Resilient Structures

- Earthquake resisting system that controls distribution of inelastic deformations
- Durable and/or easily replaceable energy dissip regions/devices
- Easy and safe post-event inspection

Vulnerabilities

- Human toll
- Property losses
- Disruption of function
- Moving from a disaster to catastrophe

The Earthquake Divide

- Casualties in Representative Earthquakes

Event	M	Deaths
2011 New Zealand	6.3	185
2011 Japan	9.0	1,575*
2010 Chile	8.8	500
1994 Northridge	6.7	33
1995 Kobe, Japan	7.2	6,400
1989 Loma Prieta	6.9	57
1987 Whittier Narrows	5.9	3
1971 San Fernando	6.6	65
1906 San Francisco	7.9	375 (3000+)

* Includes 1,331 deaths due to exposure following quake, and 18 recue workers; 14,308 more drowned; more than 2000 are still missing.

Want to avoid this

Protecting public from injuries from collapse of structures

1999 Kocaeli, Turkey, Earthquake

2008 Wenchuan, China, Earthquake

Achieving "Life Safety" remains a major issue for developing countries and other regions susceptible to large but low probability events

Education - Enforcement - Low Cost Toughness

Engineering Effective in Reducing Loss of Life

Sendai, Japan

Structural damage due to ground shaking was relatively light for new structures even in regions of heavy shaking

Older buildings vulnerable (Sendai shown)


CHIGUAYANTE
HUALPEN
A 200 MTS

Older facilities remain vulnerable to earthquakes

Earthquake damages have prompted numerous seismic evaluation and retrofit programs:

- Mandated for critical facilities
- At change in ownership, occupancy and substantial remodeling
- Voluntary upgrades

Research-backed consensus standards exist and these are being continually improved by research

Examples of Retrofit Buildings on Berkeley Campus

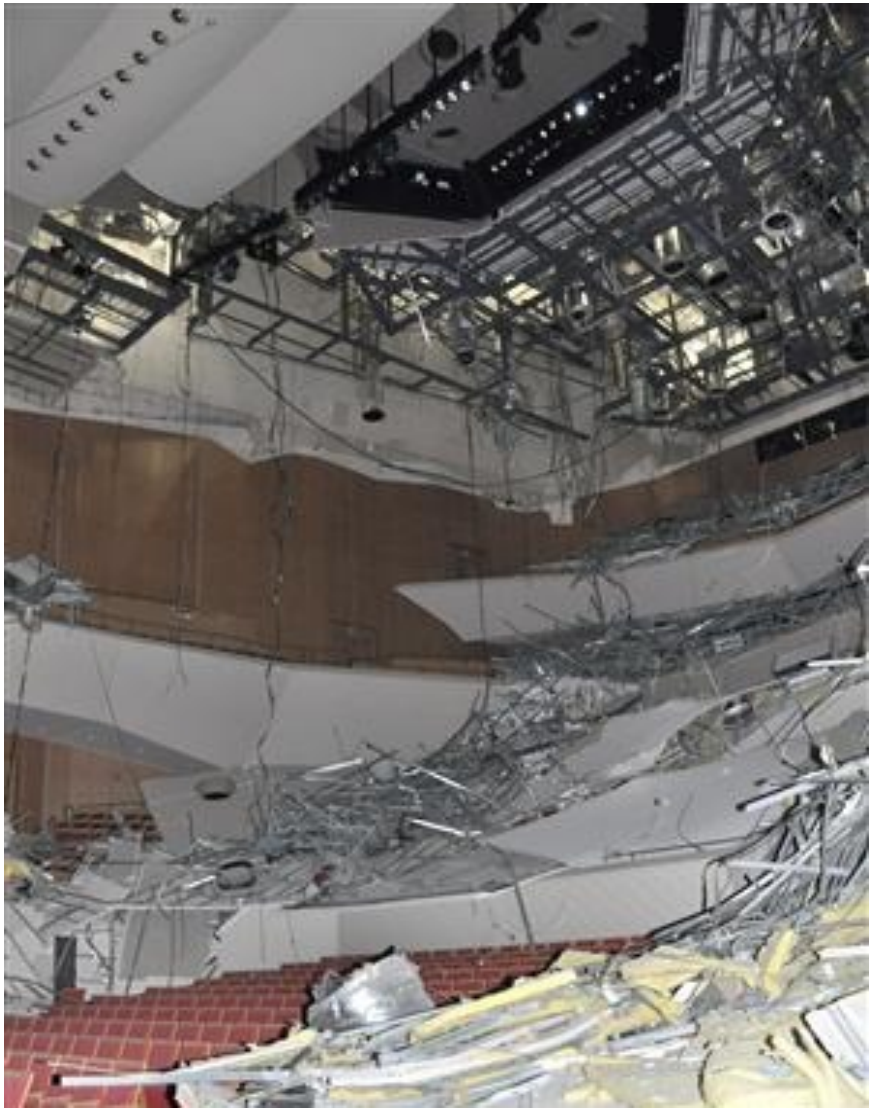
“Non-Structural” Damage - Sendai

“Non-Structural” Damage - Tokyo

Concert Hall – Kawasaki (near Tokyo)

Moderate Shaking PGA ~ 0.15g

Ref: http://sankei.jp.msn.com



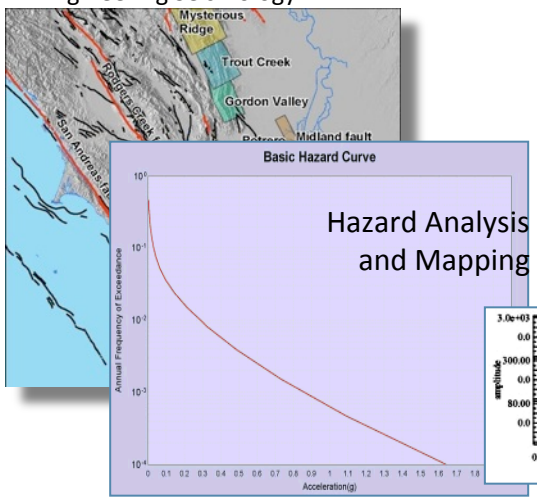
unoccupied at time of earthquake

Nonstructural Elements Also Pose Life Safety Concerns

Holistic risk-oriented view:

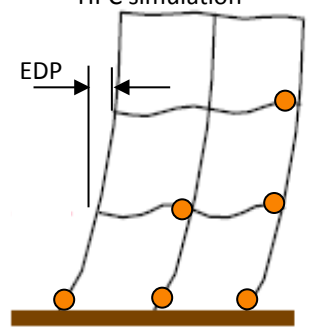
Performance-Based Seismic Design

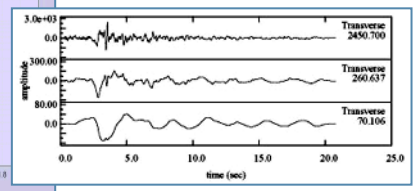
Engineering Seismology



Hazard Analysis and Mapping

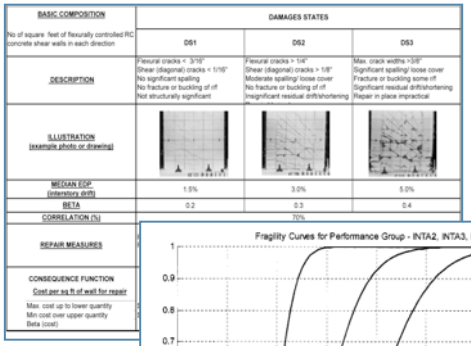
HPC simulation

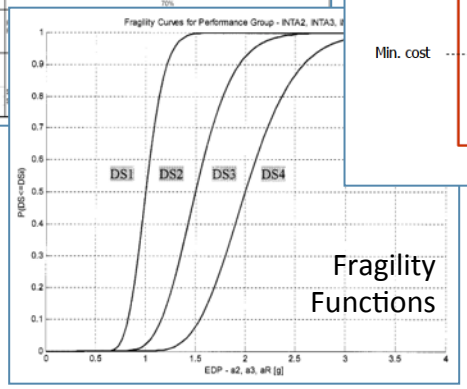




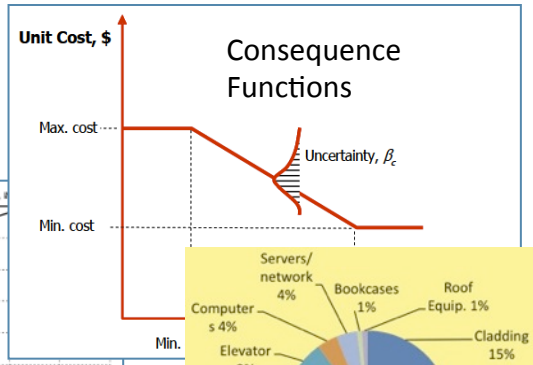
Ground motion selection and scaling

Performance Databases

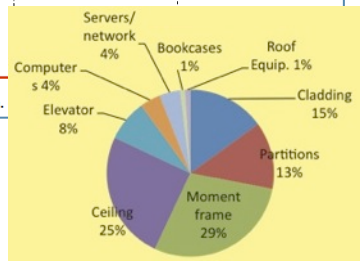




Fragility Functions



Consequence Functions



Loss Assessment

Seismic Hazard Analysis	→	Response Analysis	→	Damage Analysis	→	Loss Analysis
$\lambda(im)$		$G(edp \mid im)$		$G(dm \mid edp)$		$G(dv \mid dm)$
IM: intensity measure		**EDP**: Engineering Demand Parameter		**DM**: Damage Measure		**DV**: Decision Variable

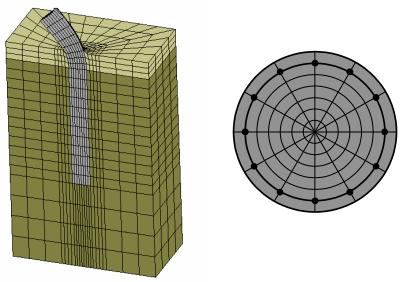
$$\lambda(DV > dv) = \int_{im}\int_{dm}\int_{edp} G(dv \mid dm)\, dG(dm \mid edp)\, dG(edp \mid im) \left| d\lambda(im) \right|$$

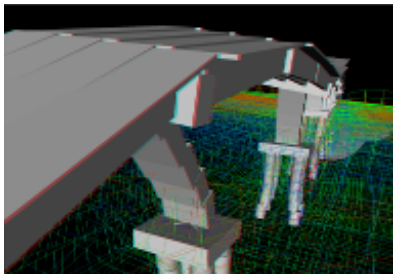
Probabilistic Assessment of:

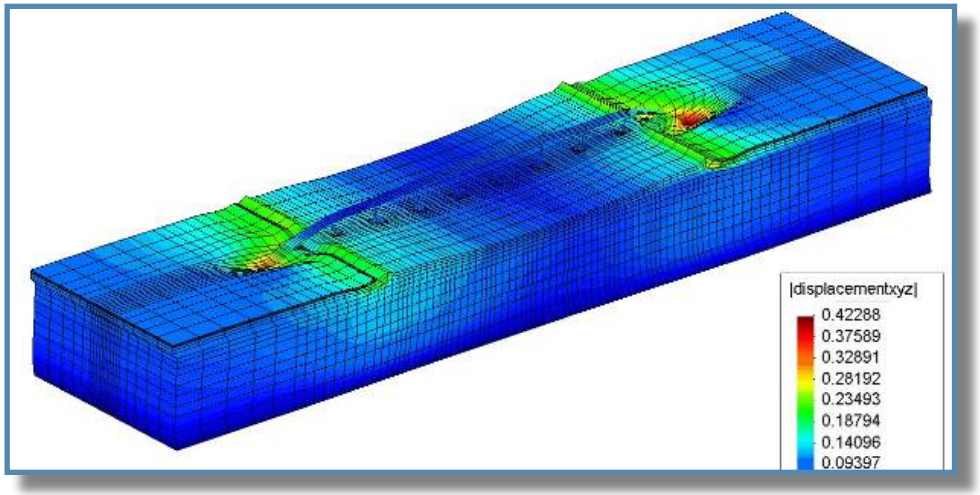
- ✓ Cost of repair and loss of function
- ✓ Downtime
- ✓ Casualties
- ✓ *Embodied energy*

Improving engineering tools: High Performance Simulation

OpenSees - Open Source, object oriented framework for seismic simulation of geotechnical and structural models





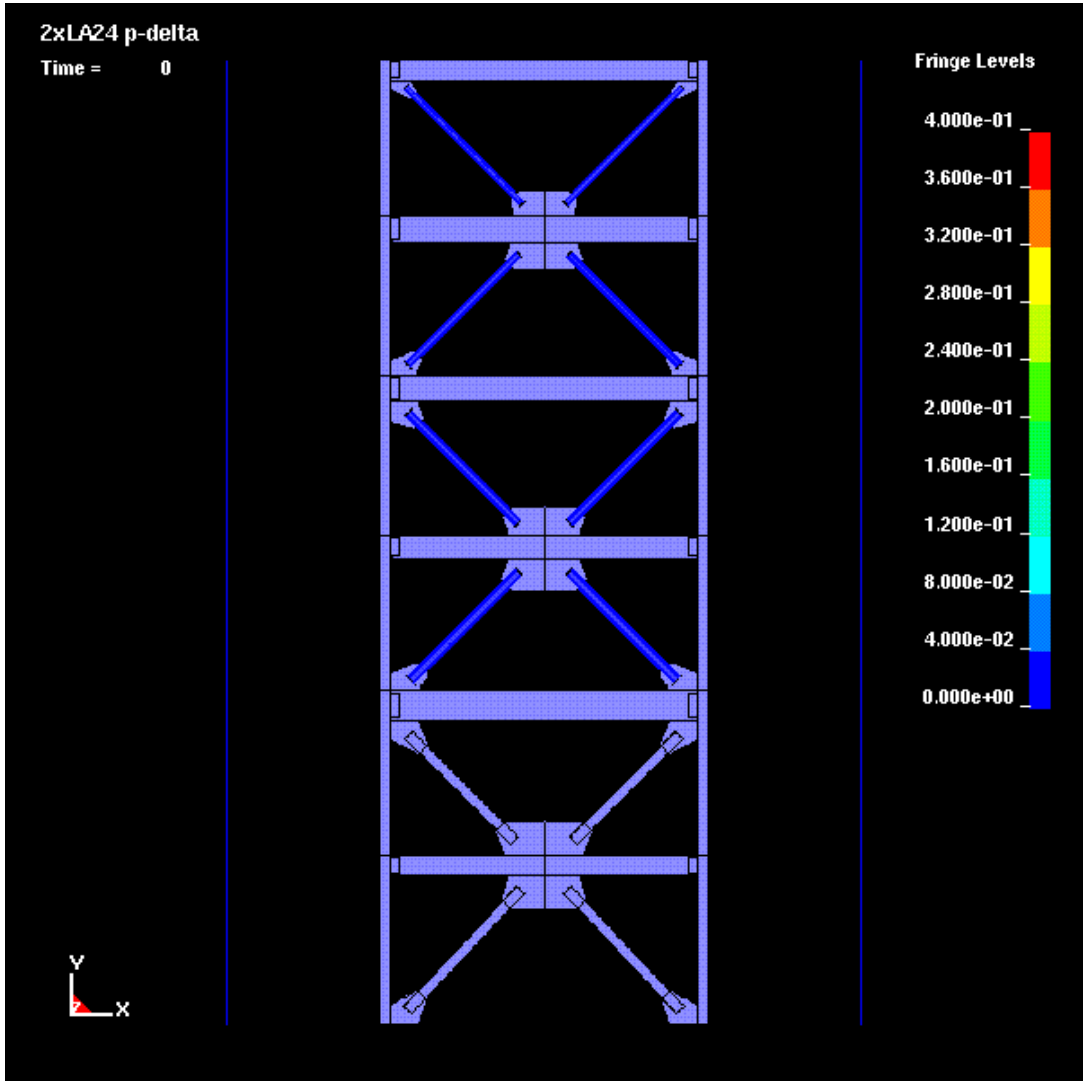


New Development Efforts by PEER:

- Optimization and reliability analyses
- New elements
- Graphical user interfaces
- Integrated PBEE tools

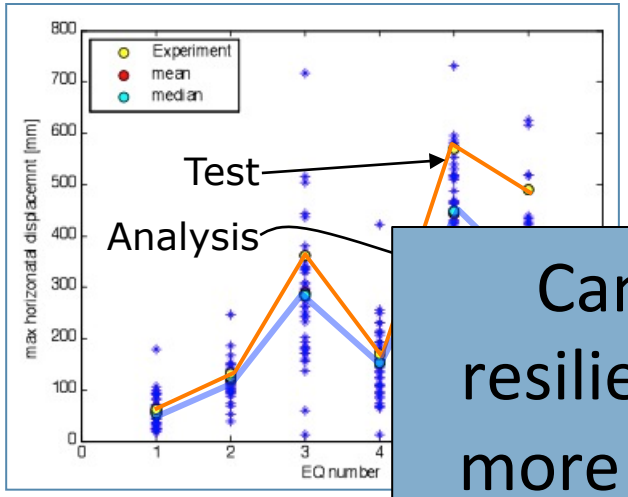
http://opensees.berkeley.edu or NEES.org

Our predictions of the future depend on computer models



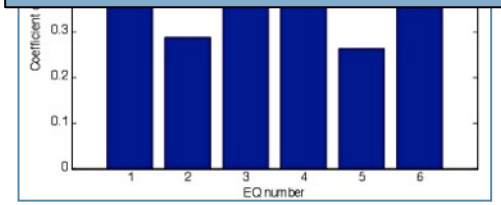
Pursuing Fundamental Knowledge: Behavior of Reinforced Concrete Columns

Tests undertaken to validate concepts and numerical models used in PBEE



Can we devise more resilient systems that are more reliable to analyze?

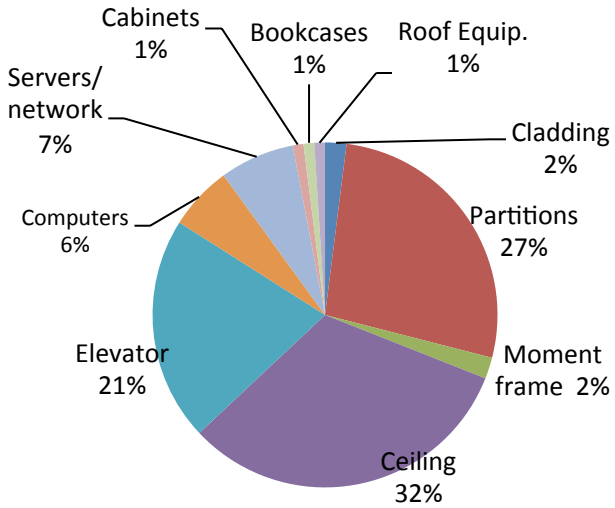
41 expert teams participated



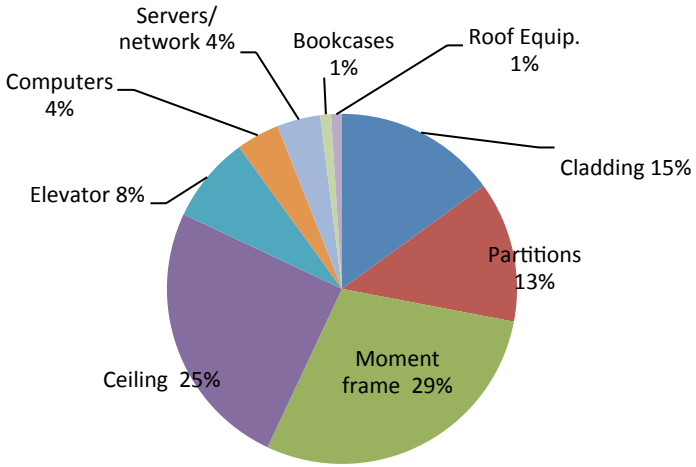
PEER-NEES RC Column Blind Analysis Contest - 2010

Full-scale 1D tests of circular column - Jose Restrepo, PI (PEER, Caltrans, UNR, FHWA, NEES@UCSD, NEEScomm & NSF)

Contributions of Damage to Economic Loss



Fixed Base, 475 year EQ

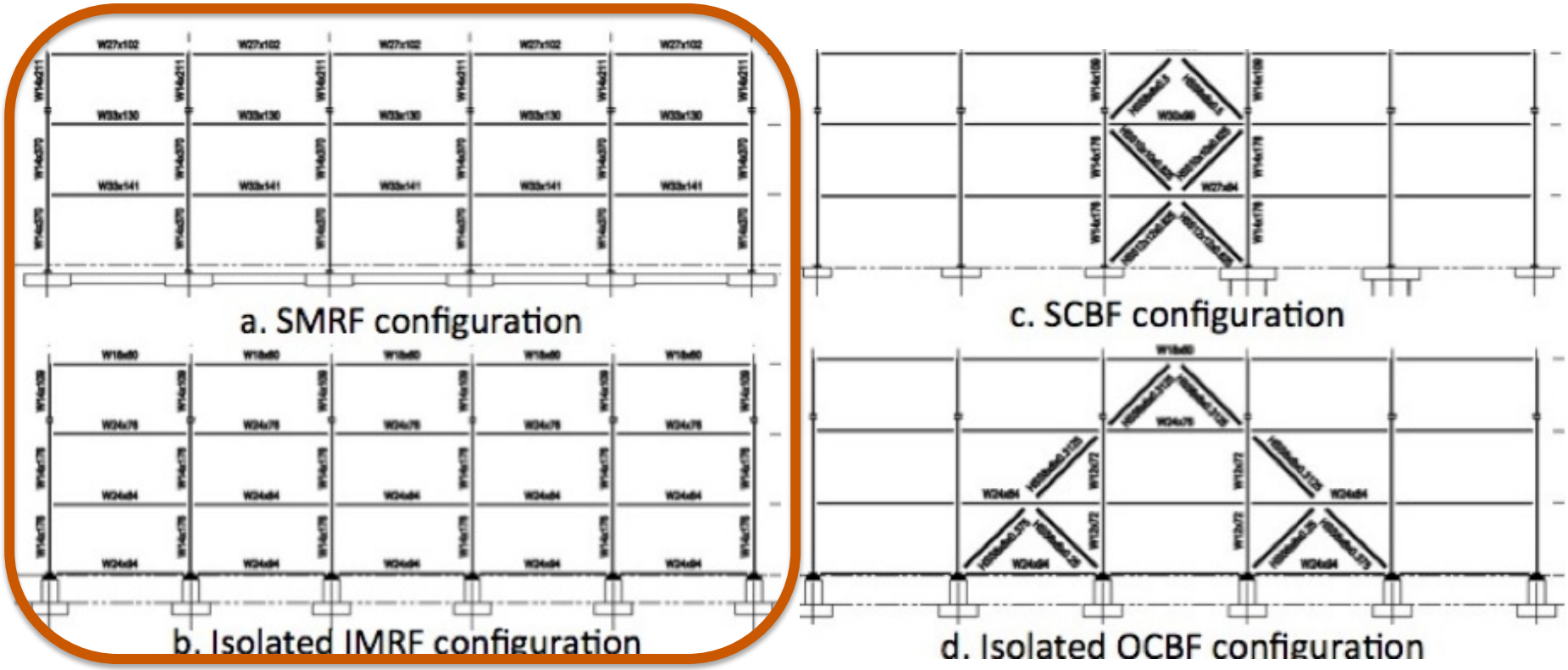


Fixed Base, 2475 year EQ

Damage in traditional fixed base buildings is costly, widespread & disrupts occupants during repair.

Nonstructural components and contents contribute 60% to 80% of cost of buildings – they may contribute 60% to 100% of loss.

Archetype Buildings Considered

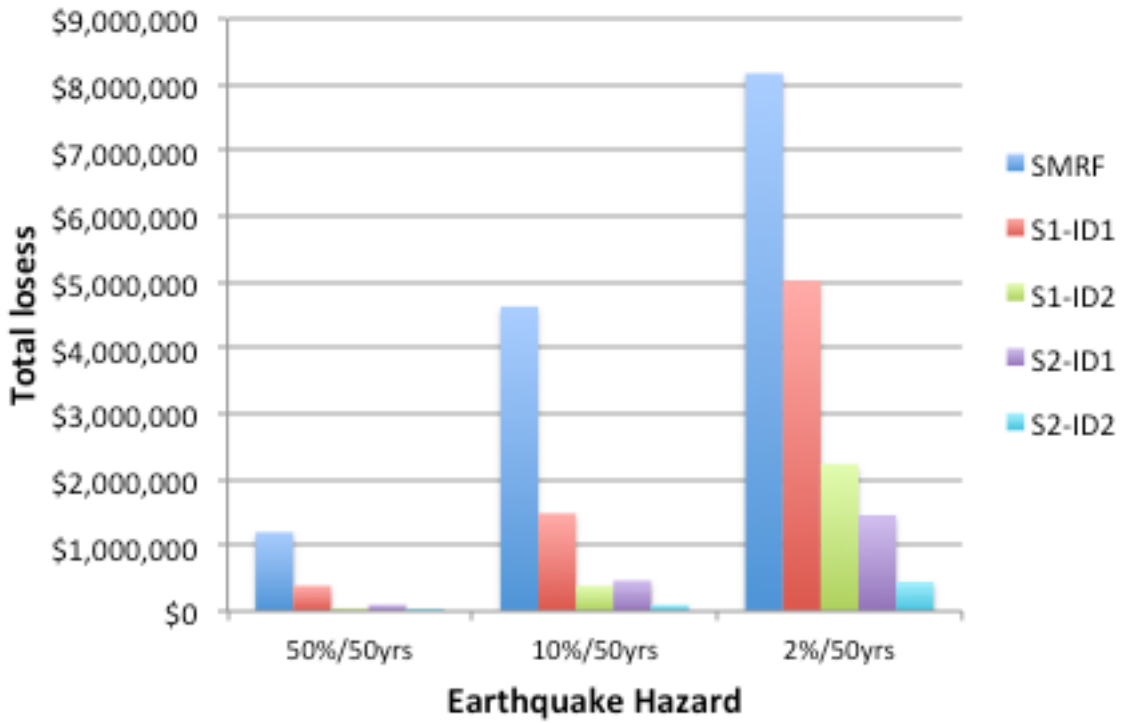


Note isolated structures are expected to be about $1 million more than fixed base cases due to excavation and construction of isolation plane

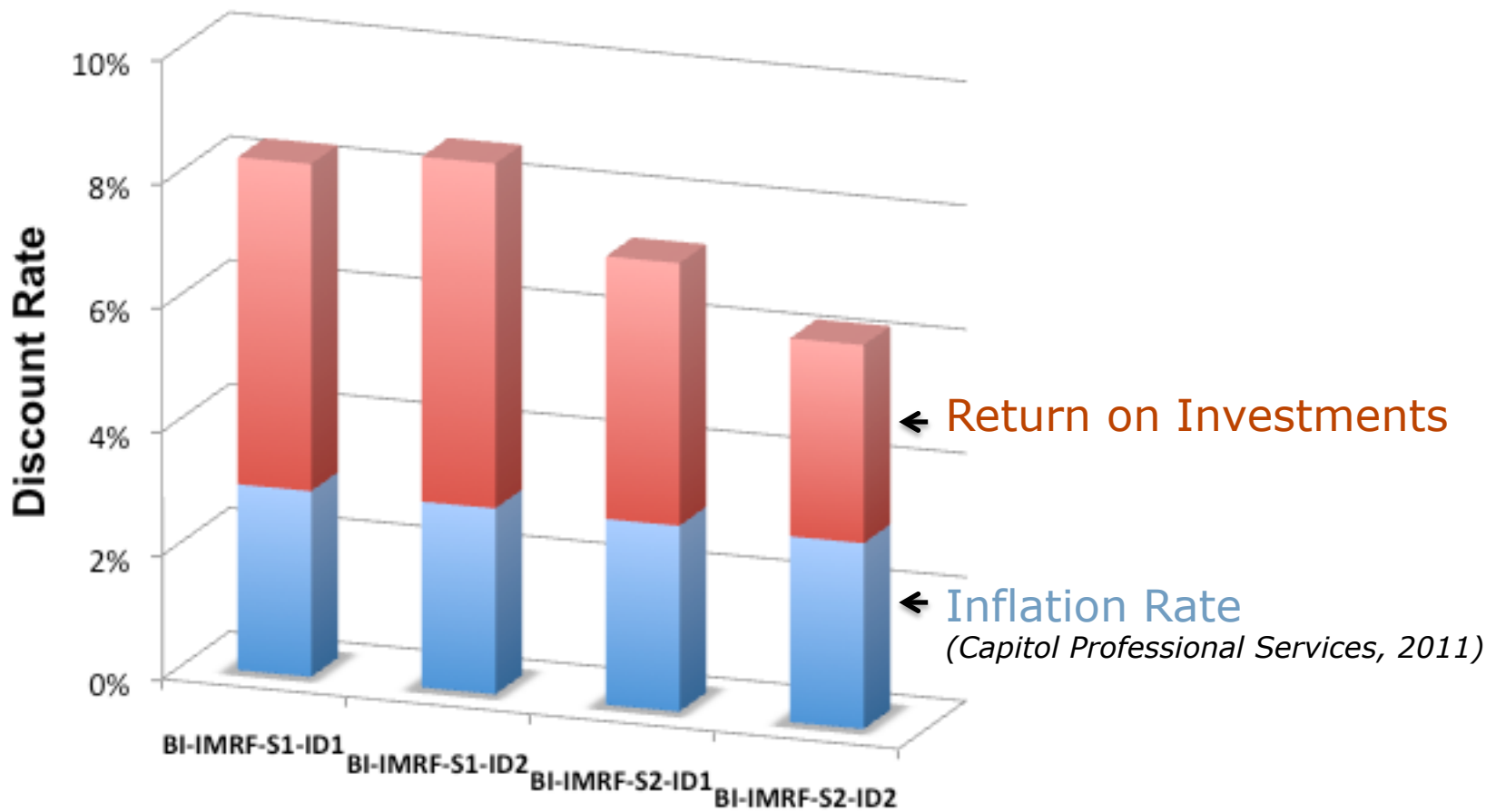
Total Losses = Repair + Business Interruption

Business interruption cost of a three storey office building in downtown Oakland = $3550/day

(LoopNet,2012)



Return on Investments



(Capitol Professional Services, 2011)

Indirect Contributions to Loss by Business Interruption (BI)

- Direct BI

Source: www.nytimes.com

Clean room in the Renesas Electronics Microcontroller Manufacturing Facility; Hitachinaka, Ibaraki Prefecture

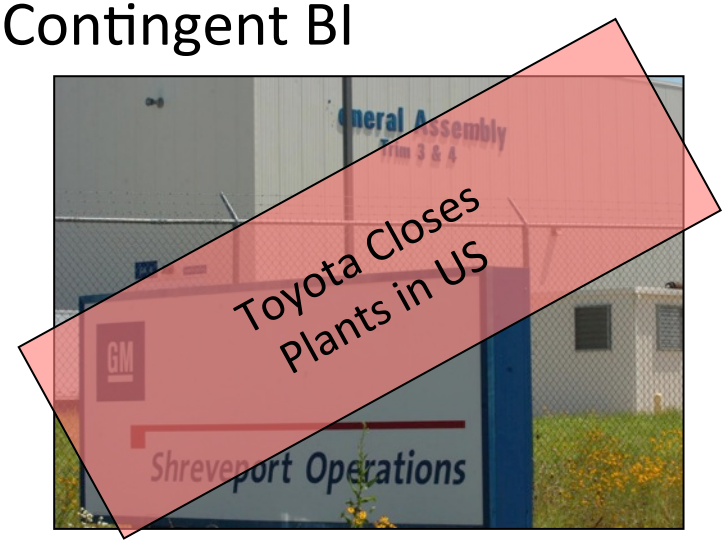
Two weeks to complete initial damage assessments and begin repairs; partial operation targeted for June 2011

More than 2,000 external contractors have been hired to assist with repair work (Source: http://am.renesas.com)

Additional interruptions due to lack of electric power.

Courtesy: Carlos Cabrera, RMS

- Contingent BI

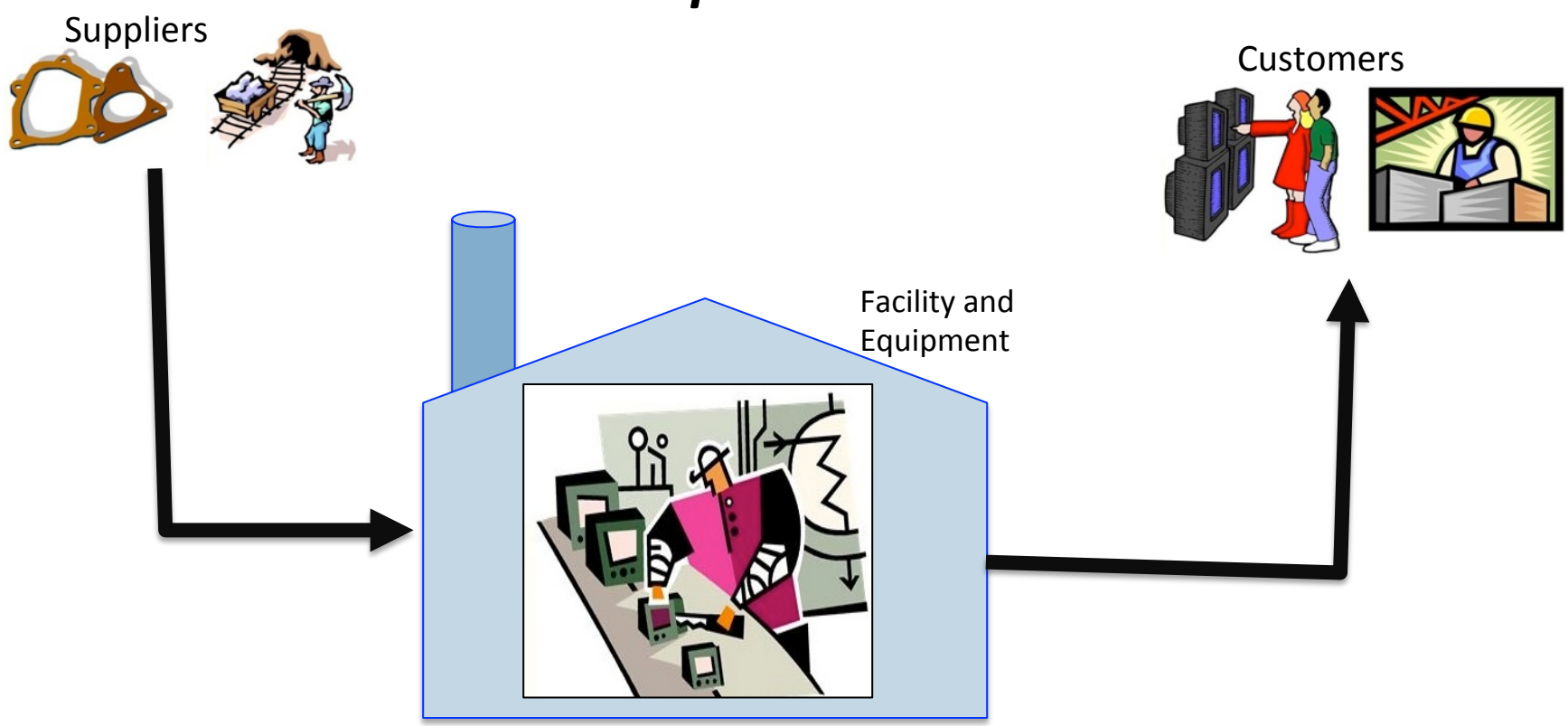


General Motors automobile assembly facility in Shreveport, Louisiana

Facility shut down for a week in March due to parts shortages

On April 22nd, Toyota announced that its manufacturing plants in North America were operating at 30% of capacity because of the parts supply situation.

Supply chains are complex and interdependent



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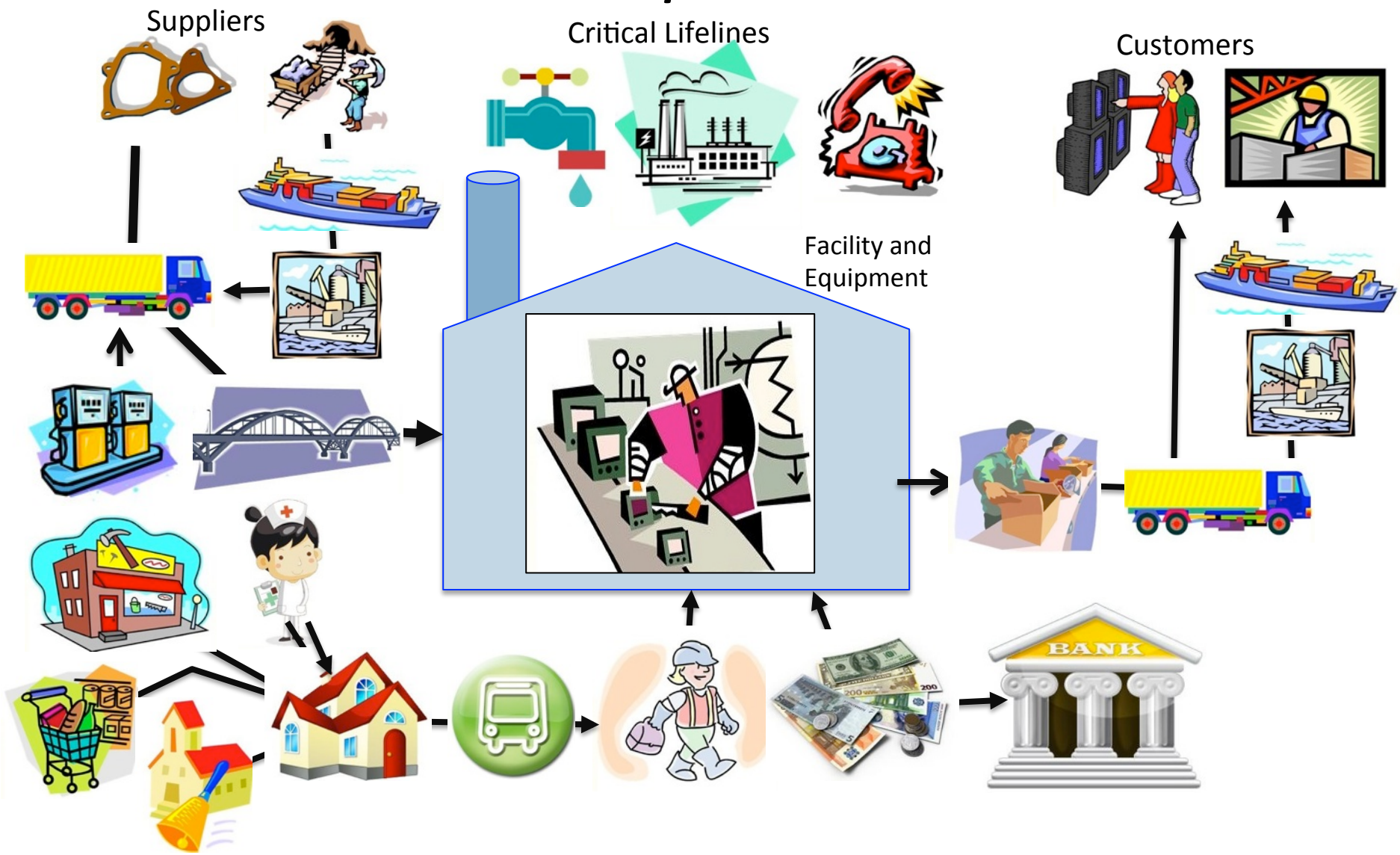
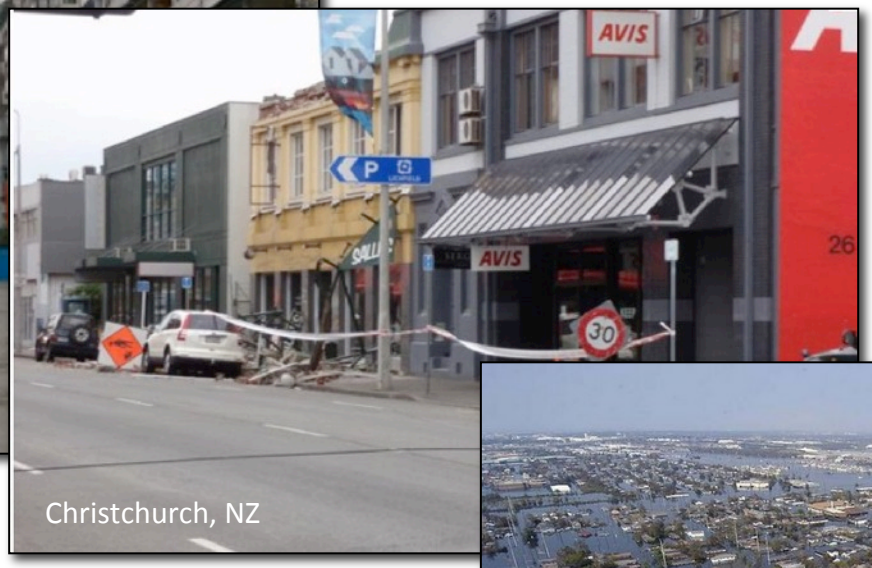


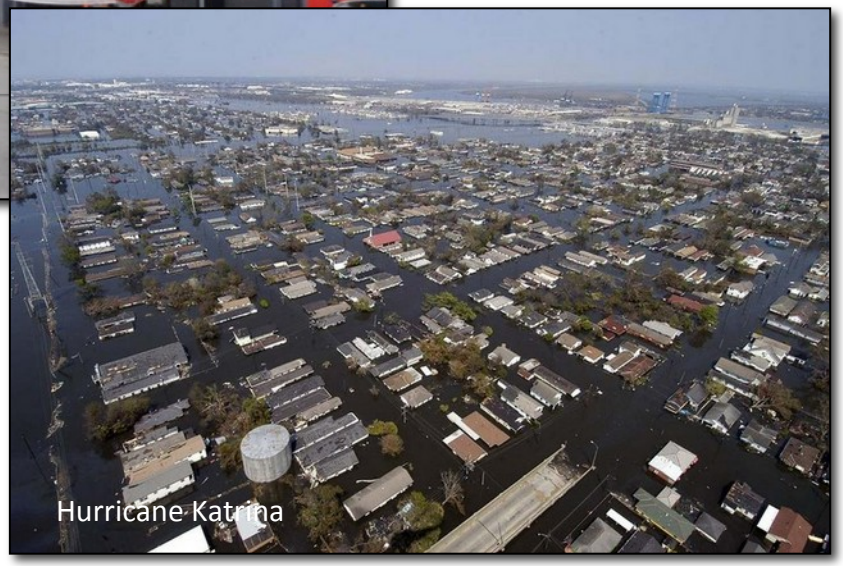
Structures Should Not Be Considered in Isolation: Disaster vs Catastrophe

Natural disasters cause wide-spread moderate to severe damage that may strain ability of a community to respond


Wenchuan Earthquake



Christchurch, NZ

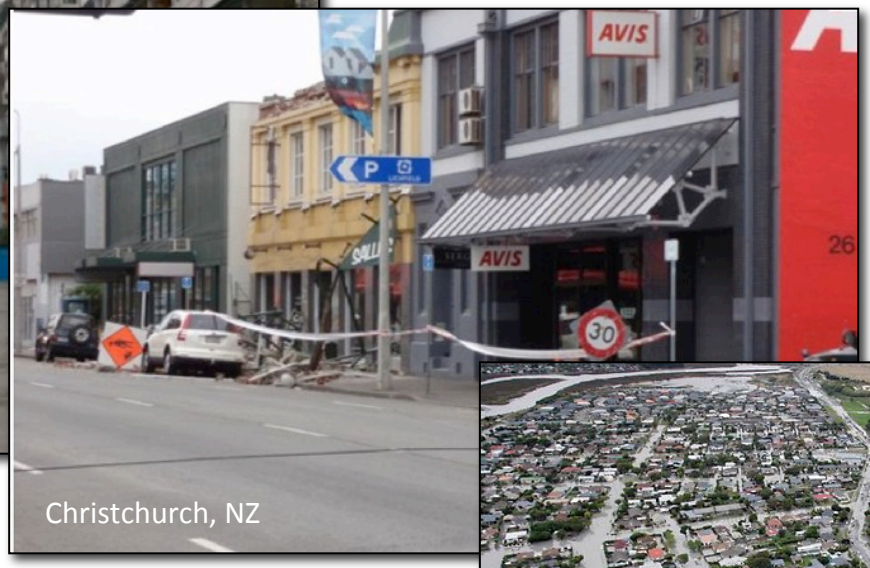

Hurricane Katrina

Widespread damage can have substantial long-lasting social, economic and cultural impact on the well-being and vitality of a city and nation

Disasters can transform into catastrophes

Natural disasters cause wide-spread moderate to severe damage that may strain ability of a community to respond


Wenchuan Earthquake



Christchurch, NZ


Christchurch, NZ

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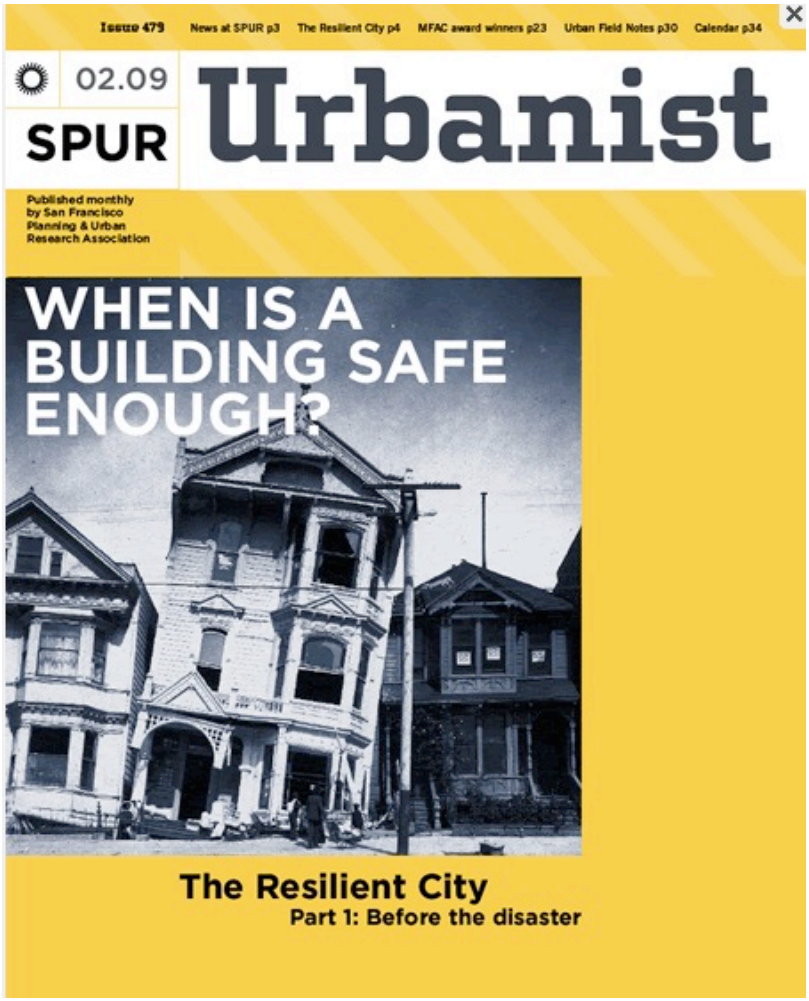
Resilient structures, networks and communities



TARGET STATES OF RECOVERY FOR SAN FRANCISCO'S BUILDINGS AND INFRASTRUCTURE

INFRASTRUCTURE CLUSTER FACILITIES	Event occurs	Phase 1 Hours			Phase 2 Days		Phase 3 Months		
		4	24	72	30	60	4	36	36+
CRITICAL RESPONSE FACILITIES AND SUPPORT SYSTEMS									
Hospitals								X	
Police and fire stations			X						
Emergency Operations Center									
Related utilities						X			
Roads and ports for emergency				X					
CalTrain for emergency traffic					X				
Airport for emergency traffic				X					
EMERGENCY HOUSING AND SUPPORT SYSTEMS									
95% residence shelter-in-place								X	
Emergency responder housing				X					
Public shelters							X		
90% related utilities								X	
90% roads, port facilities and public transit							X		
90% Muni and BART capacity						X			
HOUSING AND NEIGBORHOOD INFRASTRUCTURE									
Essential city service facilities							X		
Schools							X		
Medical provider offices								X	
90% reighborhood retail services									X
95% of all utilities								X	
90% roads and highways						X			
90% transit						X			
90% railroads							X		
Airport for commercial traffic					X				
95% transit							X		
COMMUNITY RECOVERY									
All residences repaired, replaced or relocated									X
95% neighboorhood retail businesses open								X	
50% offices and workplaces open									X
Non-emergency city service facilities								X	
All businesses open									X

TARGET STATES OF RECOVERY

Performance measure	Description of usability after expected event	BUILDINGS	LIFELINES
	Category A: Safe and operational		
	Category B: Safe and usable during repairs	100% restored in 4 hours	
	Category C: Safe and usable after moderate repairs	100% restored in 4 months	

Resilient Communities

- Provide citizens, organizations and businesses the ability to "shelter in place" following large earthquakes
  - Without this, recovery will be slow
- Communities need at least:
  - Basic infrastructure and lifelines
  - Key public/government services
  - Schools
  - Food
  - Housing
  - Business continuity for employment and services

Next challenge for engineers: Earthquake-Resilient Structures

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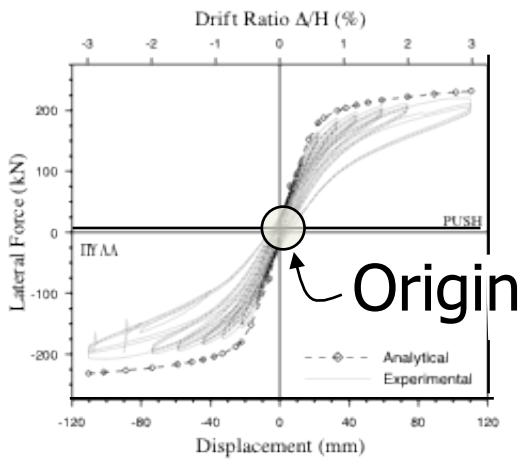
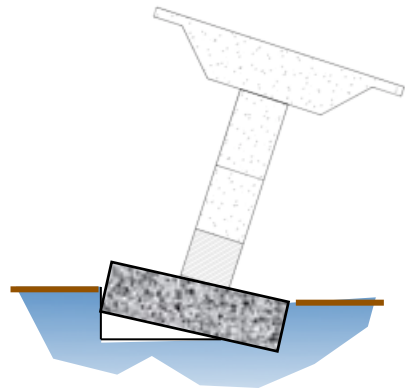
Common Characteristics of Disaster Resilient Structures

- Earthquake resisting system that controls distribution of inelastic deformations
- Durable and/or easily replaceable energy dissipation regions/devices
- Easy and safe post-event inspection
- Protect structural and nonstructural elements, and contents, by limiting
  - → Relative displacements
  - → Accelerations
- Self-centering mechanism to minimize permanent displacements.

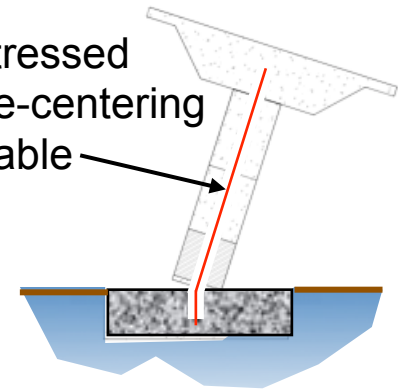
World Challenge: "Next Generation" Disaster Resilient Structures

- New systems that reduce post-earthquake disruption and speed recovery of normal operations – "Sheltering in place"



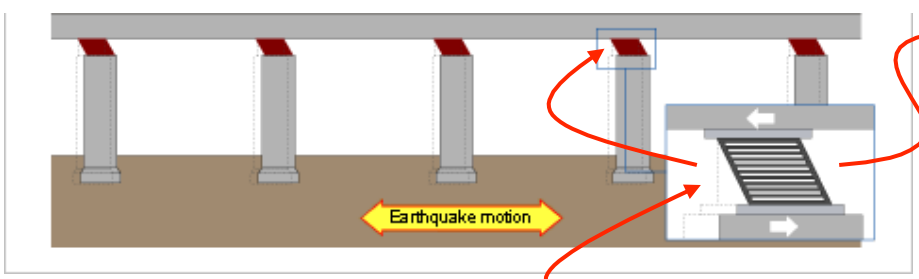


Rocking Foundation

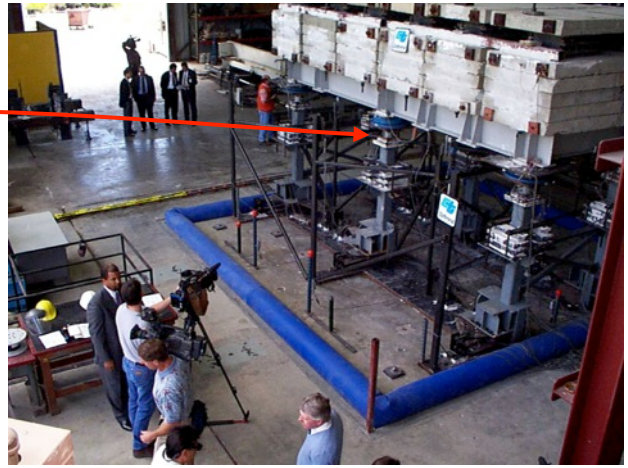


Prestressed column

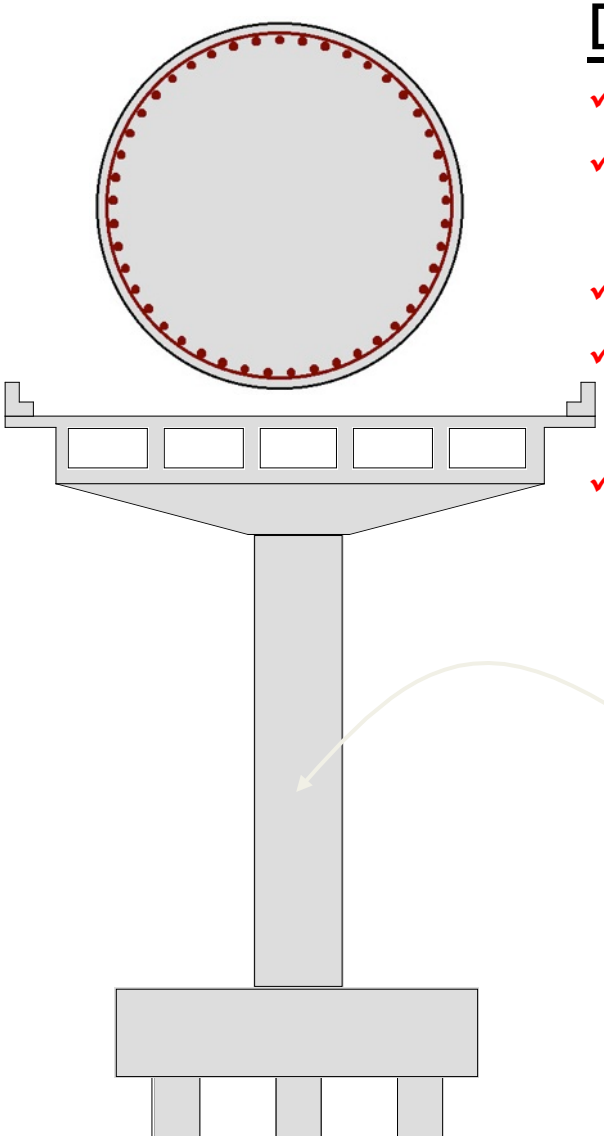
- Seismic Isolation



Seismic Isolators

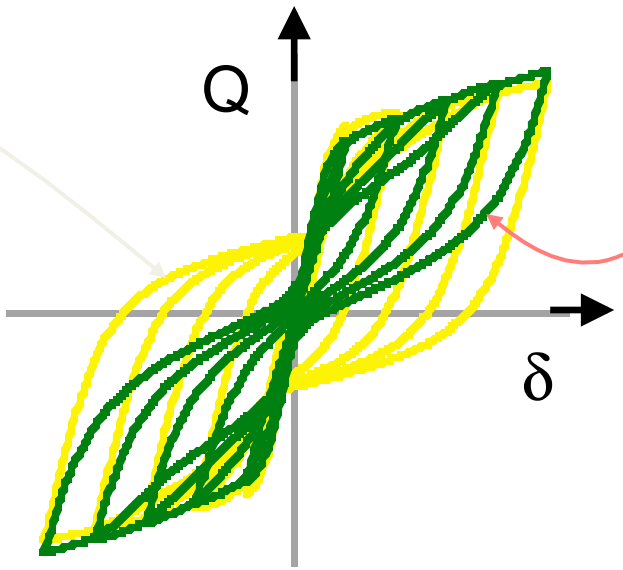


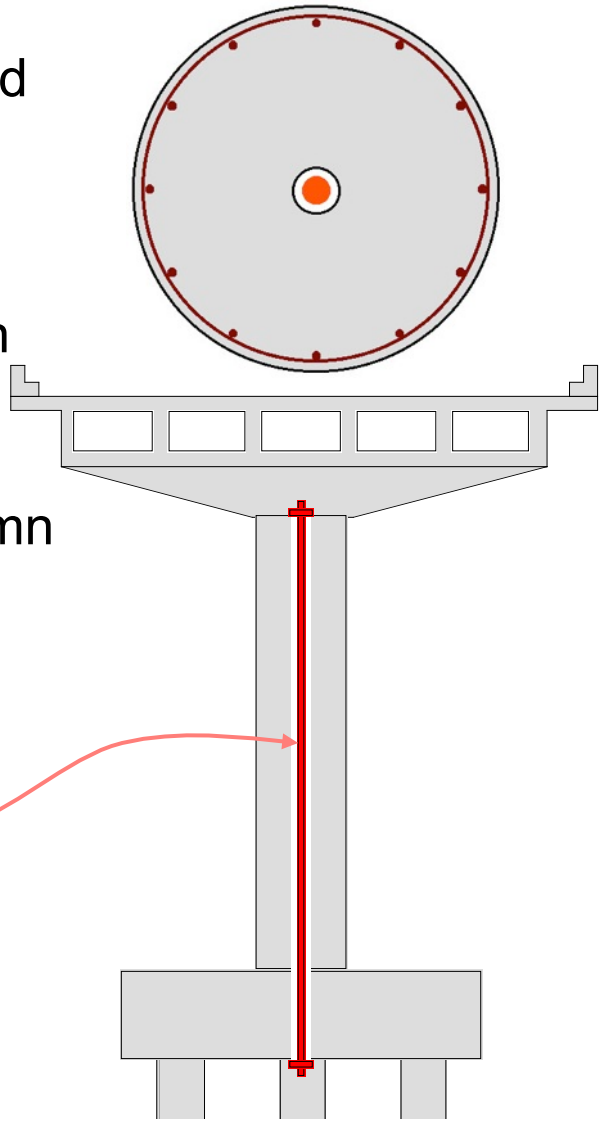
Partially Prestressed, Reinforced Concrete Self-Centering Column



Design method:

- ✓ Mild reinforcement reduced
- ✓ Prestressing force from a central unbonded tendon
- ✓ Same envelop Q-δ
- ✓ Peak displacements within 10% of RC column
- ✓ Residual displacements less than 20% of RC column

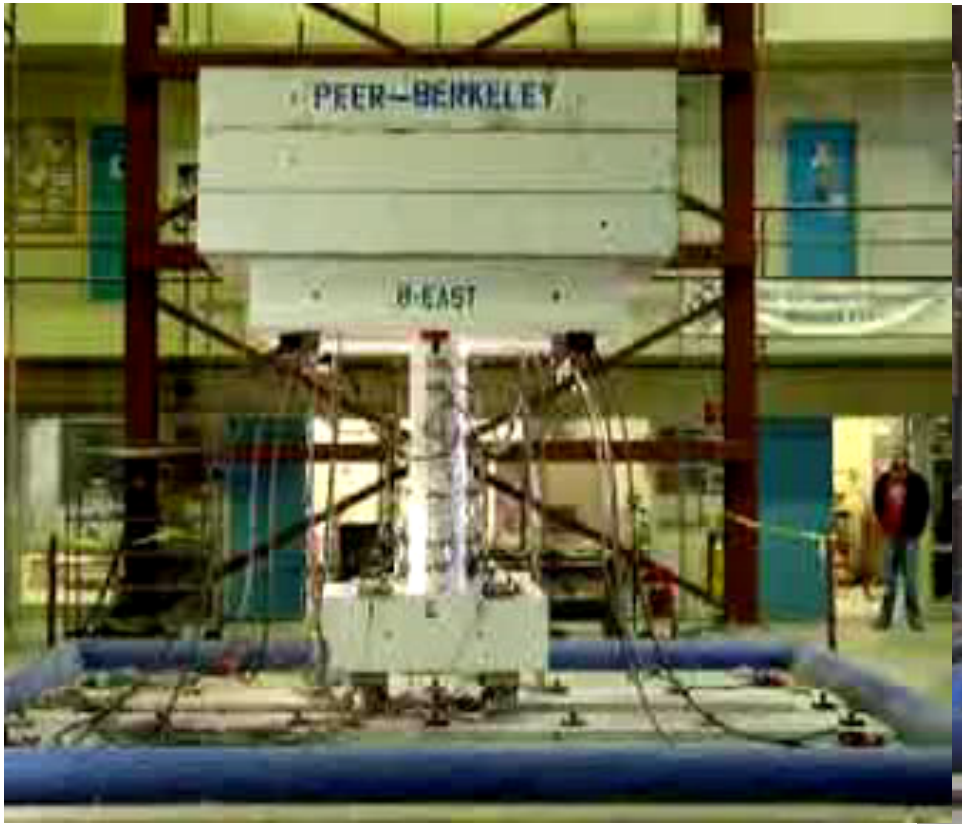




Response During Maximum Level Tests

100% of Los Gatos, Loma Prieta Earthquake Record

Similar Maximum Response Ductility = 13-14



Conventional RC Column **Partially Prestressed RC Column**

Rocking Foundations: An easier way?

UC Berkeley and *UC Davis*

Mahin, *Kutter, and Jeremic*

For soils where spread footings are feasible, engineers often find that footing width needs to be increased, or anchored using piles, so a plastic hinge can develop in column

- → Earthquake experience suggests foundation uplift can be an effective earthquake resistant mechanism
- → Significant amounts of research confirms this
- → Utilizes conventional construction and design technology

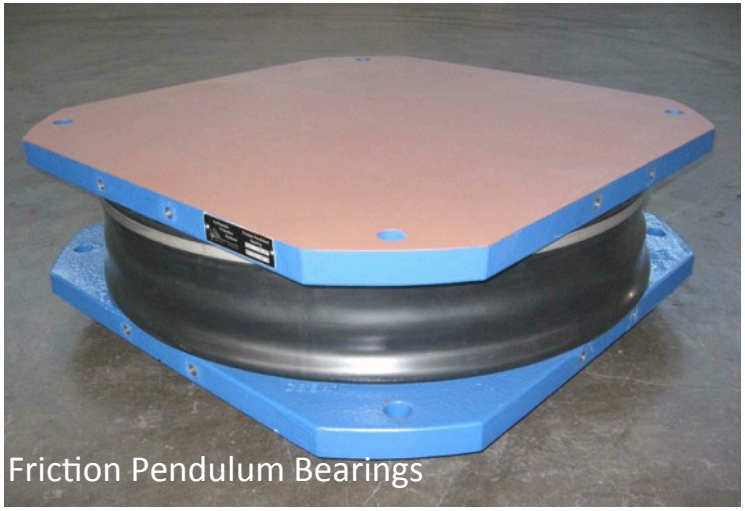
X+Y+Z Components - Los Gatos

For Fixed Base Column μ=5

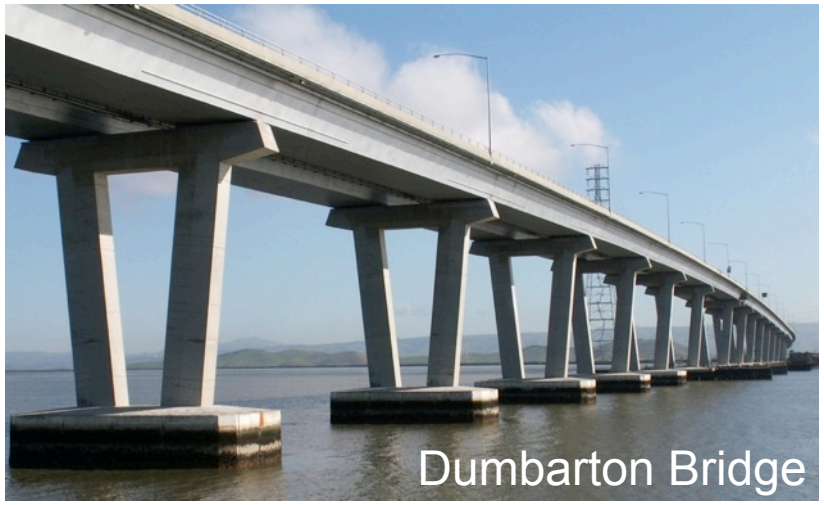
Protective Systems: Seismic Isolators and Supplemental Dampers


Lead Rubber Bearings


Viscous Dampers


Friction Pendulum Bearings

Applications of Protective Systems


Dumbarton Bridge

San Francisco Int. Airport


Computer Center, SF


Pasadena City Hall

Seismically Isolated Building
125% of largest record from Kobe

Seismic isolation designed typically to protect structure

Many nonstructural items are fragile and sensitive to vertical accelerations

Take Away

- Earthquakes are infrequent, but inevitable in most of California (and the world)
- Have a survival kit (cash, water, food, clothes, flashlight, etc.)
- Have a plan to meet up with friends and to contact important people in your lives.

Take Away

- Formal risk assessment can provide insight into planning, especially in comparing alternative strategies
- Engineering focus is moving (slowly towards) developing damage-resistant structures that minimize economic loss and allow rapid post-event recovery (resilience)
- Engineers decades ago, who built vulnerable buildings, thought they were doing a good job. So do we now.