

Tom Heaton

All Things Related To Earthquakes

PhD from Caltech in Geophysics

16 years with USGS

Joint Prof. in Geophysics and Civil Engineering since 1995

Director of the Earthquake Engineering Research Laboratory

Caltech asked me to be a “bridge” between Engineering and Science



But maybe I can be a Ferry Boat instead



Statistical Characteristics of Earthquake Ground Motion; Has PBEE Broken the Power Law?

Tom Heaton (Caltech)

Brad Aagaard (USGS)

Georgia Cua

Anna Olsen (USGS)

Masumi Yamada (Kyoto Univ.)

Performance Based Earthquake Engineering (PBEE)

- Most building codes have evolved over time following observations made after damaging earthquakes
- Have limited number of earthquakes to learn from
- PBEE says build according to a statistical model of earthquake hazard.
- Current practice is to build so that the expected time between collapse of a structure is 2,500 years (except in San Francisco, where it's 1,500 years).

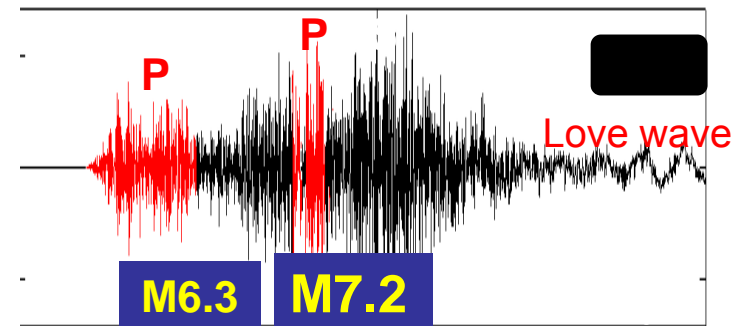
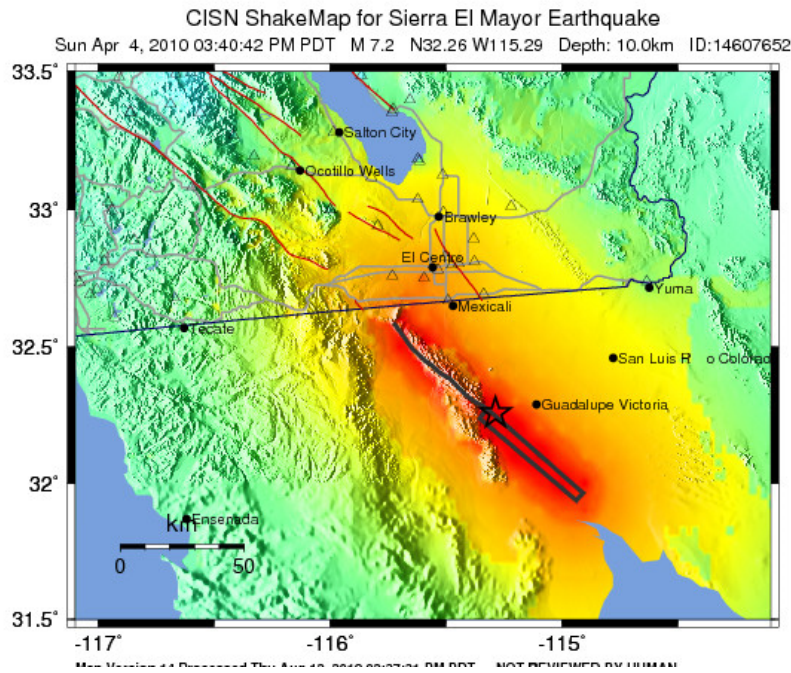
Summary

- Peak ground acceleration (pga) characterizes the high-frequency shaking of the ground (> 5 Hz)
- High-frequency ground motions saturate with magnitude and have log-normal statistics. (think heart attacks, murders, etc.)
- High-frequency ground-motion probabilities can be characterized with a rate, a median, and a std. dev.
- Low-frequency ground motion statistics are heavy-tailed power laws (think bird flu, wars, etc.)
- No correlation between near-source pga and low-frequency motions
- In the US, current probabilistic design of tall buildings and base-isolated buildings uses long-period design motions that are far smaller than is widely accepted in earth science

Key Issues

- I will concentrate on near-source (less than 10 km from rupture) motions since they are simpler to think about
- Modern high-rise buildings and base-isolated buildings have not yet experienced large long-period ground motions ($\text{pgd} > 1 \text{ m}$).
- But they will
- Is statistical prediction of long period ground motions technically feasible?
- Maybe ... but it will look very different from psha for short periods
- Will the design of long-period buildings change dramatically in the next 100 years?

2010 M7.2 El Mayor Cucapah earthquake (Baja)



- Complex double event ... M 6.3 followed 15 s later by M 7.2
- Mexicali is about 20 km from rupture

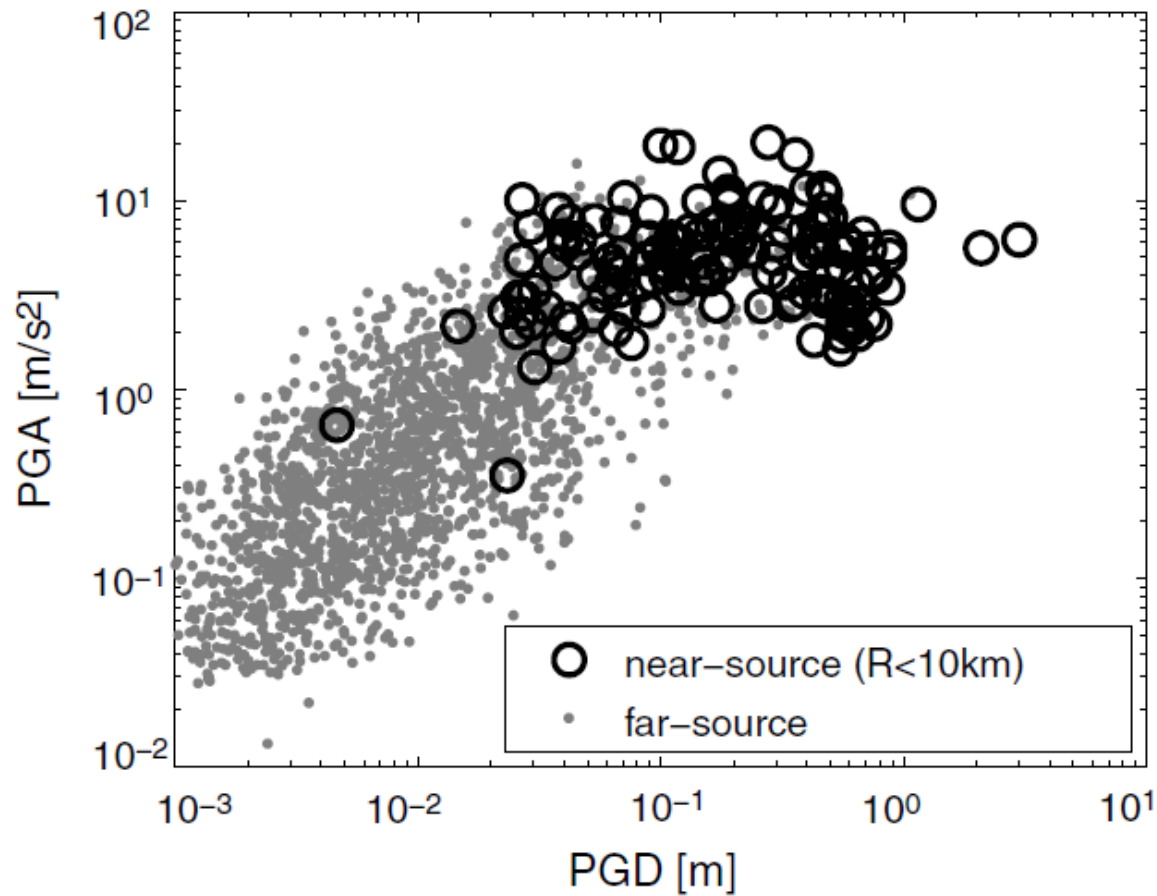
Cucapah, El Major M 7.2
Real Inn, Mexicali, 8 stories, 24 km





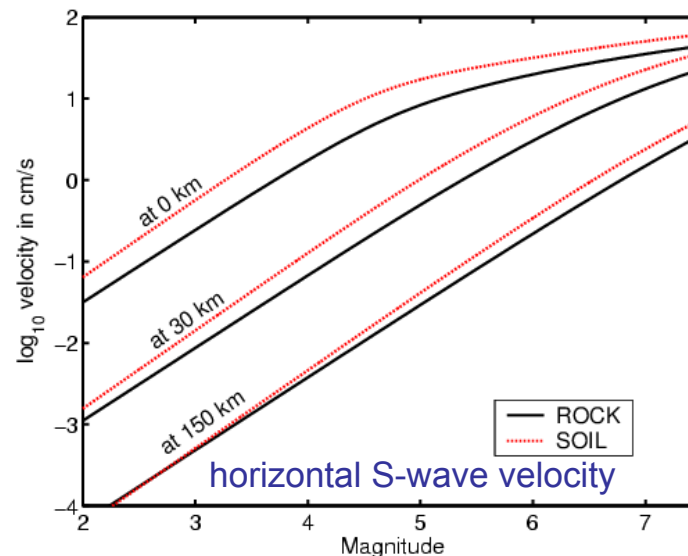
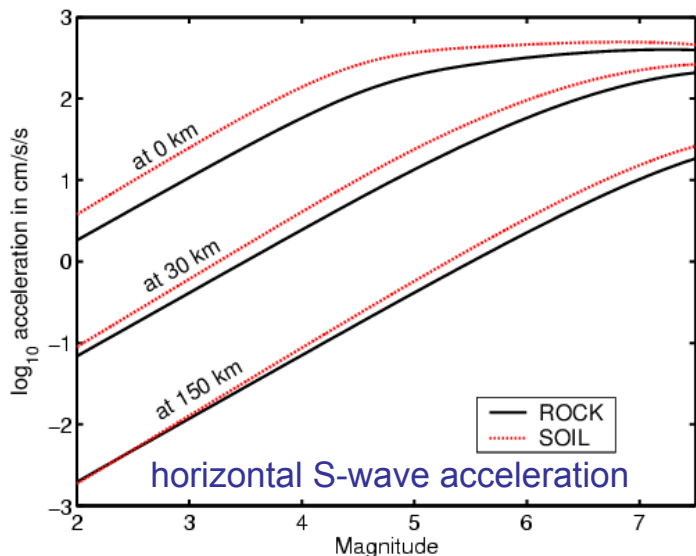
How Ground Motions vary with Magnitude and distance, R

- I will use pga as a measure of high-frequency motion
- Peak ground displacement, pgd, as a measure of low-frequency motion ... when does a building deform enough to be gravitationally unstable?
- Peak ground velocity, pgv, tells us when to expect yielding and its statistics are somewhere between pga and pgd
- Pgv is the best overall predictor of damage for most buildings

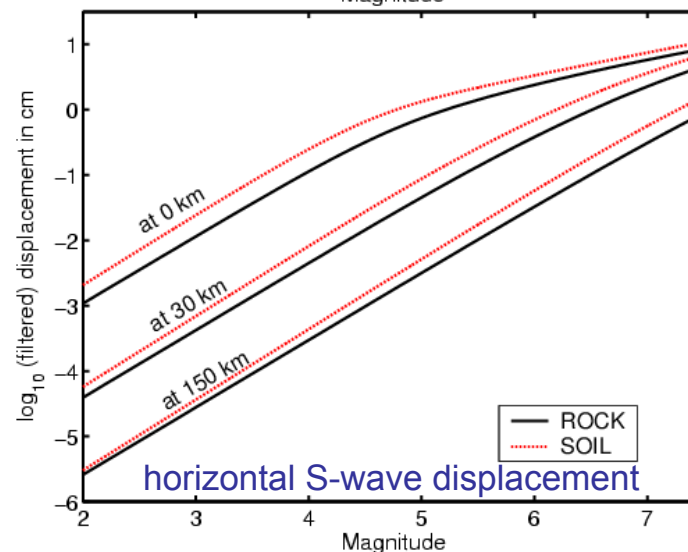


- **near-source pga is uncorrelated with pgd**
- **Pga saturates, but pgd does not**

Magnitude-dependent saturation of rock and soil sites (S-waves)

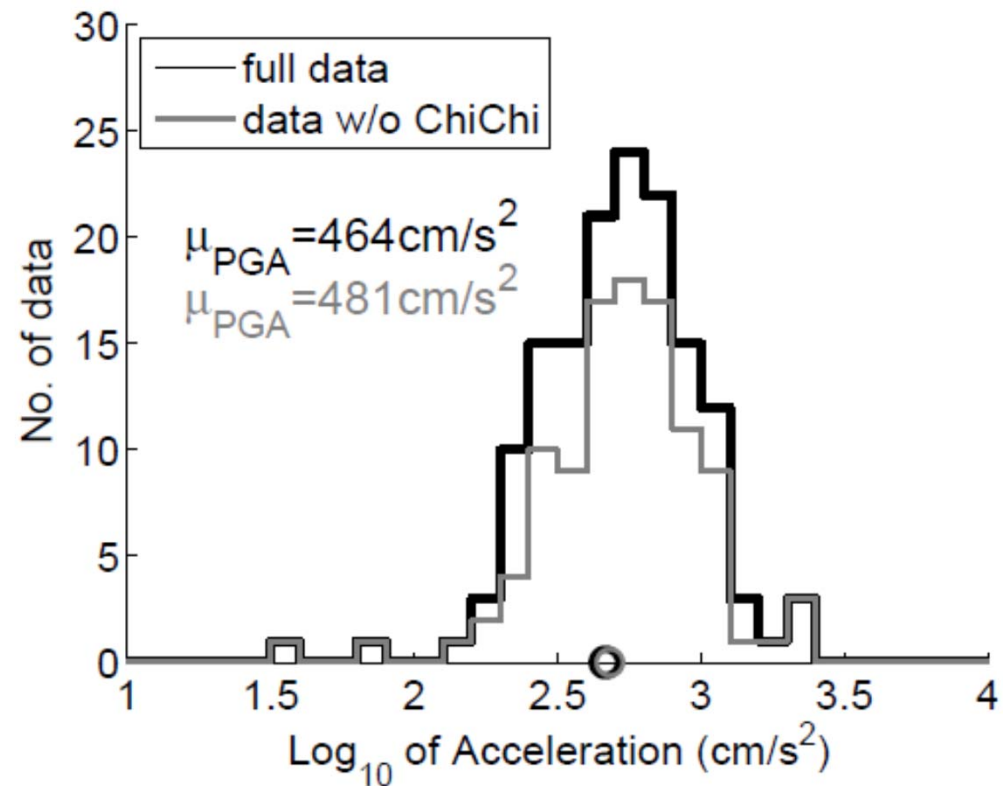


- Ground motion attenuation derived by Cua and Heaton from TriNet and Cosmos data
- For near source motions, high frequencies are log-normally distributed about 0.52 g, regardless of the magnitude and soil type
- Long-period motions do not saturate and the frequency versus size obeys a power law (variation of Gutenberg Richter)
- Log-normal statistics (high frequency hazard) is dominated by the median, whereas power law statistics (long-period hazard) is dominated by the tail



All Pga's recorded at less than 10 km from M>6

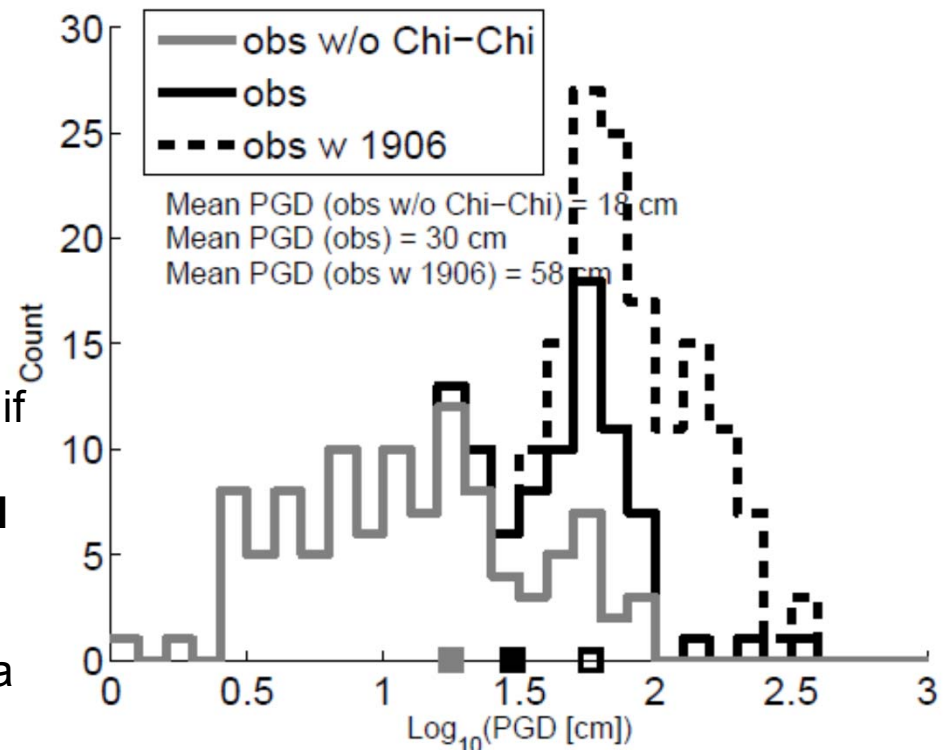
- Near-source pga's are log-normal
- Same distribution will apply 100 years from now



Short periods are Gaussian statistics

- Can reliably determine the mean and standard deviation from only a few dozen observations
- How many people will die in auto accidents?
- How many people will suffer a heart attack?
- How many buildings will experience some level of pga?
- Although we can predict short-period ground motion statistics, no one really uses them for the design of short buildings ... rule based codes function well here.

- Long-period ground motions are **not** log normal
- A few large earthquakes can completely change the distribution
- **Cannot predict** what the shape of this distribution will look like 100 years from now
- $\text{Area}(M) \sim 10^M 10^{-bM} = \text{constant}$, if $b=1$
- i.e., given that a fault slips, **all values of slip are equally likely**
- The small pgd's will come in a few at a time as smaller but numerous eq's occur
- The large pgd's will arrive in a large clump when infrequent large eq's occur



Long Periods are power law statistics aka. a Pareto Distribution

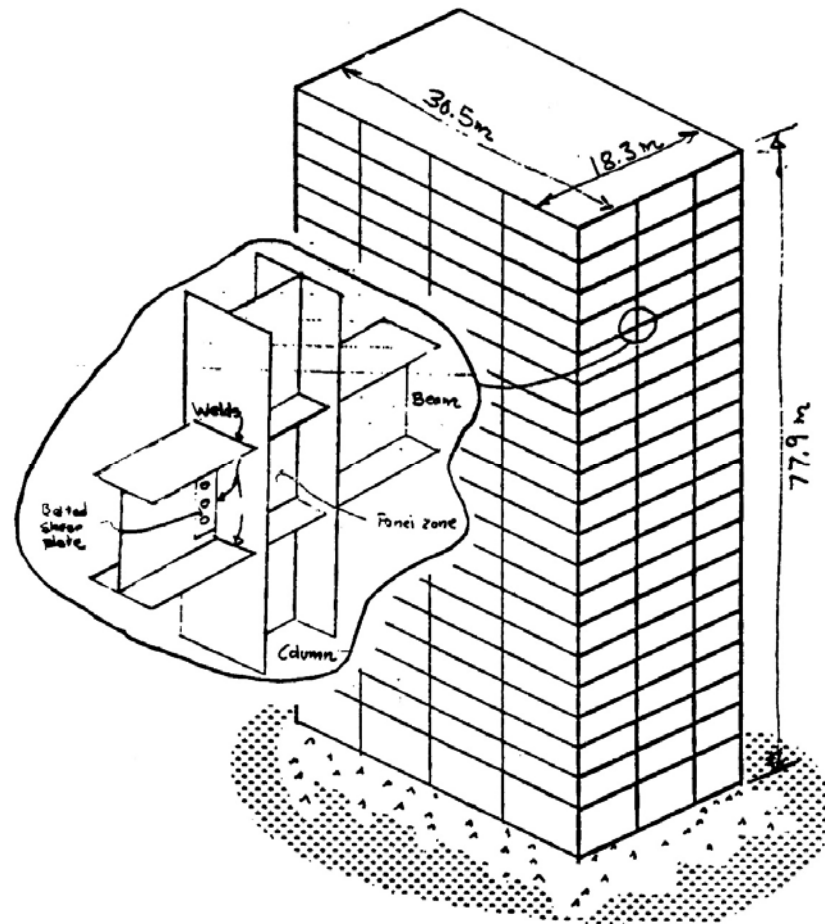
- Probabilities are difficult to estimate for power law. What is the total wealth in California?
- How many people will die in
- A war?
- A pandemic?
- What will your stock market investments look like in 20 years?

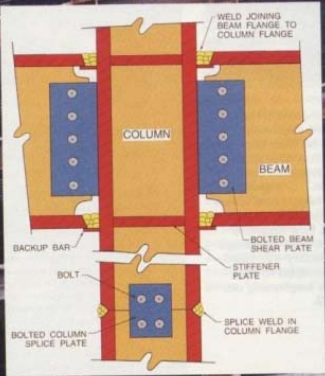
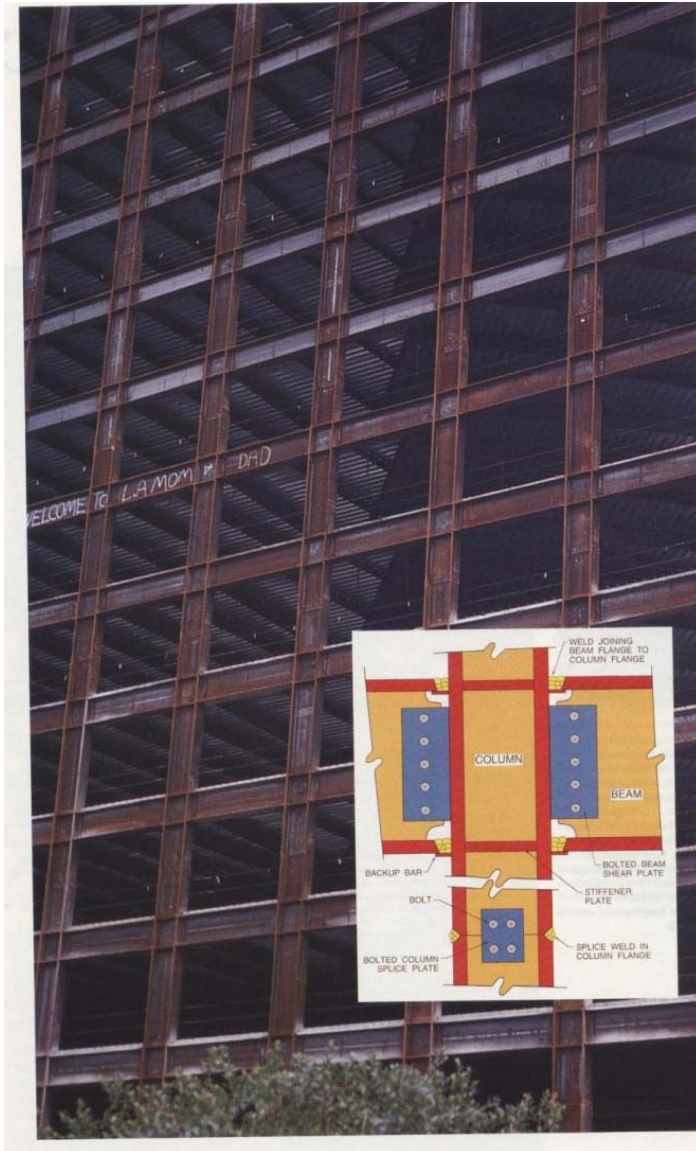
Why are pgd's and pgv's important to tall structures?

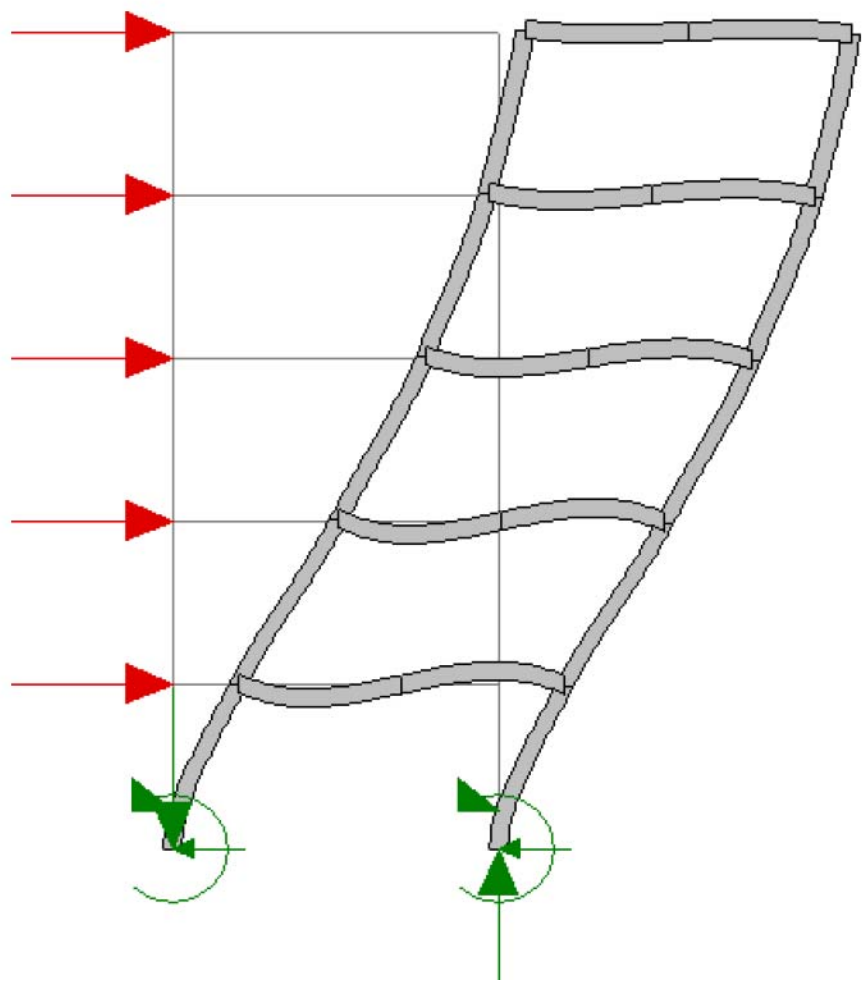
- In order to collapse, a tall building must deform enough to become gravitationally unstable; that is, there must be large enough displacement
- And the displacement must happen fast enough to cause yielding ... pgv

John Hall's design of a 20-story steel MRF building

- Building U20
 - 1994 UBC zone 4
 - Stiff soil, 3.5 sec. period
- Building J20
 - 1992 Japan code
 - 3.05 sec period
 - Similar to current IBC with highest near-source factor
- Both designs consider
 - Perfect welds
 - Brittle welds
 - Japanese typically exceed code







Intended yielding is plastic hinges in the beams ...
avoid yielding in the columns



From Chia-Ming Uang

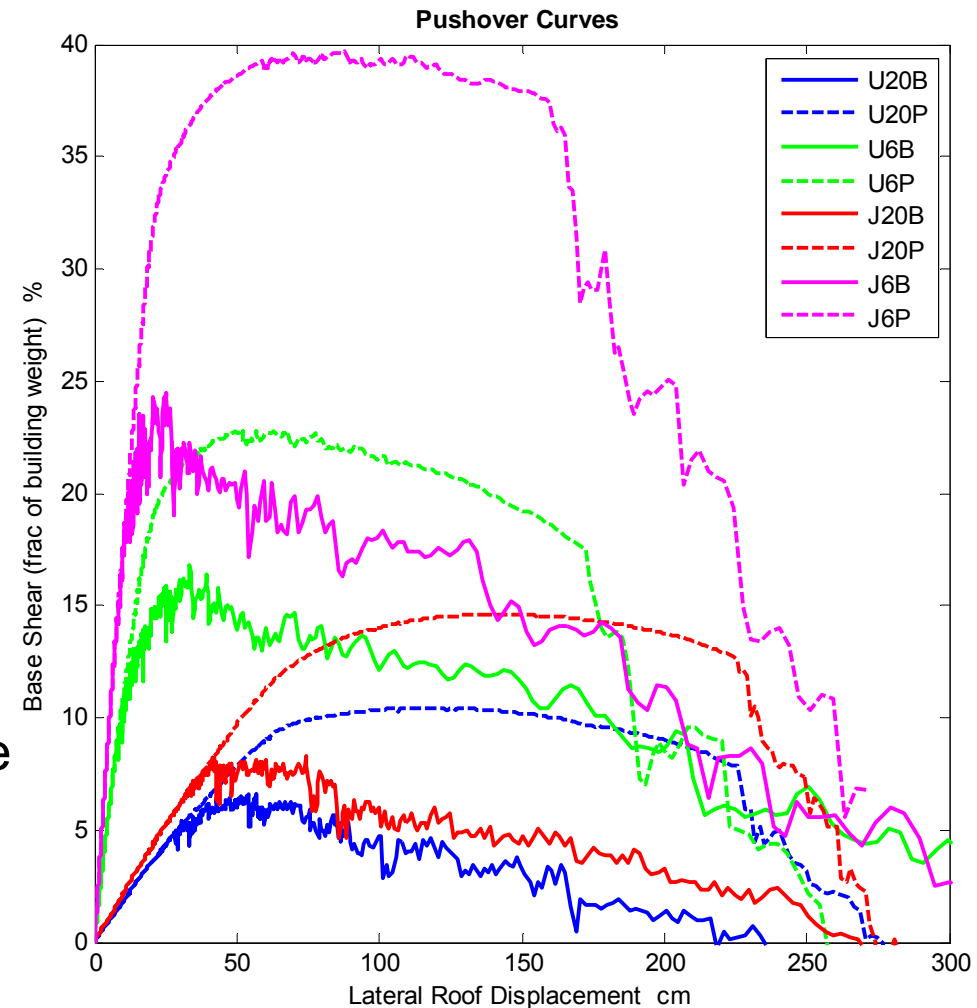
UNIVERSITY OF CALIFORNIA, SAN DIEGO



Charles Lee Powell Structural Research Laboratories

- Special attention to P-delta instability
- Story mechanism collapse
- Frame 2-D fiber-element code of Hall (1997)
- 2 m roof displacement is near the capacity of any of these designs
- Most US buildings built before 1995 have brittle welds

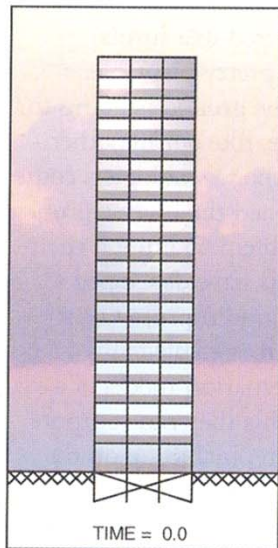
Pushover Analysis



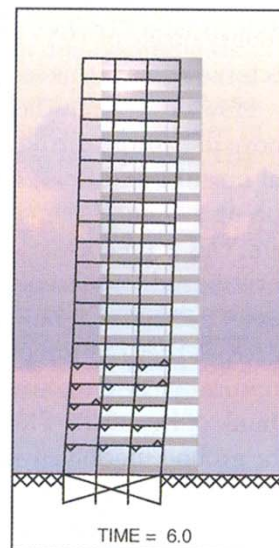
20-story steel-frame building (UBC 94) subjected to a 2-meter near-source displacement pulse (from Hall)

- triangles on the frame indicate the failures of welded column-beam connections (loss of stiffness).

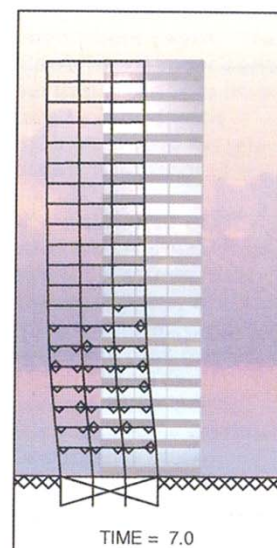
The 20-story building before the C5 ground motion hits. The displacement pulse will be toward the left.



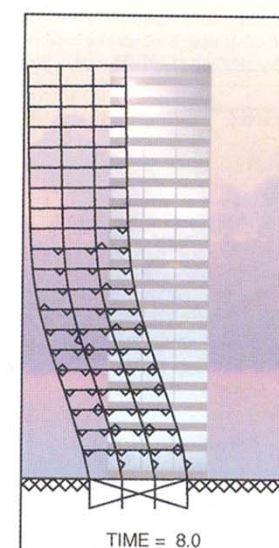
At t=6 seconds, the ground is approaching its maximum horizontal displacement of 182 centimeters.



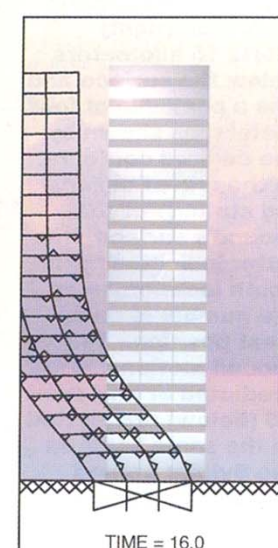
At t=7 seconds, the ground is returning to its original position, causing the building to "crack the whip."



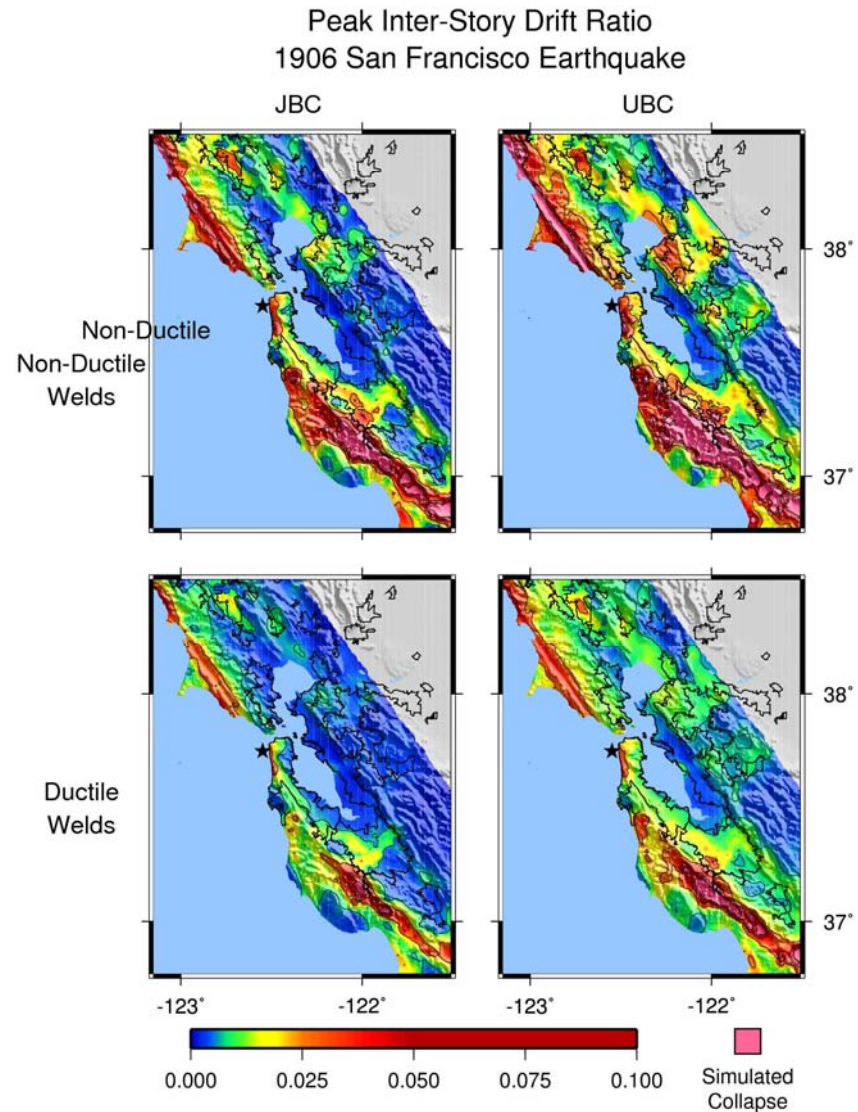
This flexure creates a ripple of breaking welds that travels up the building.



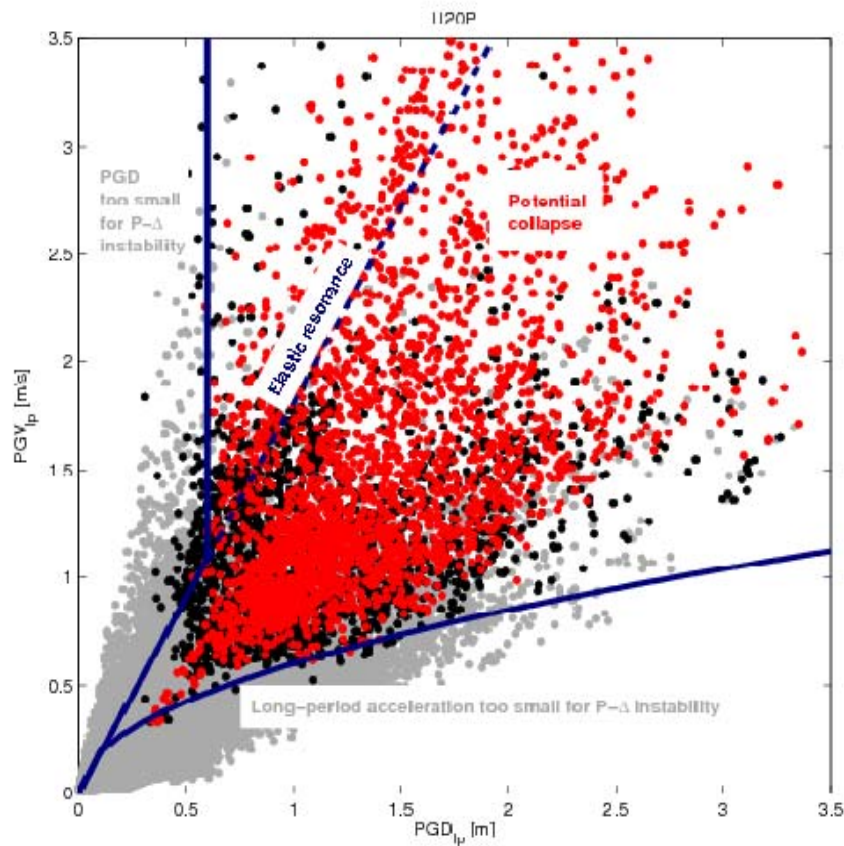
By t=16 seconds, the building is hopelessly overbalanced and on its way to oblivion.



- Severe damage or collapse in many areas
- Stronger, stiffer building (J20) performs better than more flexible building (U20)
- Brittle weld buildings 5 times more likely to collapse than perfect-weld buildings
- Least damage when the epicenter is at Golden Gate
- Would be worse if we simulated soft soils
- Results summarized in Olsen and others (BSSA, 2008)



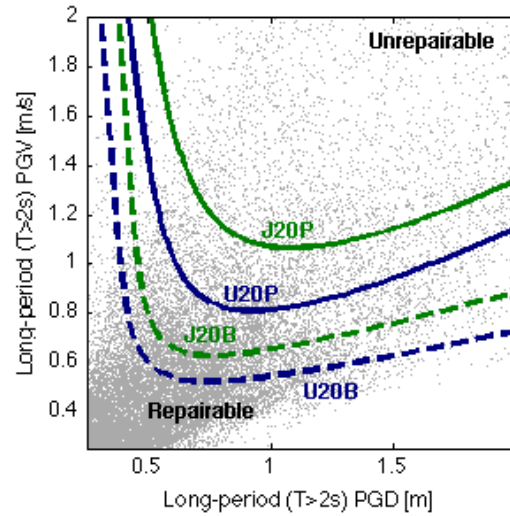
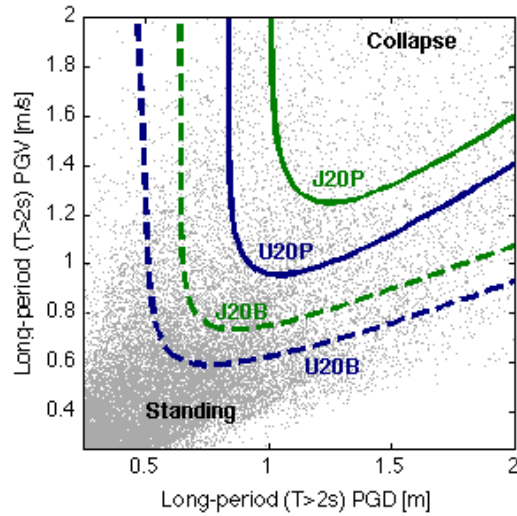
20-story US with Sound Welds



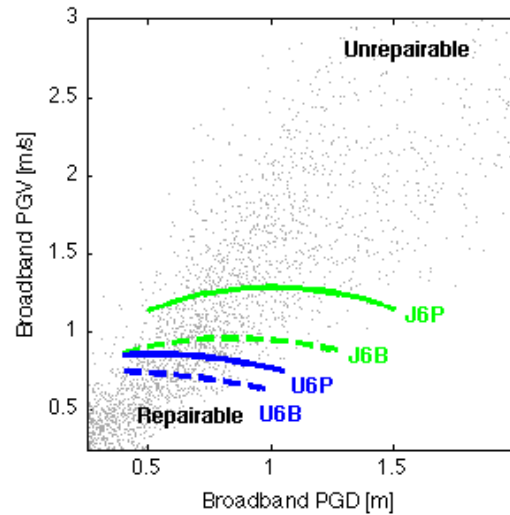
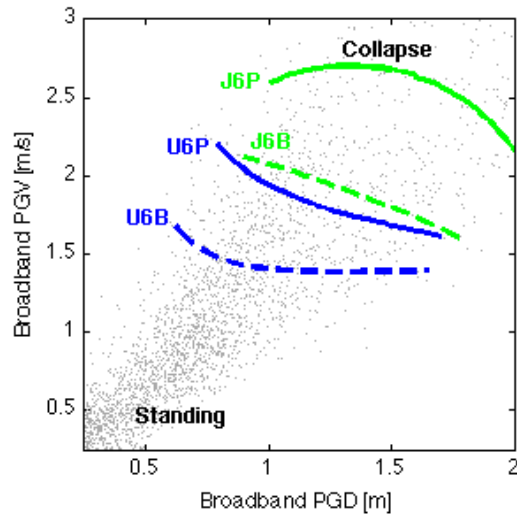
Olsen, Heaton, and Hall (in press) show that (pgv,pgd) is a better predictor of collapse than response spectral acceleration and ε

64,000 synthetic records
From SCEC

- Repairable
- Not Repairable
- Collapse

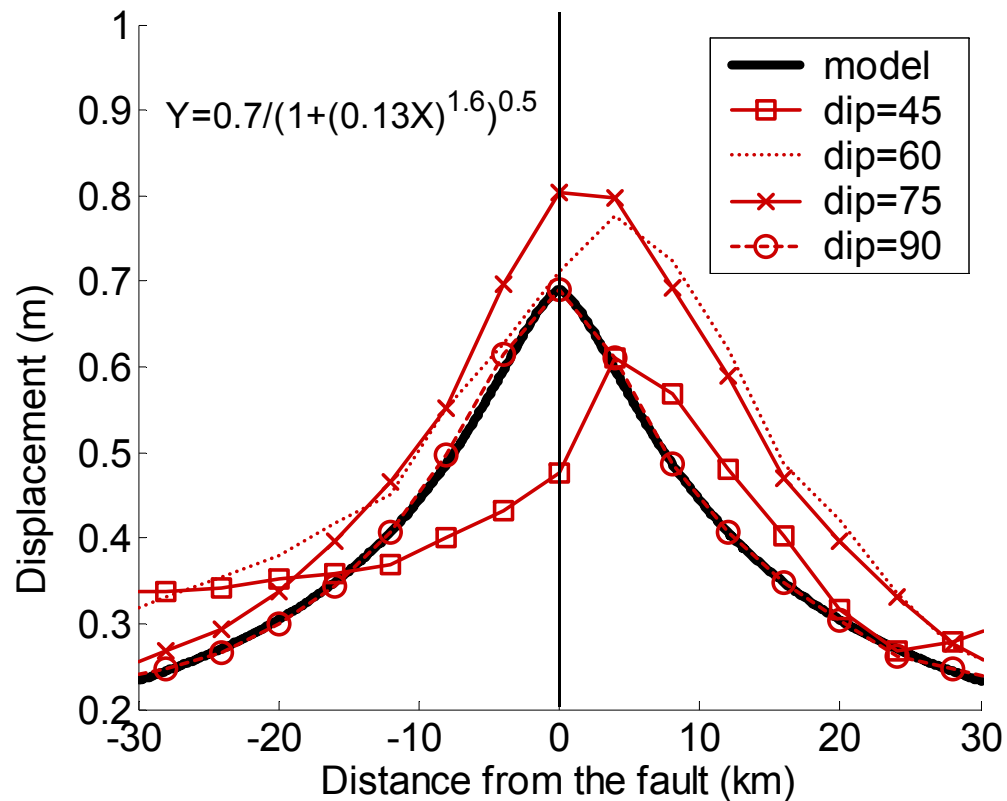


10% probability contours



- Range of motions between unrepairable and collapse is much smaller for 20-story than for 6-story
- In a sense, the taller building is more brittle because of P- Δ effect

PGD per unit fault slip



(Aagaard et al. 2001)

Near-Source
PGD's are roughly
**2/3 of the fault
slip** in nearby
segments.

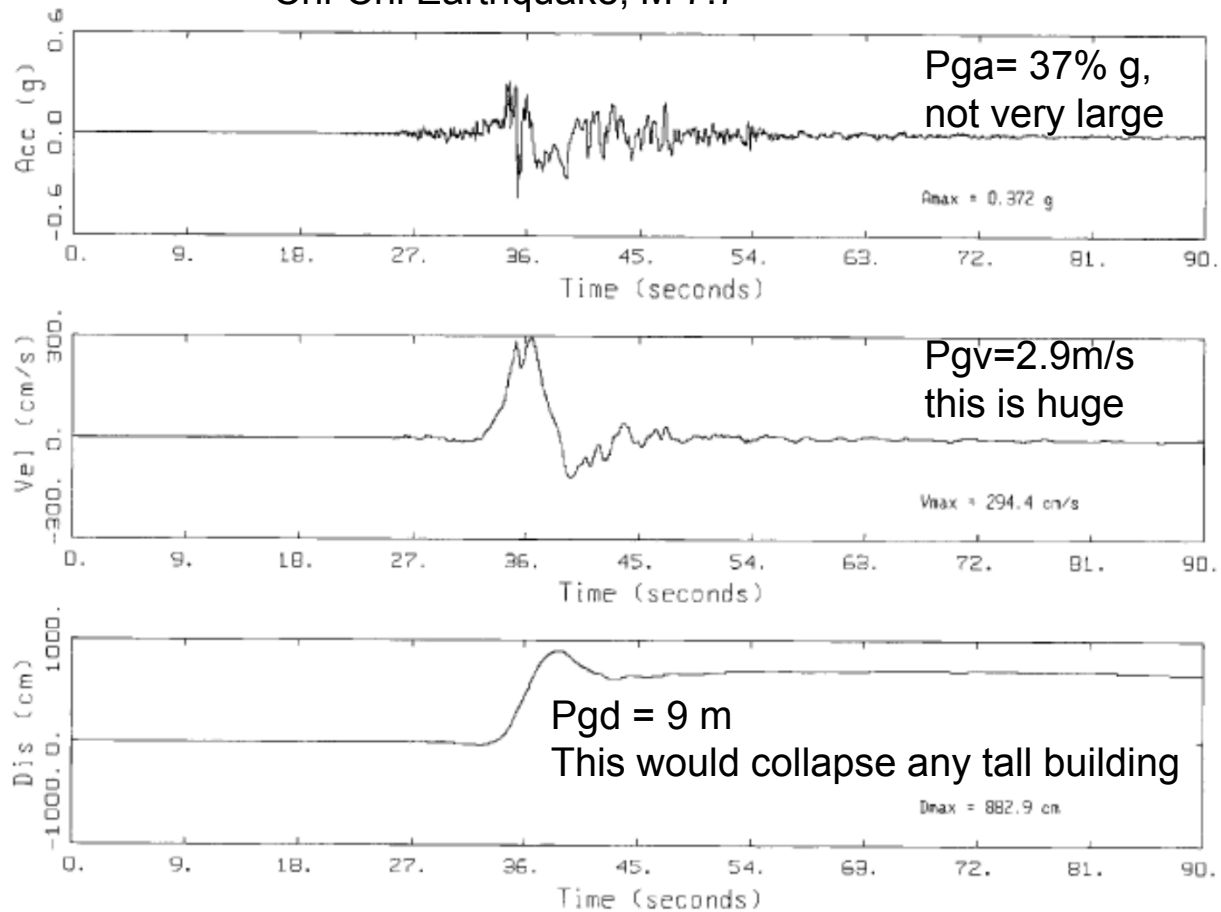
**But what will
the fault slip
be?**

For strike-slip fault,

$$D = \frac{0.7}{\sqrt{1 + (0.125r)^{1.55}}}$$

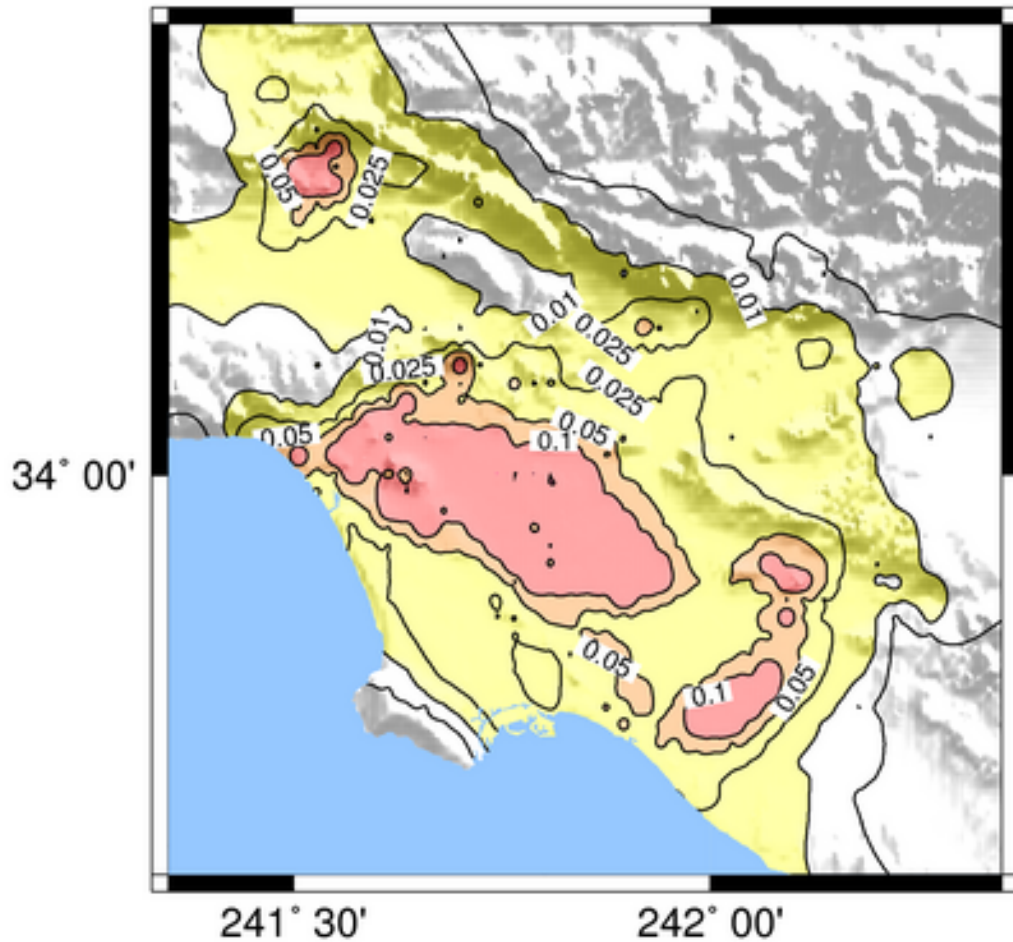
From Silva and Darragh

Chi-Chi Earthquake, M 7.7



CHICHI EQ: TCU068 (NORTH-SOUTH) STATIC TIME HISTORIES

Maximum Inter-Story Dynamic Drift Ratio Composite 20-Stories with Good Welds



M 7.3 on Puente Hills
Blind Thrust Fault

Motions simulated by Graves

Simulations in Olsen thesis

Inter-story drift > 0.8 is collapse

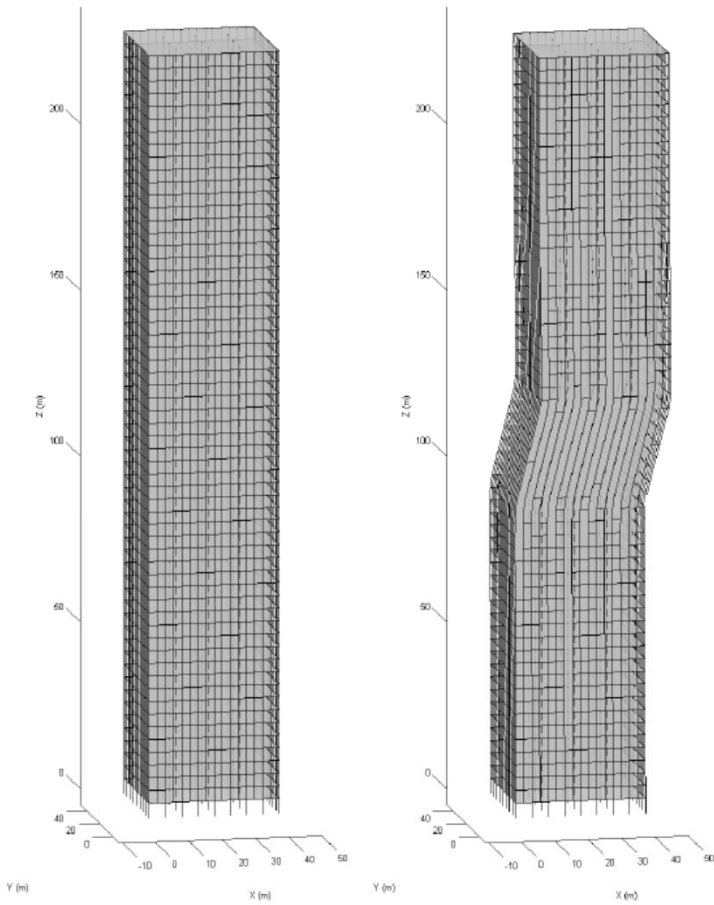


Figure 7.6: Isometric views of 60-story building at $t=0$ sec and $t=41.9$ sec subjected to the Denali earthquake ground motion at Pump station #10 (Figure E.3). Elements that failed during analysis are not shown. Deformations are unamplified.

Abel Dizon's 2015 PhD thesis

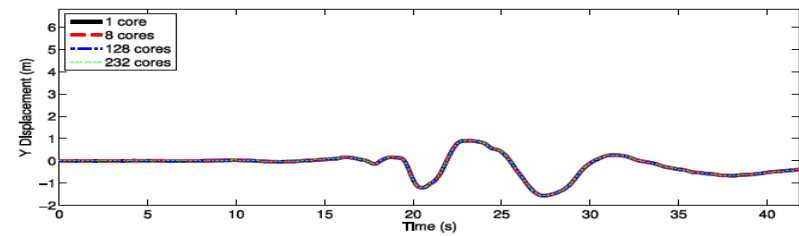
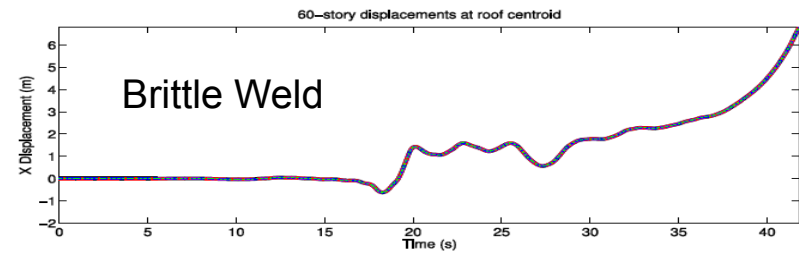
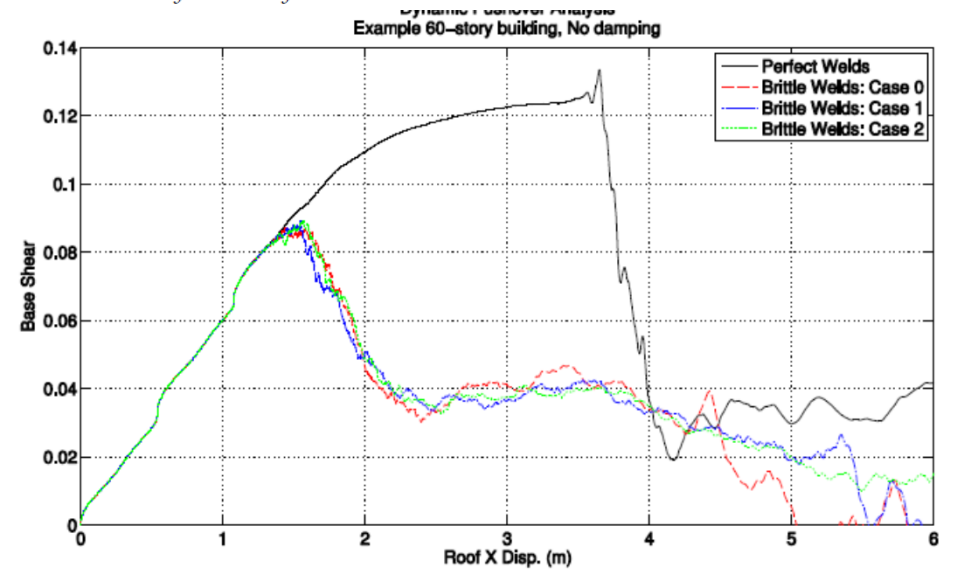
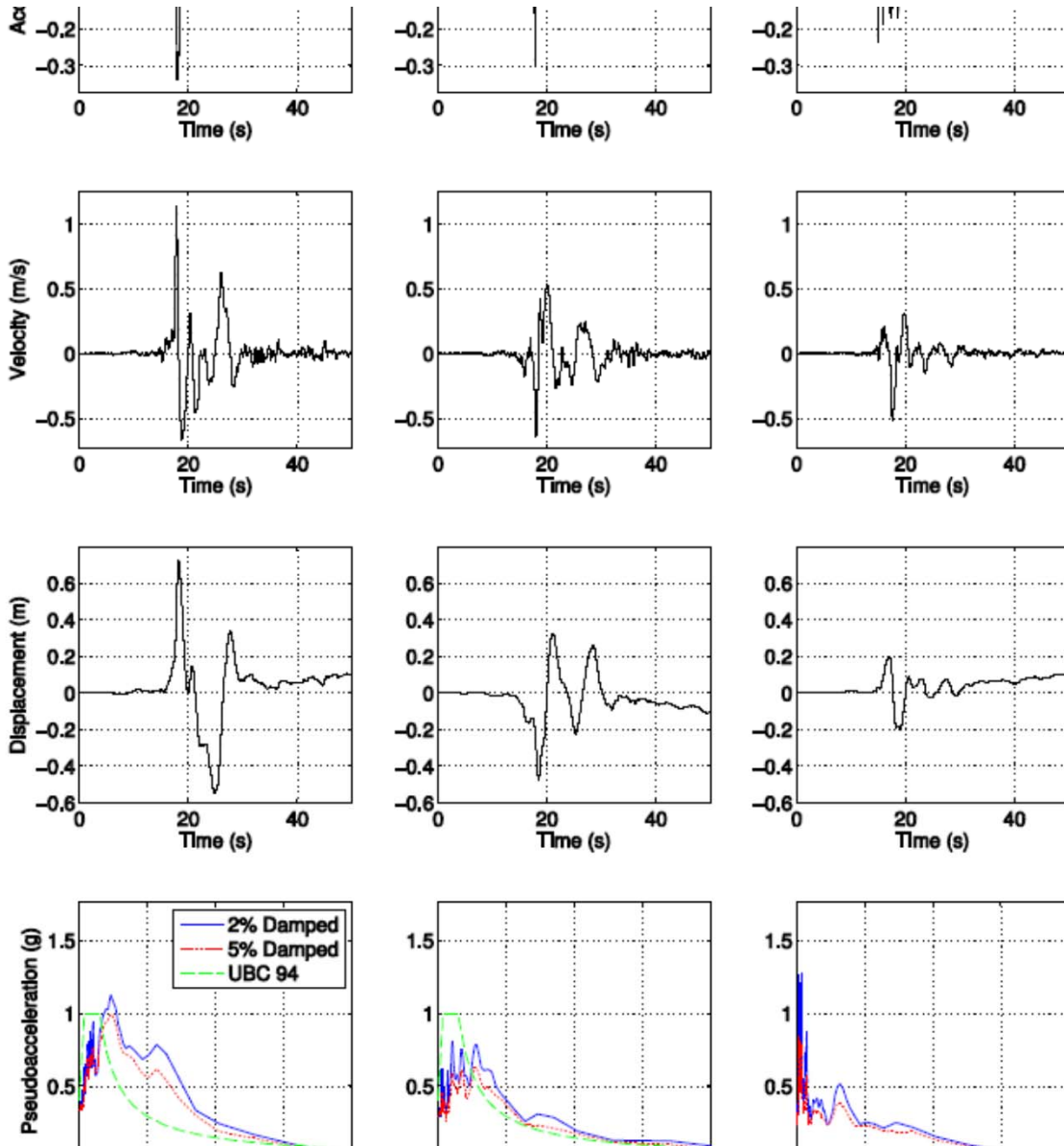
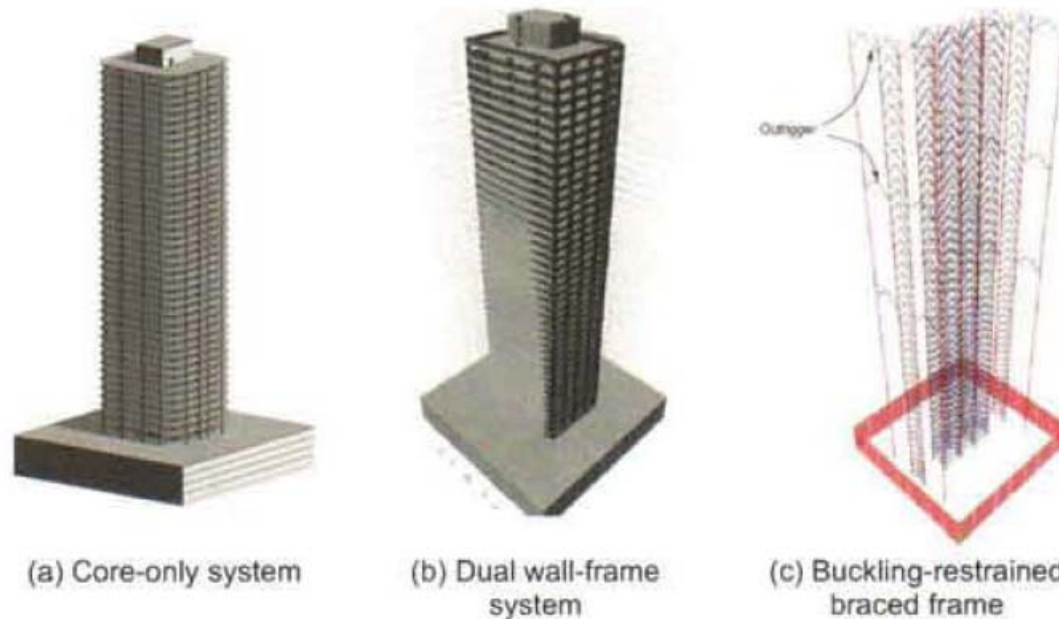


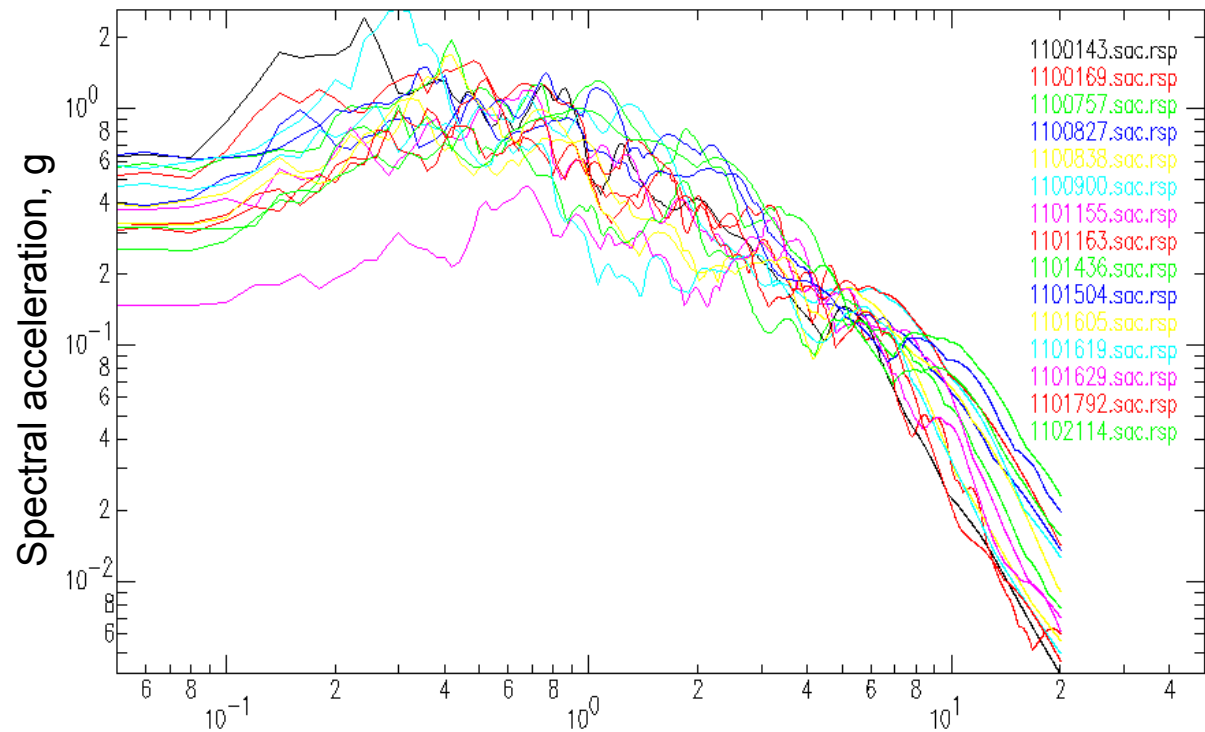
Figure 7.7: Displacement histories at the roof centroid of the 60-story building subjected to the Denali earthquake ground motion at Pump station #10 (Figure E.3). The results from 1-, 8-, 128-, and 232-core analysis are nearly identical.





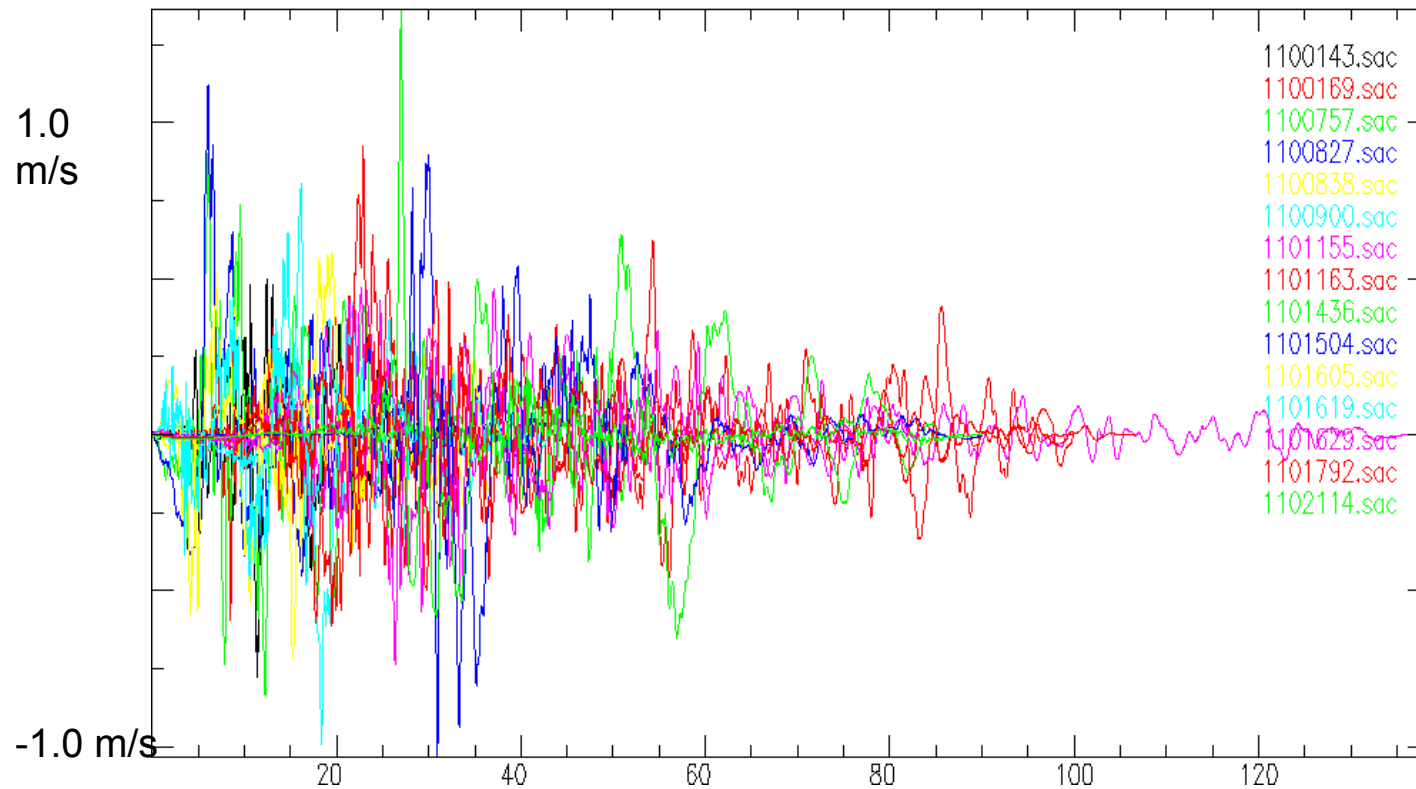


- PEER Tall Building Initiative to conduct performance based analysis of three 40-story buildings in downtown LA (5 ½ to 6 s fundamental periods).
- “Working with engineering consultants and experts at SCEC, we selected records to represent frequent (25-yr) and extremely rare (4975-yr) shaking. The latter is well beyond the shaking level commonly considered.”
- “the code-designed cases (2006 IBC, 2008 LATBDC) have acceptable performance under the 475-yr motions, and survive the 2475-yr motions. Under the 4975-yr event, however, some elements may fail.”
- Similar study of One Rincon Hill in downtown San Francisco for similar building design.

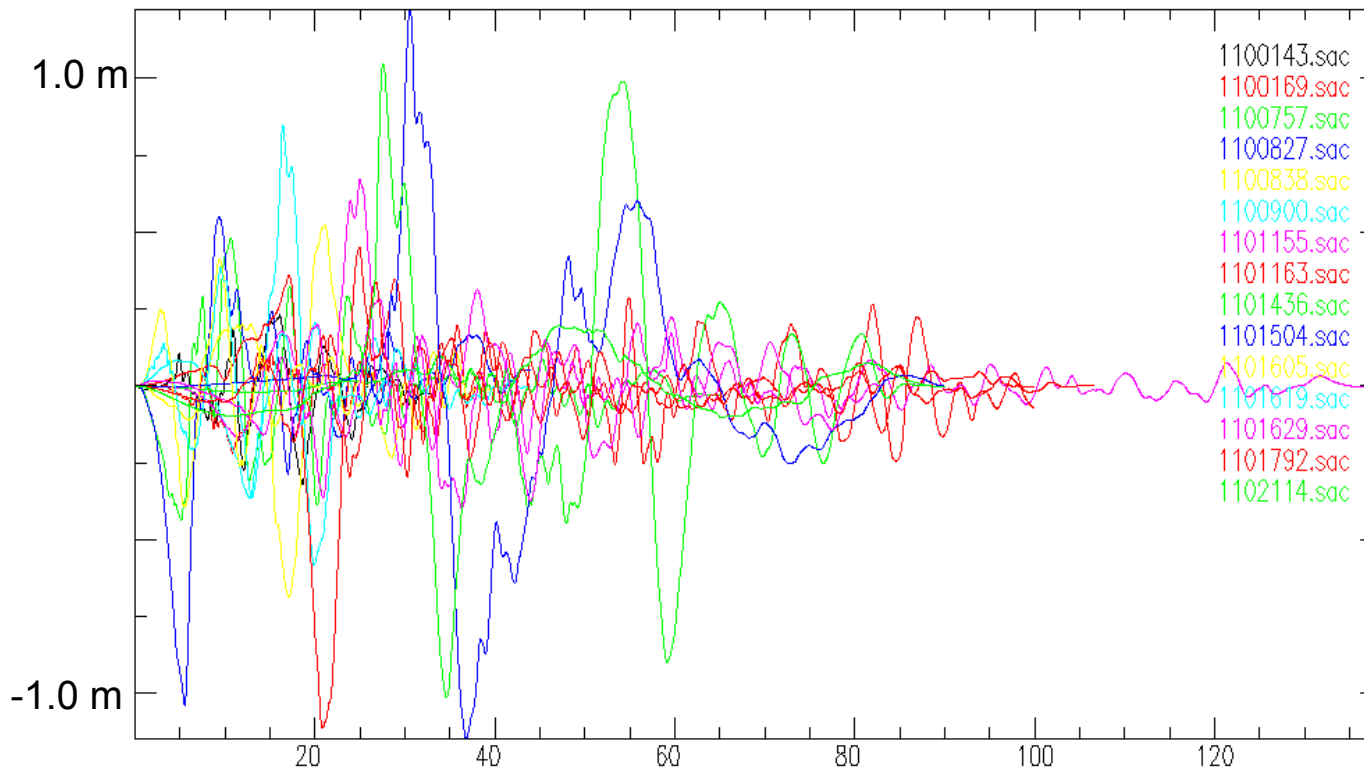


- 15 realizations of spectrum compatible motions used by PEER Tall Building Initiative for 40-story (6 second) building analysis in downtown LA
- These are the Maximum Considered Earthquake Spectra (MCE) for a 2,476-year repeat (life safety level)
- This project is considered as a PEER/SCEC collaboration

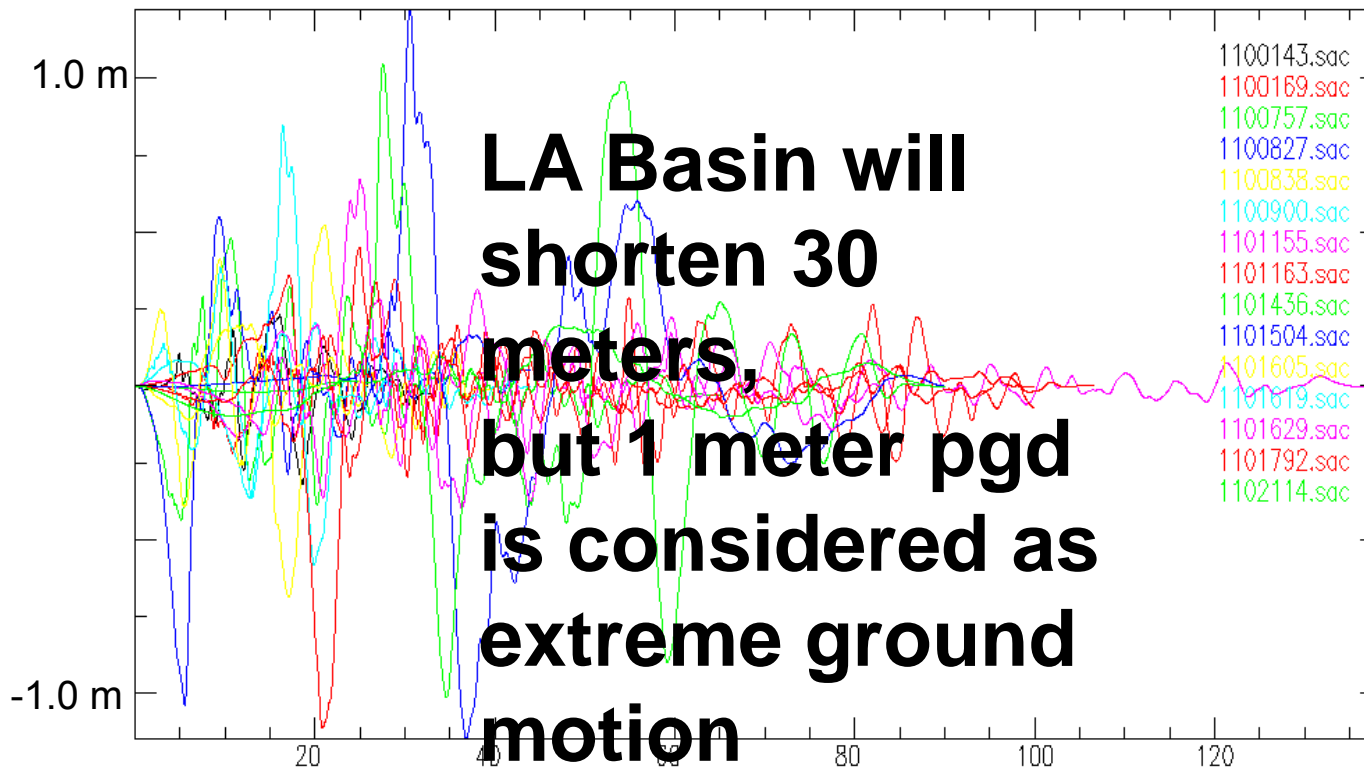
PEER Spectrum Compatible 2,500-yr Ground Velocities for 40-story 6-second Building in Los Angeles



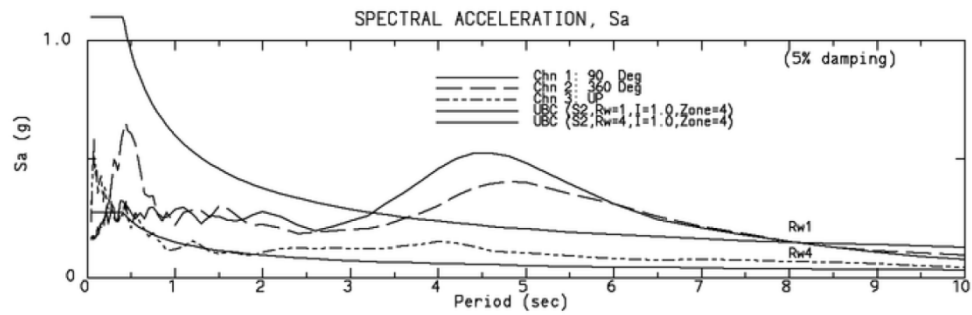
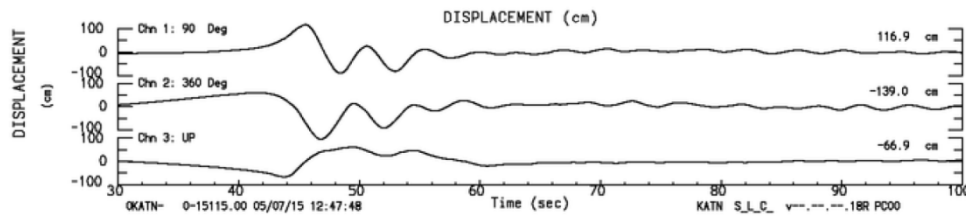
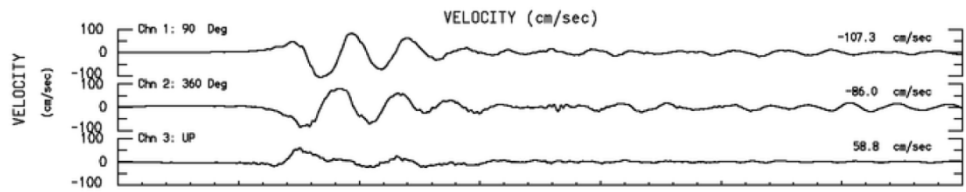
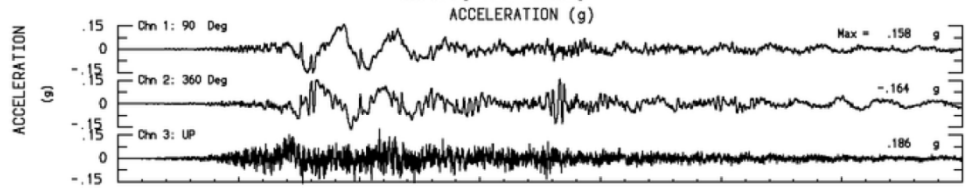
PEER Spectrum Compatible 2,500-yr Ground Displacements for 40-story 6-second Building in Los Angeles



PEER Spectrum Compatible 2,500-yr Ground Displacements for 40-story 6-second Building in Los Angeles

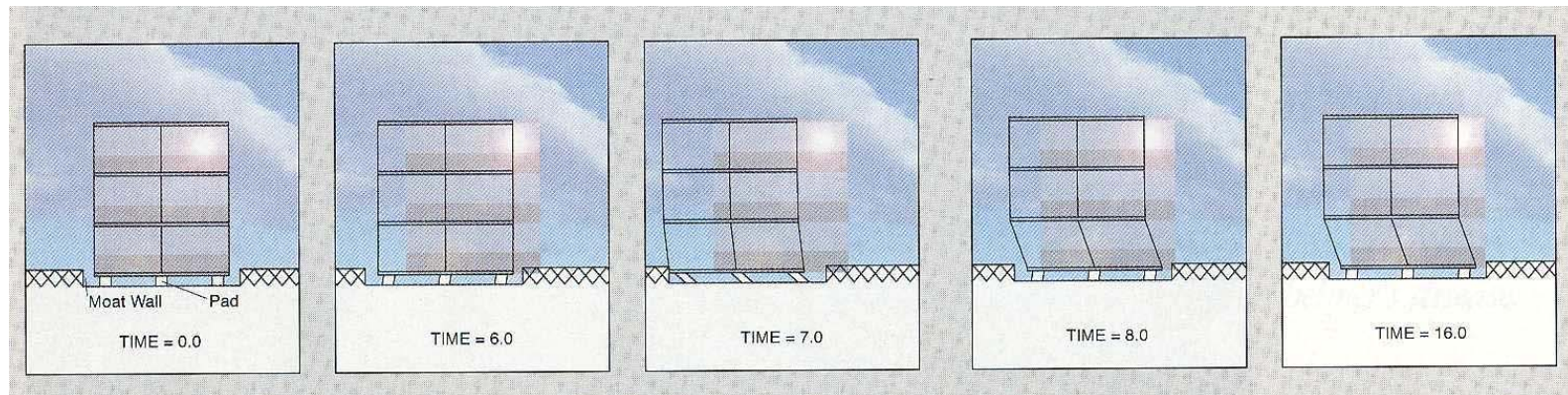


Kanti Path, Kathmandu, Nepal USGS Sta KATNP
 Record of Sat Apr 25, 2015 06:11:46.6 GMT
 Filtering: Highpass at .02 Hz (50 secs)
 USGS Strong Motion Processing



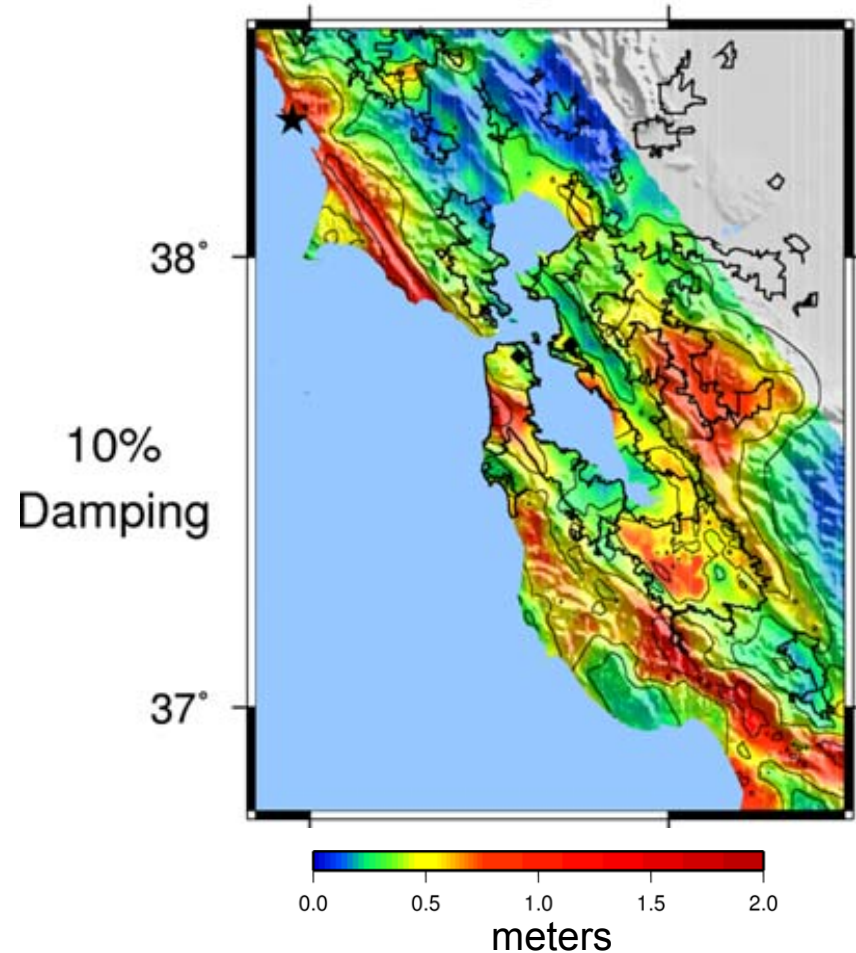
Large displacements can overwhelm base isolation systems

- 2-meter displacement pulse as input for a simulation of the deformation of a 3-story base-isolated building (Hall, Heaton, Wald, and Halling)
- The Sylmar record from the 1994 M 6.7 Northridge earthquake also causes the building to collide with the stops



3-sec spectral displacement

- Typical US base isolator is 3 sec with a maximum allowed displacement of 40 cm
- Nonlinear isolator displacements exceed linear by 20% to 40% (Ryan and Chopra)
- Described in Olsen and others (BSSA, 2008)
- Anything in **yellow** or **red** would exceed current typical base isolation system



11-story San Bernardino Law and Justice Center



Designing for the Known

- Architect chooses the geometry of a design
- Define probability of forces that design will be subjected to
- Determine the size of elements that will satisfy statistical limits
- This is “performance based design”

Designing for the Unknown

- Determine the functional requirements of a structure
- Consider several geometries of the structure (different architectures)
- Determine the cost of different designs
- Assess the strengths and weaknesses of different designs ...
make sure the earth scientist knows what the designer assumes won't happen
- Choose the design that is most robust
- Our real job is to find the flaws in current practice and fix them
- Better is ALWAYS better