PBEE-2 simulation exercise

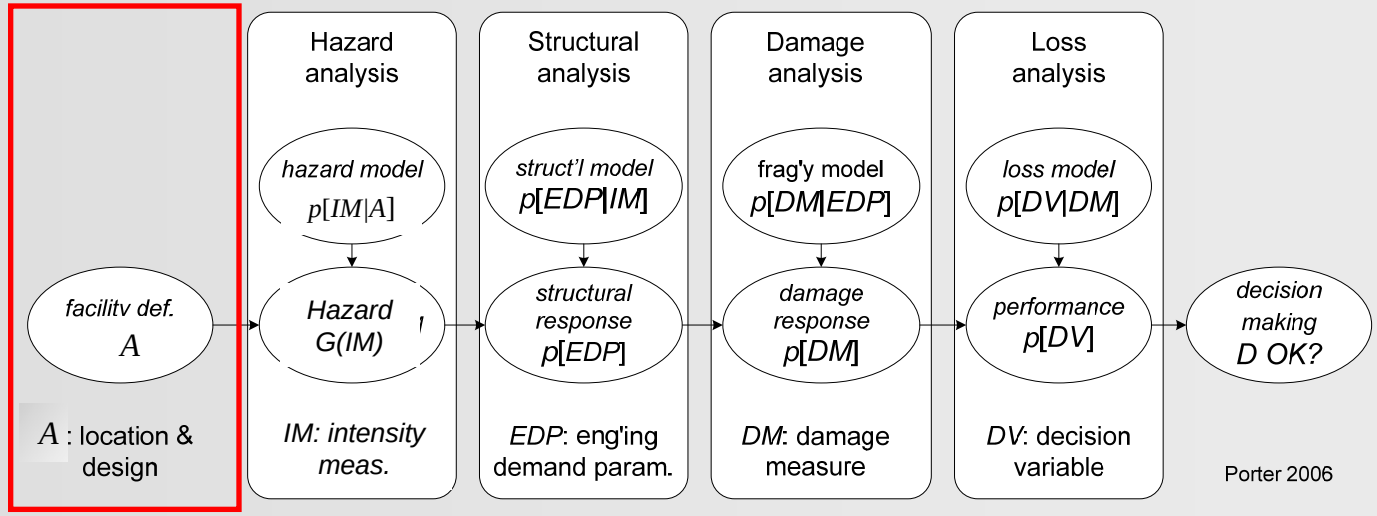
CVEN 5835-02
SPTPS: Nonlinear Structural Analysis; Theory and Applications
21 Apr 2011

Keith Porter, Associate Research Professor
Civil, Environmental, and Architectural Engineering
University of Colorado at Boulder

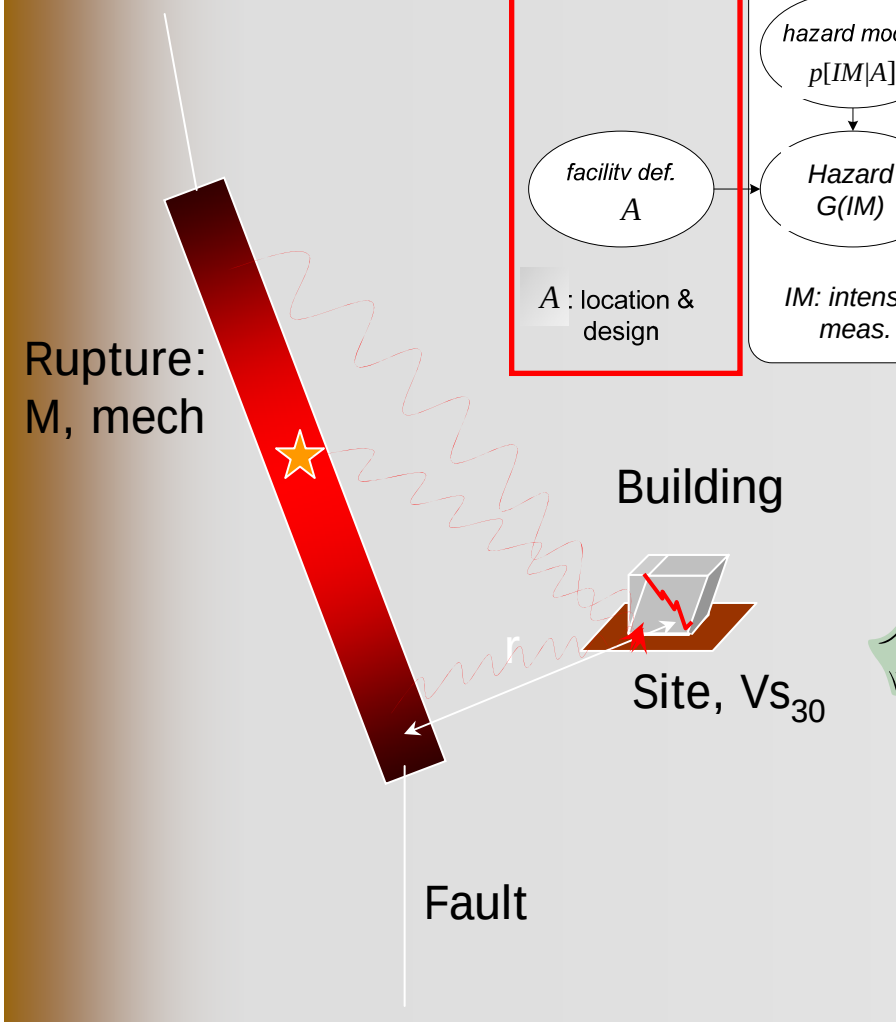
Today's objectives

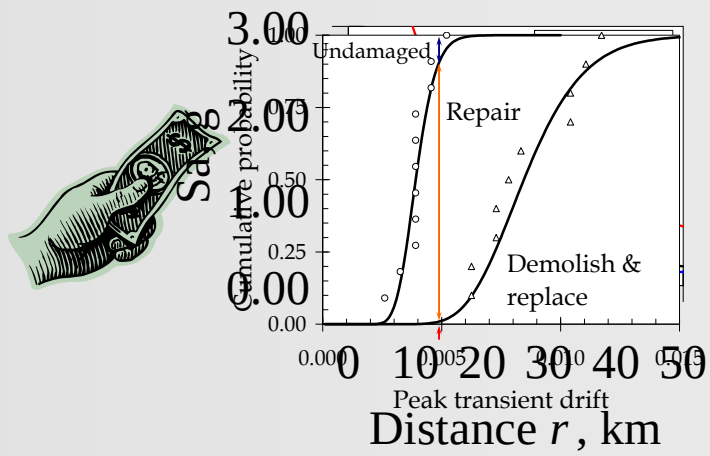
- Recap 5 stages of PBEE-2
- Repair costs
- Exercise
  - Define the asset
  - Hazard analysis
  - Structural analysis
  - Damage analysis
  - Loss analysis

Recap PEER-style PBEE



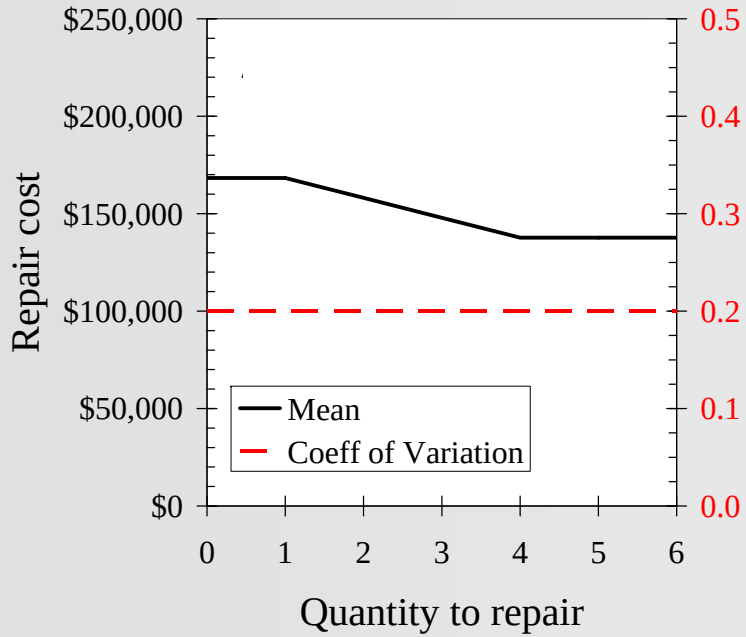
Porter 2006





Repair costs

- Component & damage state → repair effort
- Construction cost estimators judge the unit repair cost for each component & damage state
- They consider economies of scale, uncertain cost
- An example:



Component: D3031.011b, "Chiller - Capacity: 100 to <350 Ton - Unanchored equipment that is anchored or if vibration isolated has seismic snubbers - Equipment fragility only"

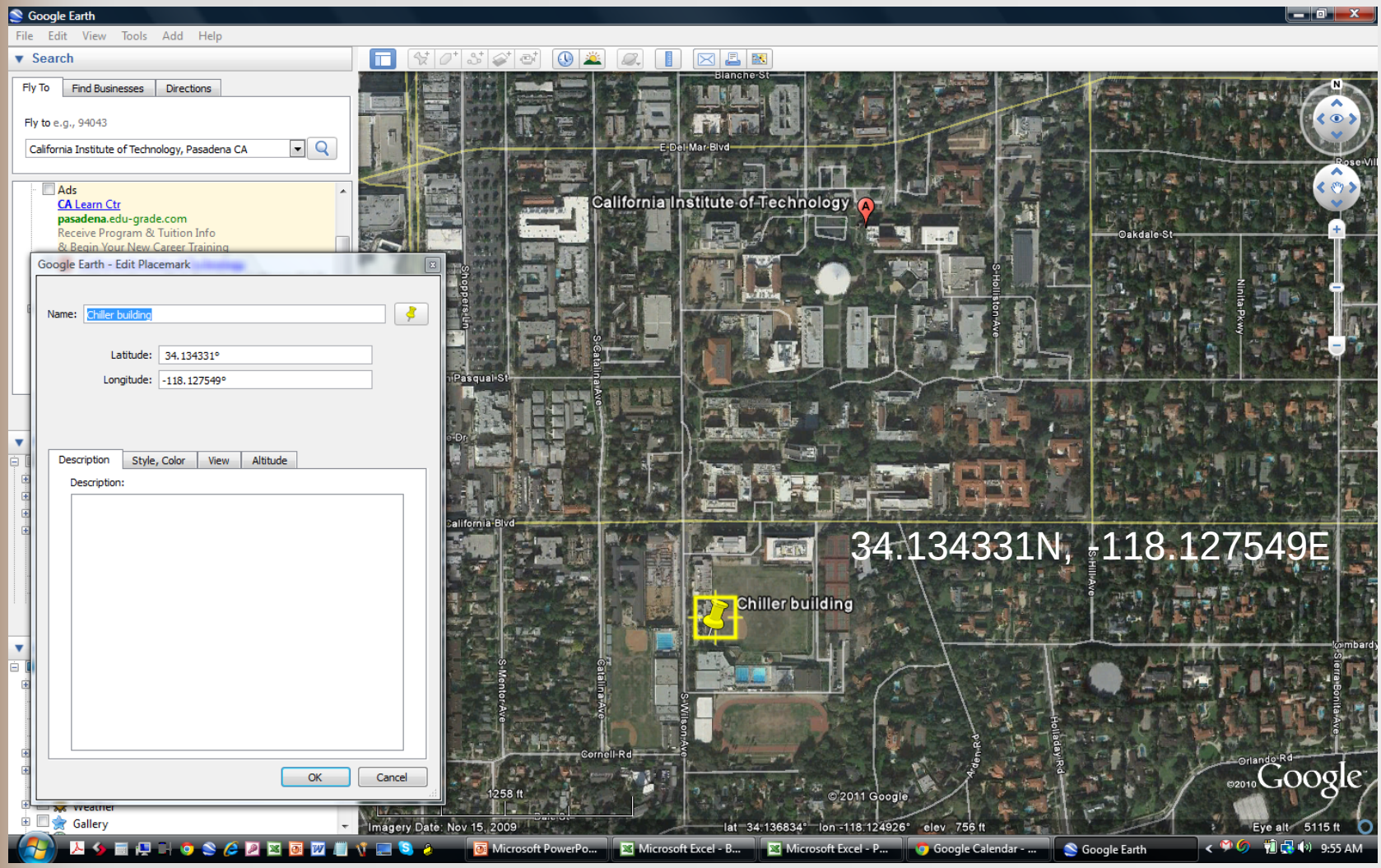
Damage state: "Damaged, inoperative"

Repair effort: "Repair chiller and attached piping."

Exercise

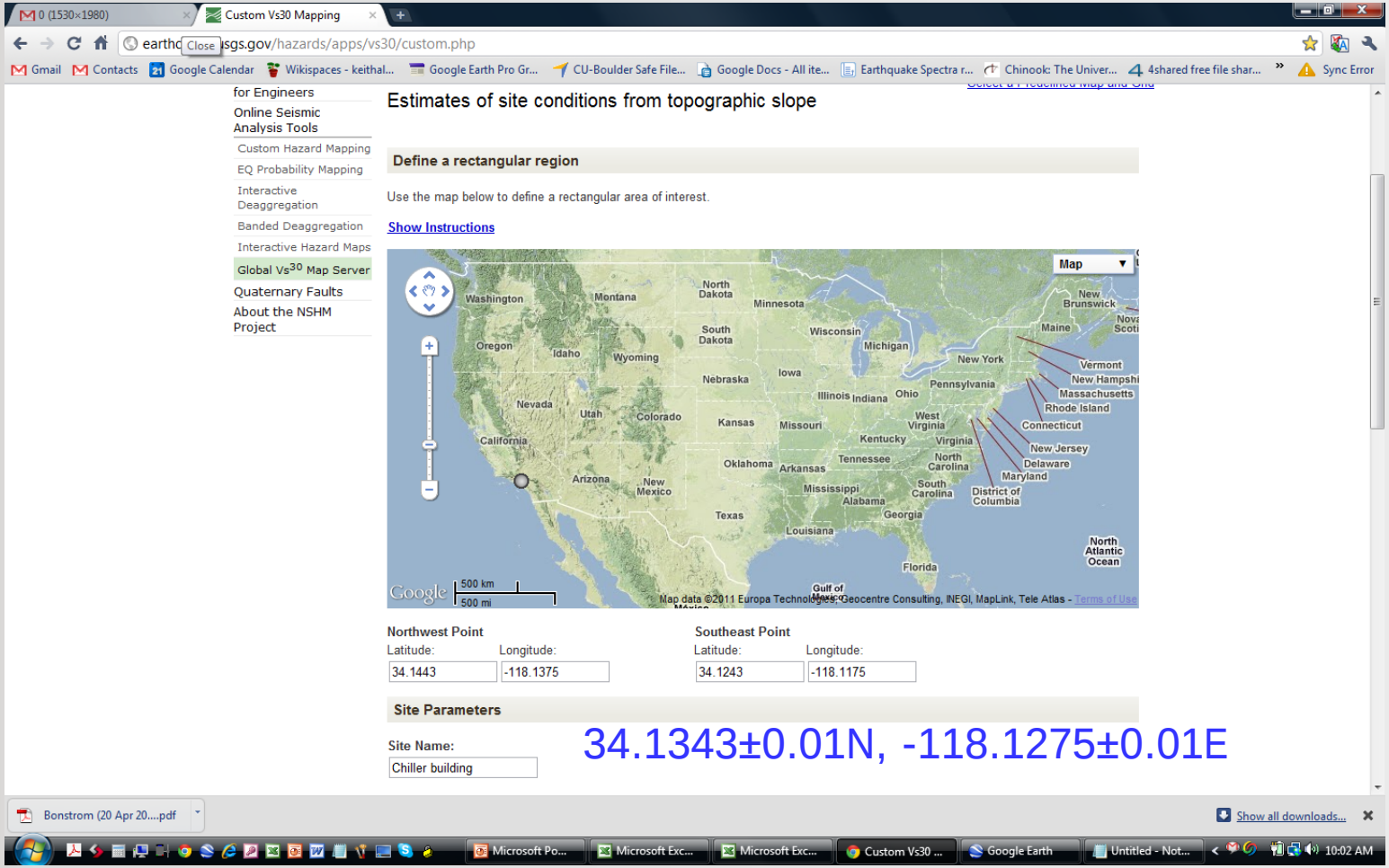
- Given: A 20x20x20-ft 1-story woodframe structure built this year next to the Caltech cogen plant, with 7/8-in stucco over 7/16-in oriented strandboard (OSB), a steel door, no windows, a mission-style ceramic tile roof over OSB roof sheathing, no interior finishes, housing two 200-ton chillers hard-mounted on a concrete slab on grade. Construction cost = $350,000.
- Required: repair cost with 10% exceedance probability given shaking with 1/475-yr mean recurrence frequency

1. Hazard analysis, location



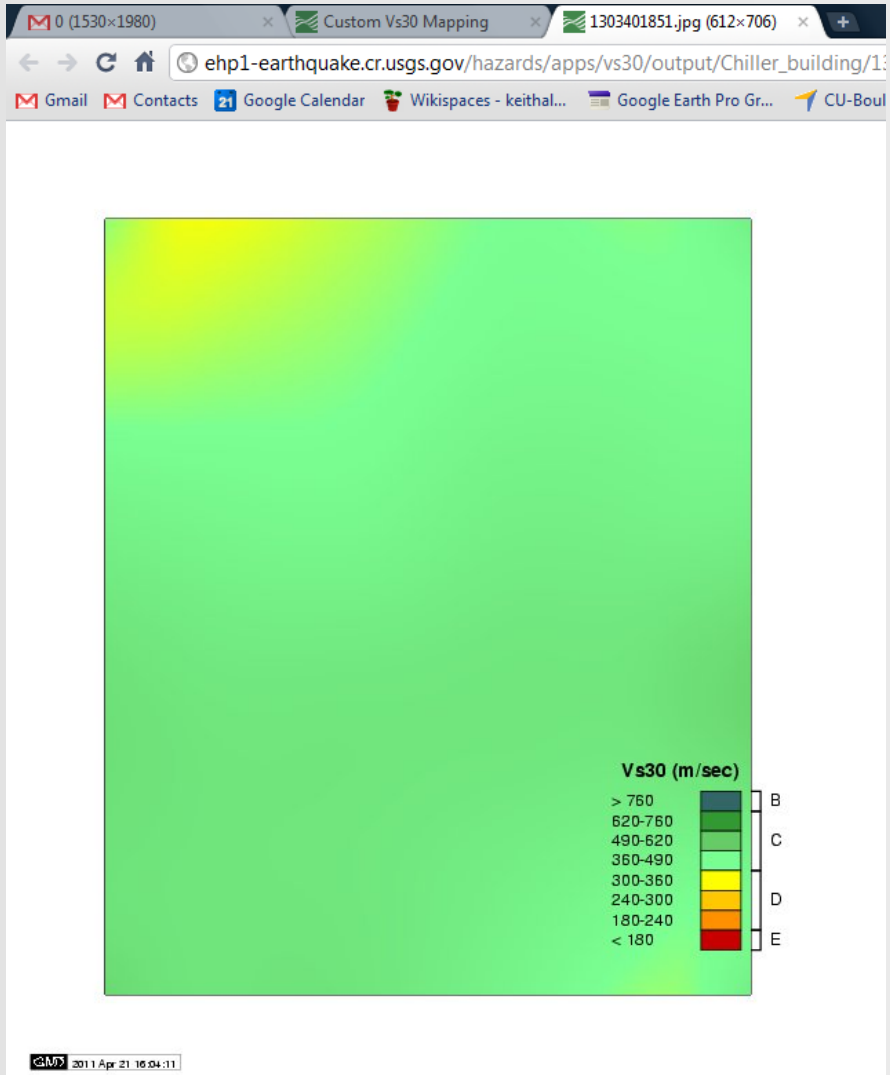
Site class w/o soil boring

http://earthquake.usgs.gov/hazards/apps/vs30/custom.php



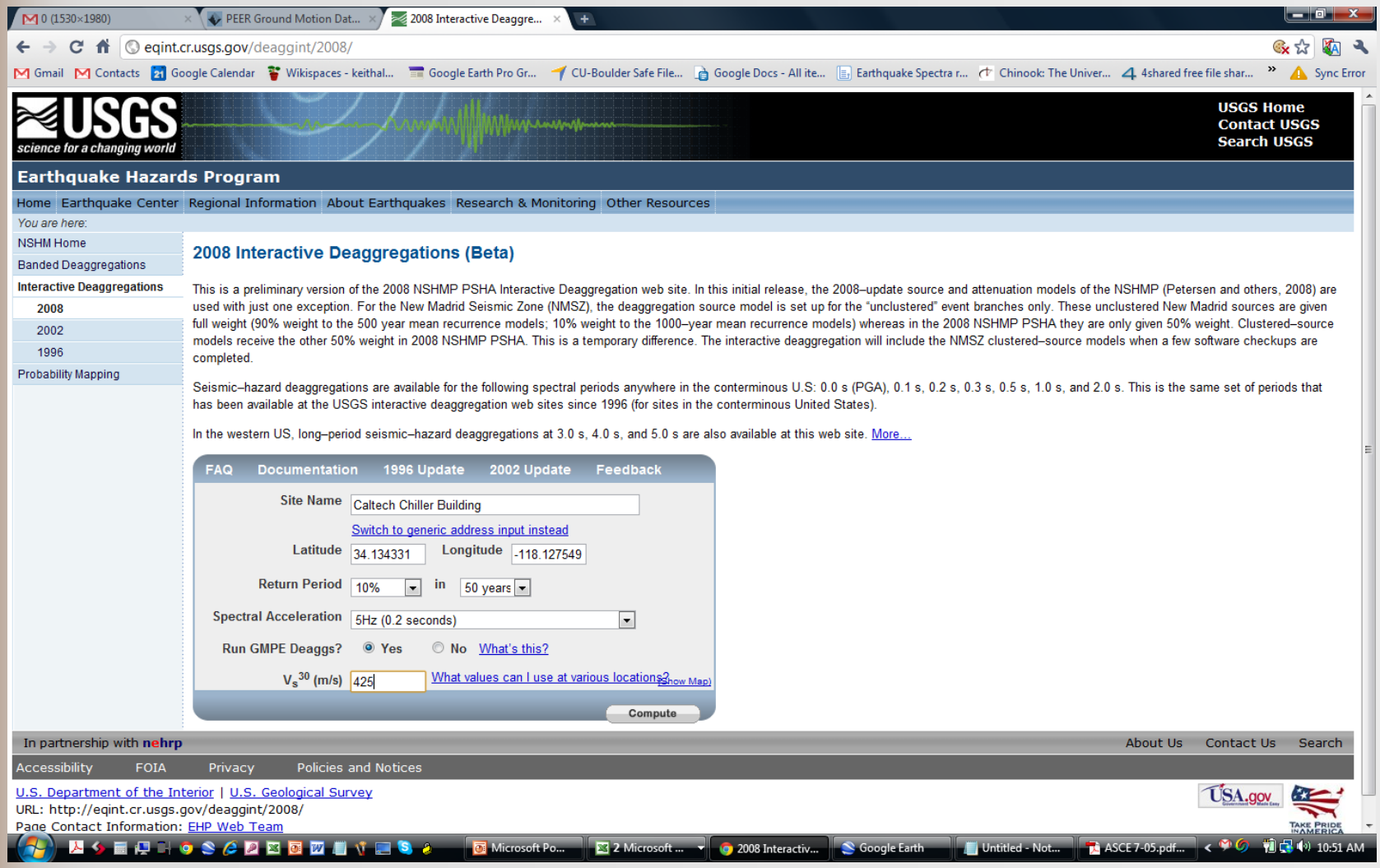
Site class w/o soil boring

- Site class ≈ C
- Vs30 ≈ 425 m/sec
- Accuracy similar to Wills et al. (2000)
- A nearby soil boring would be preferred

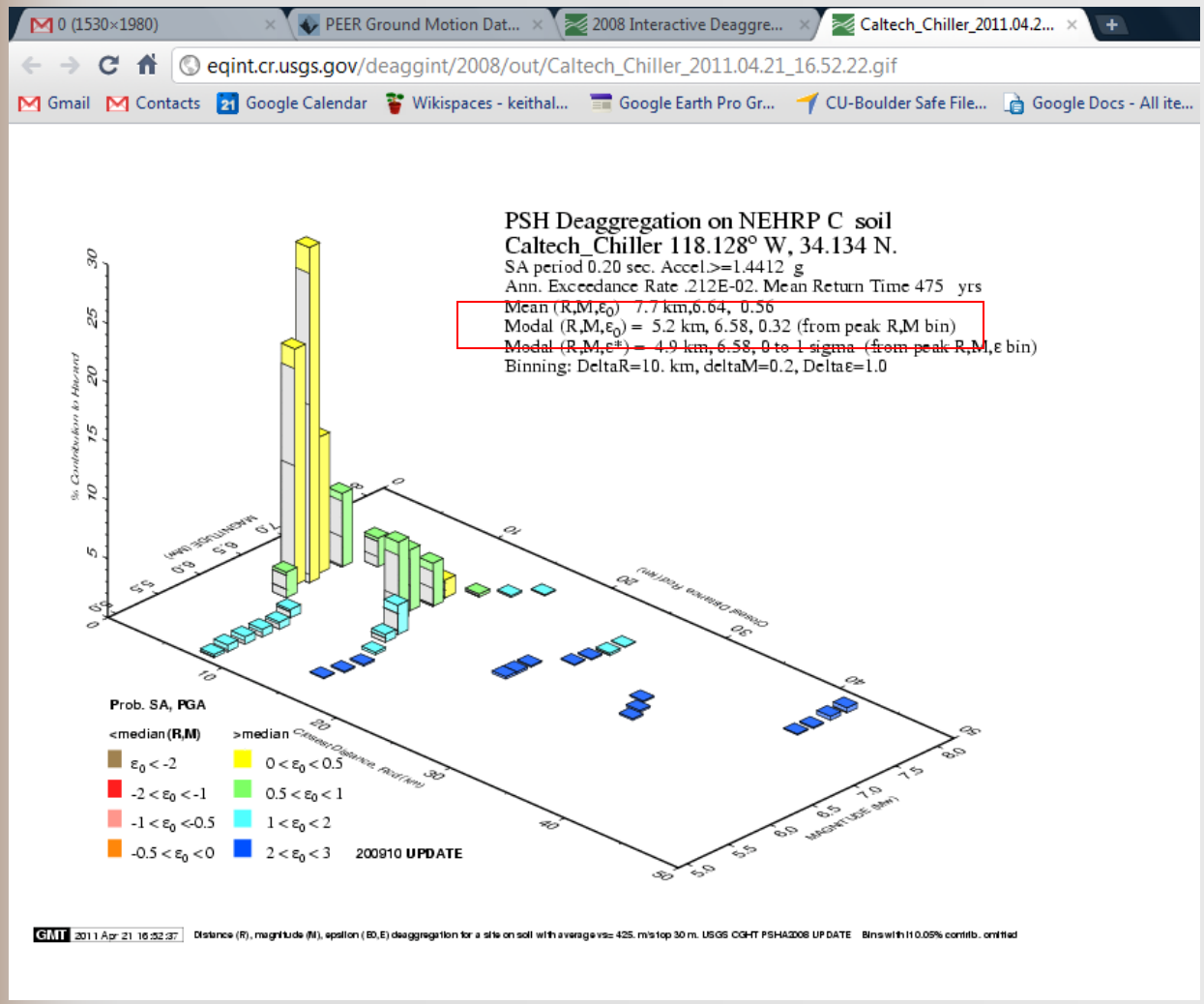


Hazard deaggregation

http://eqint.cr.usgs.gov/deaggint/2008/



Hazard deaggregation

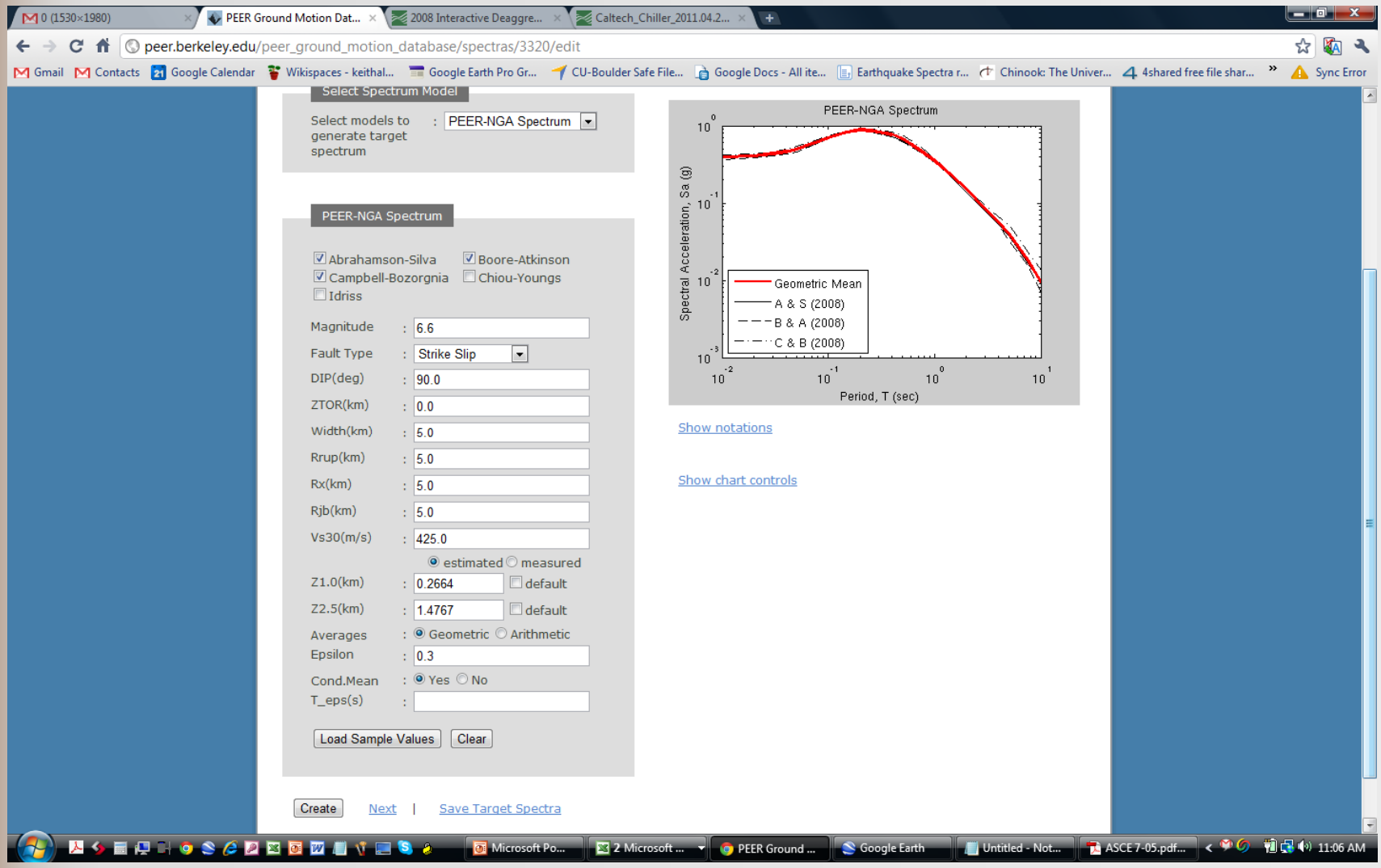


R=5 km
M = 6.6
epsilon = 0.3

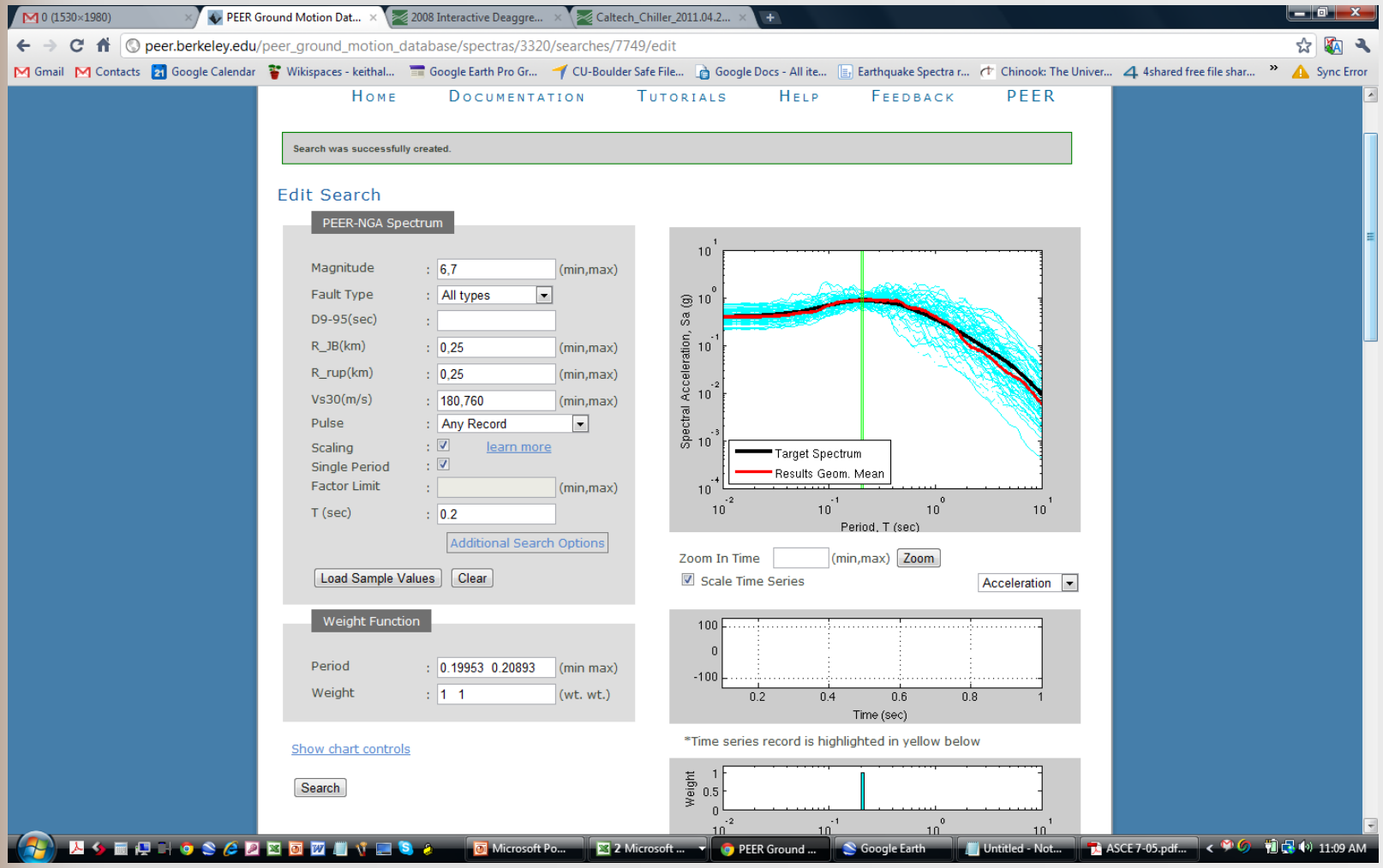
Ground-motion time histories

http://peer.berkeley.edu/peer_ground_motion_database/

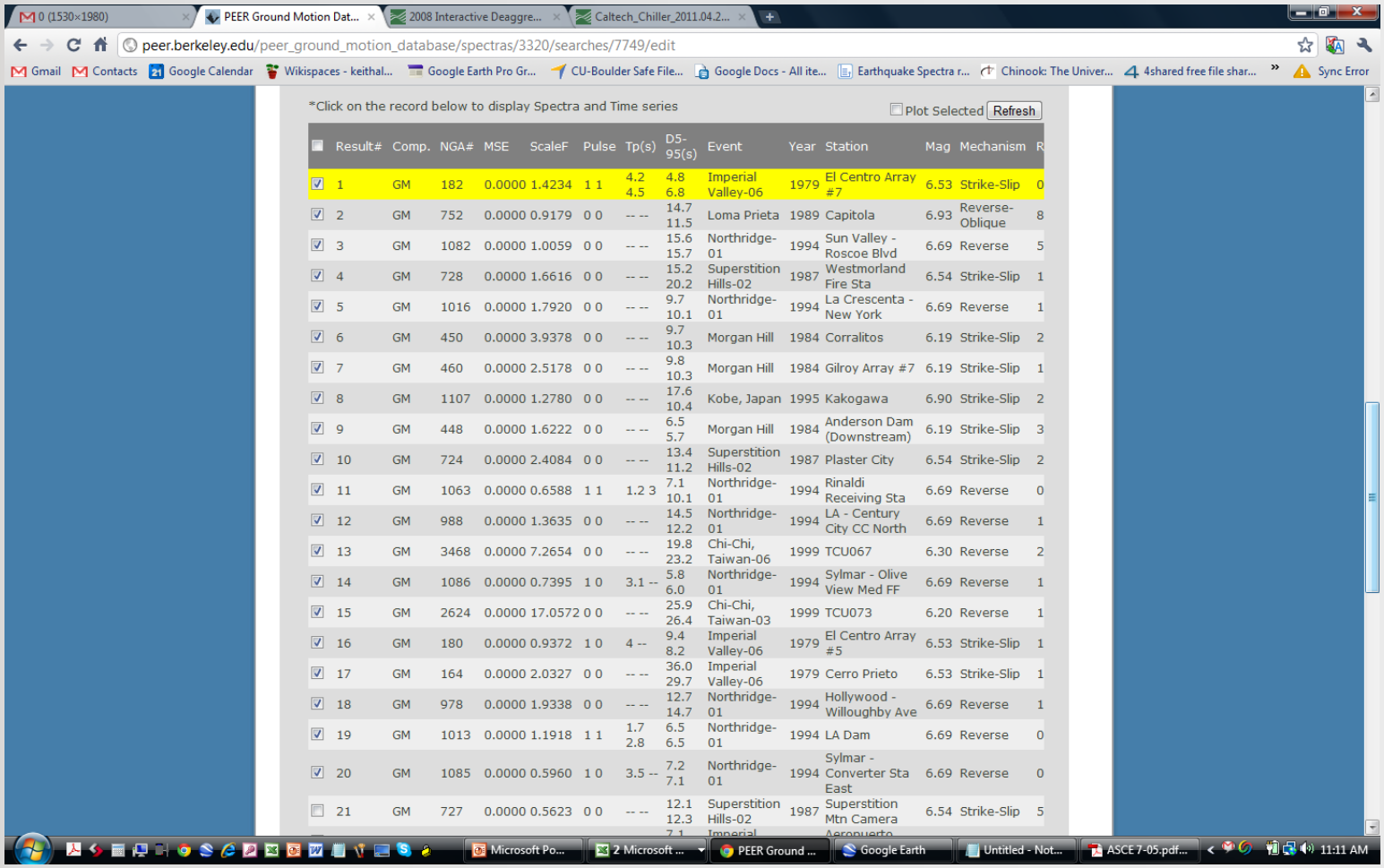
Ground-motion time histories



Ground-motion time histories

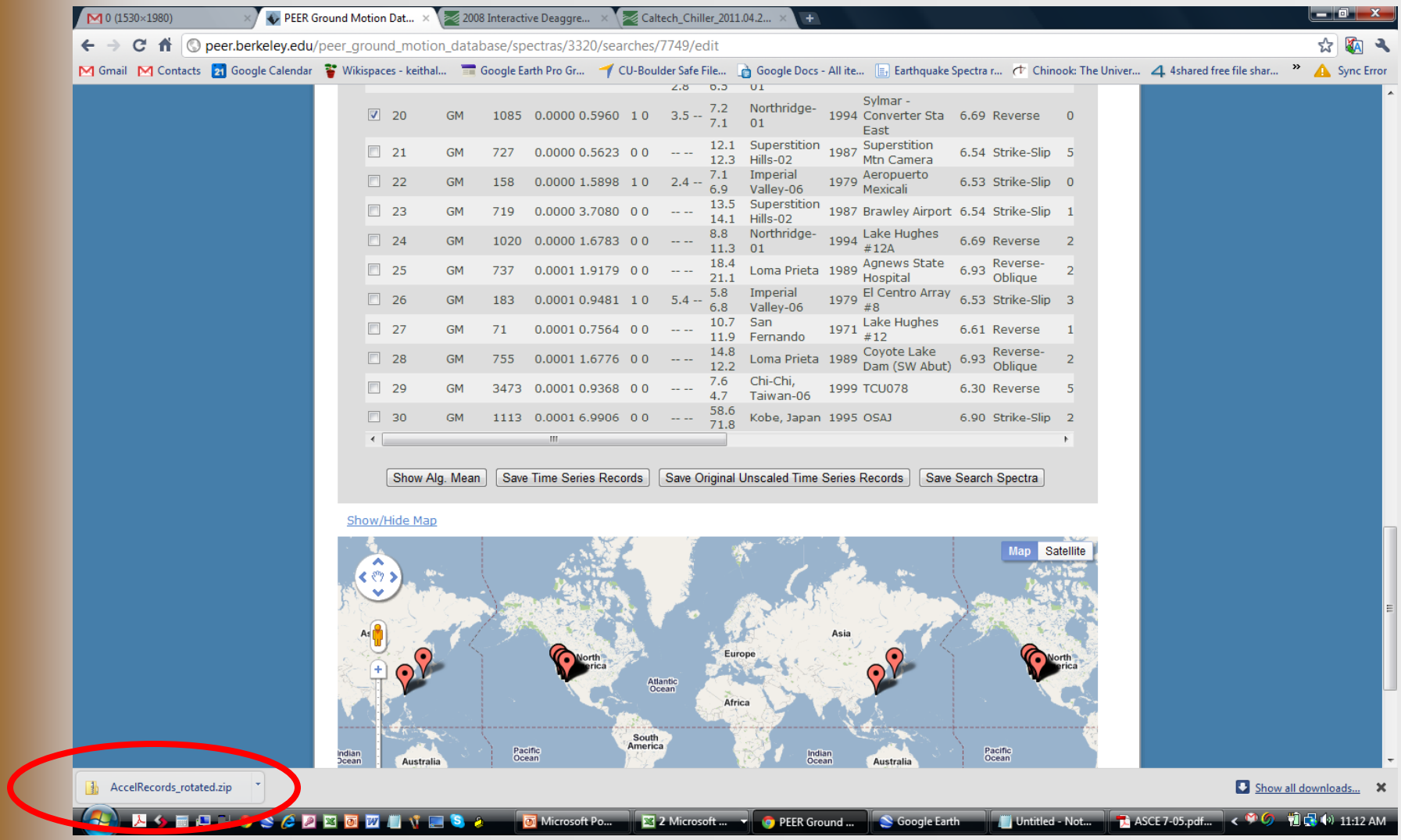


Ground-motion time histories



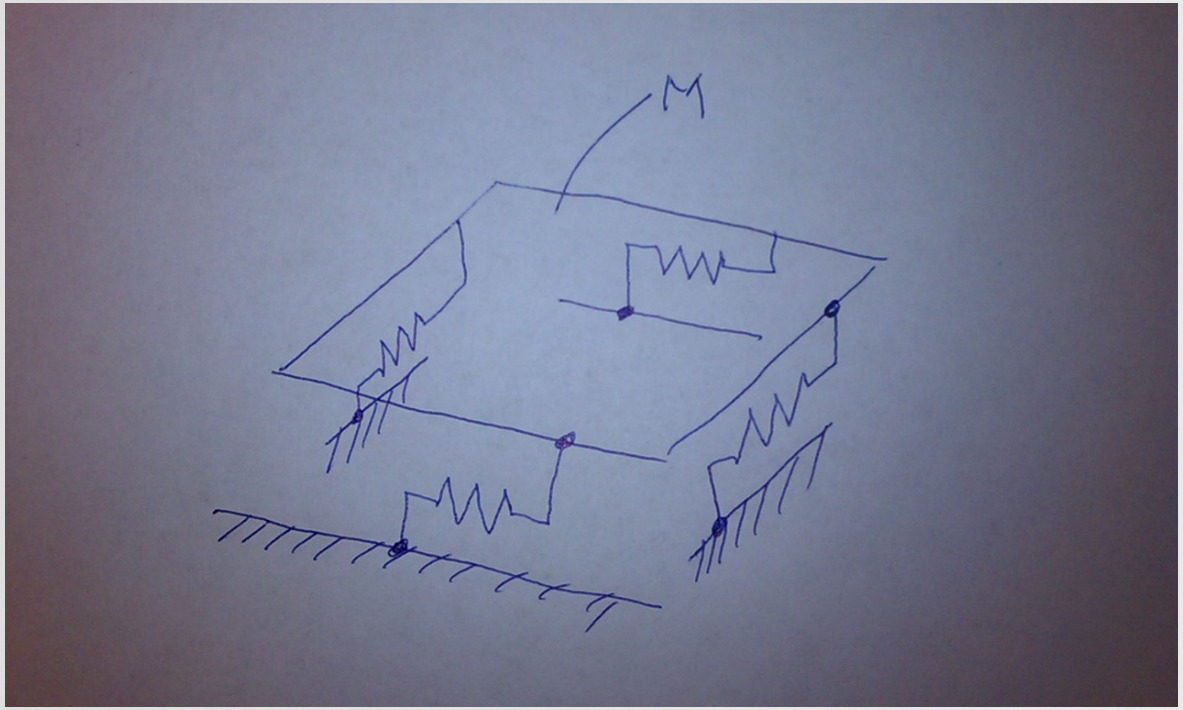
	Result#	Comp.	NGA#	MSE	ScaleF	Pulse	Tp(s)	D5-95(s)	Event	Year	Station	Mag	Mechanism	R
☑	1	GM	182	0.0000	1.4234	1 1	4.2 4.5	4.8 6.8	Imperial Valley-06	1979	El Centro Array #7	6.53	Strike-Slip	0
☑	2	GM	752	0.0000	0.9179	0 0	-- --	14.7 11.5	Loma Prieta	1989	Capitola	6.93	Reverse-Oblique	8
☑	3	GM	1082	0.0000	1.0059	0 0	-- --	15.6 15.7	Northridge-01	1994	Sun Valley - Roscoe Blvd	6.69	Reverse	5
☑	4	GM	728	0.0000	1.6616	0 0	-- --	15.2 20.2	Superstition Hills-02	1987	Westmorland Fire Sta	6.54	Strike-Slip	1
☑	5	GM	1016	0.0000	1.7920	0 0	-- --	9.7 10.1	Northridge-01	1994	La Crescenta - New York	6.69	Reverse	1
☑	6	GM	450	0.0000	3.9378	0 0	-- --	9.7 10.3	Morgan Hill	1984	Corralitos	6.19	Strike-Slip	2
☑	7	GM	460	0.0000	2.5178	0 0	-- --	9.8 10.3	Morgan Hill	1984	Gilroy Array #7	6.19	Strike-Slip	1
☑	8	GM	1107	0.0000	1.2780	0 0	-- --	17.6 10.4	Kobe, Japan	1995	Kakogawa	6.90	Strike-Slip	2
☑	9	GM	448	0.0000	1.6222	0 0	-- --	6.5 5.7	Morgan Hill	1984	Anderson Dam (Downstream)	6.19	Strike-Slip	3
☑	10	GM	724	0.0000	2.4084	0 0	-- --	13.4 11.2	Superstition Hills-02	1987	Plaster City	6.54	Strike-Slip	2
☑	11	GM	1063	0.0000	0.6588	1 1	1.2 3	7.1 10.1	Northridge-01	1994	Rinaldi Receiving Sta	6.69	Reverse	0
☑	12	GM	988	0.0000	1.3635	0 0	-- --	14.5 12.2	Northridge-01	1994	LA - Century City CC North	6.69	Reverse	1
☑	13	GM	3468	0.0000	7.2654	0 0	-- --	19.8 23.2	Chi-Chi, Taiwan-06	1999	TCU067	6.30	Reverse	2
☑	14	GM	1086	0.0000	0.7395	1 0	3.1 --	5.8 6.0	Northridge-01	1994	Sylmar - Olive View Med FF	6.69	Reverse	1
☑	15	GM	2624	0.0000	17.0572	0 0	-- --	25.9 26.4	Chi-Chi, Taiwan-03	1999	TCU073	6.20	Reverse	1
☑	16	GM	180	0.0000	0.9372	1 0	4 --	9.4 8.2	Imperial Valley-06	1979	El Centro Array #5	6.53	Strike-Slip	1
☑	17	GM	164	0.0000	2.0327	0 0	-- --	36.0 29.7	Imperial Valley-06	1979	Cerro Prieto	6.53	Strike-Slip	1
☑	18	GM	978	0.0000	1.9338	0 0	-- --	12.7 14.7	Northridge-01	1994	Hollywood - Willoughby Ave	6.69	Reverse	1
☑	19	GM	1013	0.0000	1.1918	1 1	1.7 2.8	6.5 6.5	Northridge-01	1994	LA Dam	6.69	Reverse	0
☑	20	GM	1085	0.0000	0.5960	1 0	3.5 --	7.2 7.1	Northridge-01	1994	Sylmar - Converter Sta East	6.69	Reverse	0
☐	21	GM	727	0.0000	0.5623	0 0	-- --	12.1 12.3	Superstition Hills-02	1987	Superstition Mtn Camera	6.54	Strike-Slip	5

Ground-motion time histories



20	GM	1085	0.0000	0.5960	1 0	3.5 --	7.2 7.1	Northridge-01	1994	Sylmar - Converter Sta East	6.69	Reverse	0
21	GM	727	0.0000	0.5623	0 0	-- --	12.1 12.3	Superstition Hills-02	1987	Superstition Mtn Camera	6.54	Strike-Slip	5
22	GM	158	0.0000	1.5898	1 0	2.4 --	7.1 6.9	Imperial Valley-06	1979	Aeropuerto Mexicali	6.53	Strike-Slip	0
23	GM	719	0.0000	3.7080	0 0	-- --	13.5 14.1	Superstition Hills-02	1987	Brawley Airport	6.54	Strike-Slip	1
24	GM	1020	0.0000	1.6783	0 0	-- --	8.8 11.3	Northridge-01	1994	Lake Hughes #12A	6.69	Reverse	2
25	GM	737	0.0001	1.9179	0 0	-- --	18.4 21.1	Loma Prieta	1989	Agnews State Hospital	6.93	Reverse-Oblique	2
26	GM	183	0.0001	0.9481	1 0	5.4 --	5.8 6.8	Imperial Valley-06	1979	El Centro Array #8	6.53	Strike-Slip	3
27	GM	71	0.0001	0.7564	0 0	-- --	10.7 11.9	San Fernando	1971	Lake Hughes #12	6.61	Reverse	1
28	GM	755	0.0001	1.6776	0 0	-- --	14.8 12.2	Loma Prieta	1989	Coyote Lake Dam (SW Abut)	6.93	Reverse-Oblique	2
29	GM	3473	0.0001	0.9368	0 0	-- --	7.6 4.7	Chi-Chi, Taiwan-06	1999	TCU078	6.30	Reverse	5
30	GM	1113	0.0001	6.9906	0 0	-- --	58.6 71.8	Kobe, Japan	1995	OSAJ	6.90	Strike-Slip	2

2. Structural analysis



M = roof + ½ of wall mass

Roof: W/sf = 150 tiles/100 sf x 7lb/tile + 10 psf for roof, framing, etc. = 20.5 psf

Roof mass = 450 sf x 20.5 psf / 32.2 lbm/slug = 287 slug

½ of wall mass: 15 psf · 10 ft (high)· 80 ft (perimeter)/ 32.2 lbm/slug = 373 slug

M = 287 slug + 373 slug = 660 slug

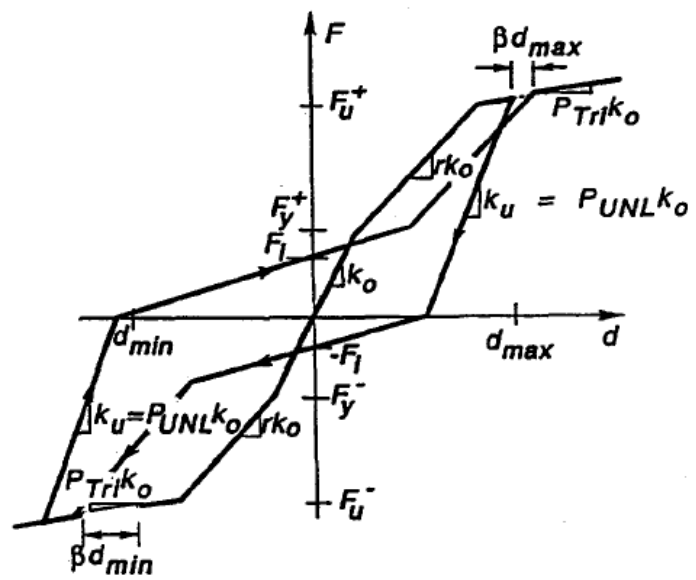
Stucco sheathing springs
from UCI COLA tests

Elastic properties

- K_0 = 2.5 kip/in/lf wall

Wayne Stewart
degrading stiffness parameter values

- F_Y = ±0.168 kip/lf wall
- r = 0.16
- F_U = 0.368 kip/lf wall
- P_{TRI} = -0.064
- F_I = 0.25 FY, as did Wayne Stewart
- P_{UNL} = 1.45
- Beta = 1.09
- Alpha = 0.38



Wayne Stewart Degrading Hysteresis

Structural analysis

- Create springs for each wall, each material
  - E.g., each stucco wall : 20 ft x K_0, F_Y, & F_U
  - Repeat for OSB sheathing
- Create roof diaphragm element
- Perform nonlinear dynamic structural analyses, 1 for each ground-motion time history $i \in \{1, 2, \ldots 20\}$
- Response $\underline{R}_i = [PTD_{Ei}, PTD_{Wi}, PTD_{Ni}, PTD_{Si}, PGA_i, PRA_i]^T$
- Response $\underline{R} = [\underline{R}_1; \underline{R}_2; \ldots \underline{R}_{20}]$

Structural response R =

Sim	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
PTDE, in/in	0.0028	0.0064	0.0040	0.0040	0.0034	0.0035	0.0048	0.0051	0.0032	0.0026	0.0022	0.0035	0.0040	0.0032	0.0047	0.0053	0.0052	0.0042	0.0036	0.0034
PTDW, in/in	0.0028	0.0064	0.0040	0.0040	0.0034	0.0035	0.0048	0.0051	0.0032	0.0026	0.0022	0.0035	0.0040	0.0032	0.0047	0.0053	0.0052	0.0042	0.0036	0.0034
PTDN, in/in	0.0033	0.0050	0.0013	0.0022	0.0008	0.0042	0.0026	0.0025	0.0048	0.0048	0.0017	0.0030	0.0041	0.0012	0.0148	0.0040	0.0021	0.0025	0.0014	0.0033
PTDS, in/in	0.0033	0.0050	0.0013	0.0022	0.0008	0.0042	0.0026	0.0025	0.0048	0.0048	0.0017	0.0030	0.0041	0.0012	0.0148	0.0040	0.0021	0.0025	0.0014	0.0033
PGA, g	0.52	0.55	0.28	0.71	0.45	0.56	0.95	0.59	0.84	0.68	0.35	0.46	0.92	0.59	1.58	0.59	0.73	1.10	1.09	0.40
PRA, g	1.48	2.76	1.12	1.45	0.82	1.88	1.74	1.74	1.92	1.75	0.95	1.58	1.99	0.96	4.10	2.26	1.63	1.59	1.10	1.65

Sim	1	2	3	
PTDE, in/in	0.0028	0.0064	0.0040	0.0
PTDW, in/in	0.0028	0.0064	0.0040	0.0
PTDN, in/in	0.0033	0.0050	0.0013	0.0
PTDS, in/in	0.0033	0.0050	0.0013	0.0
PGA, g	0.52	0.55	0.28	
PRA, g	1.48	2.76	1.12	

Damage analysis

- Chillers: $N_D = 1$; damaged, inoperative; repair chiller and connections
  - $\theta_1 = 0.72$, $\beta_1 = 0.2$;
- Stucco on 7/16-in OSB: $N_D = 2$ sequential states
  - fracture sheathing-framing connection; remove damaged stucco, renail, replace stucco:
    $\theta_1 = 0.005$, $\beta_1 = 0.3$,
  - tearout connectors on 2 edges; dem & replace:
    $\theta_2 = 0.011$, $\beta_2 = 0.5$
- Roof tile: $N_D = 2$ sequential states
  - Minor damage, tiles dislodged; reinstall tiles
    $\theta_1 = 1.8g$, $\beta_1 = 0.3$
  - Major portion (>10-20%?) of tiles dislodged; replace
    $\theta_2 = 2.2g$, $\beta_2 = 0.3$

Damage analysis

Sim	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
chiller 1																				
θ	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
β	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Pf	0.06	0.09	0.00	0.47	0.01	0.11	0.92	0.16	0.78	0.40	0.00	0.01	0.89	0.17	1.00	0.16	0.52	0.98	0.98	0.00
u	0.58	0.98	0.21	0.91	0.61	0.68	0.83	0.66	0.34	0.77	0.82	0.91	0.89	0.73	0.76	0.85	0.29	0.30	0.32	0.79
f	0	0	0	0	0	0	1	0	1	0	0	0	0	0	1	0	1	1	1	0
chiller 2																				
θ	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
β	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Pf	0.06	0.09	0.00	0.47	0.01	0.11	0.92	0.16	0.78	0.40	0.00	0.01	0.89	0.17	1.00	0.16	0.52	0.98	0.98	0.00
u	0.70	0.07	0.50	0.92	0.71	0.08	0.20	0.63	0.67	0.07	0.78	0.43	0.88	0.83	0.72	0.21	0.61	0.08	0.46	0.89
f	0	1	0	0	0	1	1	0	1	1	0	0	1	0	1	0	0	1	1	0
Wall E																				
θ1	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
β1	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
θ2	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011
β2	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Pf1	0.03	0.79	0.22	0.23	0.10	0.12	0.43	0.53	0.07	0.02	0.00	0.11	0.22	0.06	0.42	0.57	0.55	0.28	0.13	0.10
Pf2	0.00	0.14	0.02	0.02	0.01	0.01	0.05	0.06	0.01	0.00	0.00	0.01	0.02	0.01	0.04	0.07	0.07	0.03	0.01	0.01
u	0.58	0.94	0.98	0.77	0.06	0.29	0.91	0.82	0.83	0.06	0.75	0.35	0.85	0.31	0.70	0.18	0.68	0.57	0.09	0.07
f	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1
Wall W																				
θ1	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
β1	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
θ2	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011
β2	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Pf1	0.03	0.79	0.22	0.23	0.10	0.12	0.43	0.53	0.07	0.02	0.00	0.11	0.22	0.06	0.42	0.57	0.55	0.28	0.13	0.10
Pf2	0.00	0.14	0.02	0.02	0.01	0.01	0.05	0.06	0.01	0.00	0.00	0.01	0.02	0.01	0.04	0.07	0.07	0.03	0.01	0.01
u	0.13	0.33	0.18	0.07	0.90	0.26	0.77	0.92	0.19	0.40	0.42	0.24	0.86	0.40	0.50	0.30	0.13	0.20	0.02	0.65
f	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0
Wall N																				
θ1	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
β1	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
θ2	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011
β2	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Pf1	0.08	0.49	0.00	0.00	0.00	0.27	0.02	0.01	0.45	0.45	0.00	0.04	0.27	0.00	1.00	0.23	0.00	0.01	0.00	0.08
Pf2	0.01	0.06	0.00	0.00	0.00	0.03	0.00	0.00	0.05	0.05	0.00	0.00	0.03	0.00	0.73	0.02	0.00	0.00	0.00	0.01
u	0.91	0.39	0.14	0.88	0.80	0.33	0.59	0.94	0.48	0.19	0.20	0.97	0.28	0.20	0.32	0.14	0.08	0.57	0.77	0.21
f	0	1	0	0	0	0	0	0	0	1	0	0	0	0	2	1	0	0	0	0
Wall S																				
θ1	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
β1	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
θ2	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011
β2	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Pf1	0.08	0.49	0.00	0.00	0.00	0.27	0.02	0.01	0.45	0.45	0.00	0.04	0.27	0.00	1.00	0.23	0.00	0.01	0.00	0.08
Pf2	0.01	0.06	0.00	0.00	0.00	0.03	0.00	0.00	0.05	0.05	0.00	0.00	0.03	0.00	0.73	0.02	0.00	0.00	0.00	0.01
u	0.34	0.21	0.56	0.65	0.54	0.88	0.54	0.72	0.14	0.83	0.01	0.94	0.29	0.04	0.75	0.59	0.38	0.31	0.49	0.25
f	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0

Damage analysis: east wall, sim 1

θ1	0.005	0.
β1	0.3	
θ2	0.011	0.
β2	0.5	
Pf1	0.03	0
Pf2	0.00	0
u	0.58	0
f	0	

- R_1 = 0.0028 in/in, θ_1 = 0.005, β_1 = 0.3
- P[D≥1|R=0.0028] = Φ(ln(0.0028/0.005)/0.3) = 0.025
- P[D≥2|R=0.0028] = Φ(ln(0.0028/0.011)/0.5) = 0.003
- rand() = 0.58 > 0.025 → not failed DS1 or DS2

Damage summary

Damage summary

Sim	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	1
Walls 1	0	18.75	6.25	6.25	6.25	0	0	0	6.25	6.25	0	0	0	0	6.25	18.7
Walls 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.25	
Chiller	0	1	0	0	0	1	2	0	2	1	0	0	1	0	2	
Roof 1	0	0	0	0	0	4	4	0	0	4	0	0	0	0	0	
Roof 2	0	4	0	0	0	0	0	0	0	0	0	0	4	0	4	

Sim	1	2	
Walls 1	0	18.75	6
Walls 2	0	0	
Chiller	0	1	
Roof 1	0	0	
Roof 2	0	4	

(units of 64 sf)

(units of 100 sf)

Loss analysis: unit costs

i.e., cost to repair 1 “unit”

- Chillers: (as shown earlier)
- Stucco on 7/16-in OSB: N_D = 2 damage states
  - q_1 = \$131/64 sf; b_1 = 0.2; independent of qty
  - q_2 = \$742/64 sf, b_2 = 0.2; independent of qty
- Tile roof: N_D = 2 damage states
  - q_1 = \$ 80/100 sf; b_1 = 0.3; independent of qty
  - q_2 = \$800/100 sf; b_1 = 0.3; independent of qty

Loss analysis

$$C/unit = q \cdot \exp\left(b \cdot \Phi^{-1}(u)\right)$$
$$= \$131/64sf \cdot \exp\left(0.2 \cdot \Phi^{-1}(0.19)\right)$$
$$= \$110/64sf$$
$$C = Units \cdot C/unit$$
$$= 18.75 \cdot \$110$$
$$= \$2,058$$

Sim	1	2		3	4								
q, $/64sf	$ 131	$ 131	$	131	$ 131	$							$ 13
b	0.2	0.2		0.2	0.2								(
rand()	0.73	0.19		0.76	0.14								0.
Cost/64sf, $	$ 148	$ 110	$	151	$ 106	$							$ 9
Count 64 sf	0	18.75		6.25	6.25								
Cost, $	$ -	$ 2,058	$	944	$ 661	$							$ -
q, $/64sf	$ 742	$ 742	$	742	$ 742	$							$ 74
b	0.2	0.2		0.2	0.2								(
rand()	0.58	0.80		0.11	0.77								0.
Cost/64sf, $	$ 772	$ 878	$	581	$ 861	$ 574	$ 674	$ 706	$ 732	$ 880	$ 806	$ 58	$ 73
Count 64 sf	0	0		0	0	0	0	0	0	0	0	0	
Cost, $	$ -	$ -											$ -
Lower plateau count	1	1											
q lower, $/each	$ 160,000	$ 160,000											$ 160,00
Upper plateau count	4	4											
q upper, $/each	$ 140,000	$ 140,000											$ 140,00
Count	0	1											
q at count, $/each	$ 160,000	$ 160,000											$ 160,00
b	0.2	0.2											(
rand()	0.83	0.20											0.
Cost/each, $	$ 193,965	$ 135,463											$ 150,60
Cost, $	$ -	$ 135,463											$ -
q, $/100 sf	$ 80	$ 80											$ 8
b	0.3	0.3											(
rand()	0.69	0.68											0.
Cost/100sf	$ 93	$ 92											$ 13
Count 100sf	0	0											
Cost	$ -	$ -	$ -	$ -	$ -	$ 355	$ 235	$ -	$ -	$ 208	$ -		$ -

Sim	1	2	
q, $/64sf	$ 131	$ 131	$
b	0.2	0.2	
rand()	0.73	0.19	
Cost/64sf, $	$ 148	$ 110	$
Count 64 sf	0	18.75	
Cost, $	$ -	$ 2,058	$

Results

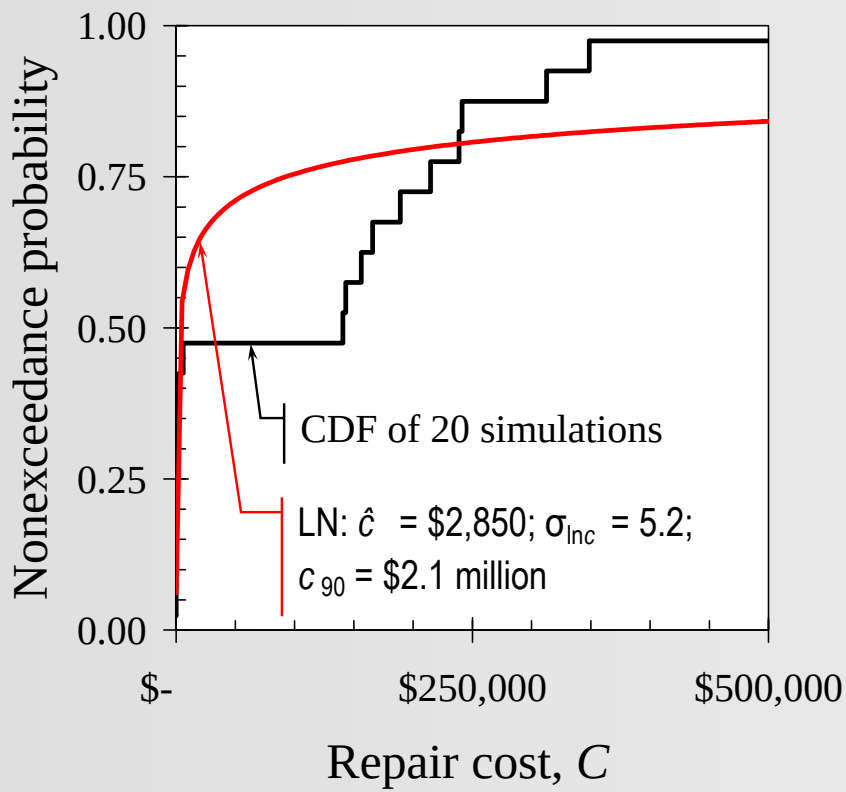
Rank	Cost	Percentile
1	$ -	2.5
2	$ -	7.5
3	$ -	12.5
4	$ -	17.5
5	$ -	22.5
6	$ 661	27.5
7	$ 944	32.5
8	$ 947	37.5
9	$ 2,661	42.5
10	$ 5,980	47.5
11	$ 140,762	52.5
12	$ 143,239	57.5
13	$ 156,330	62.5
14	$ 165,778	67.5
15	$ 189,209	72.5
16	$ 214,773	77.5
17	$ 238,845	82.5
18	$ 241,441	87.5
19	$ 312,759	92.5
20	$ 348,710	97.5

Total cost simulations sorted in increasing order

90th percentile = (241,441 + 313,759)/2
= $277,100
Call it ≈ $280,000

Results

- NB: a lognormal fits the simulations badly; fails Lilliefors goodness-of-fit test



Thanks

keith.porter@colorado.edu
(626) 233-9758