Fragility of the Electric Power Grid

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Perspective

- In nearly every M 5+ earthquake, there are reports of "Power Outages"
- 1971 - 2013. Many earthquakes damage high voltage equipment at substations. Outcome: IEEE 693 (1997) (ShakeTable tests at PGA = 0.5g for 220 kV - 500 kV equipment)
- 2014. Napa M 6.0 earthquake. No damage at high voltage substations (PGA ~0.2g to 0.4g). Still, 90,000 customers still lose power.

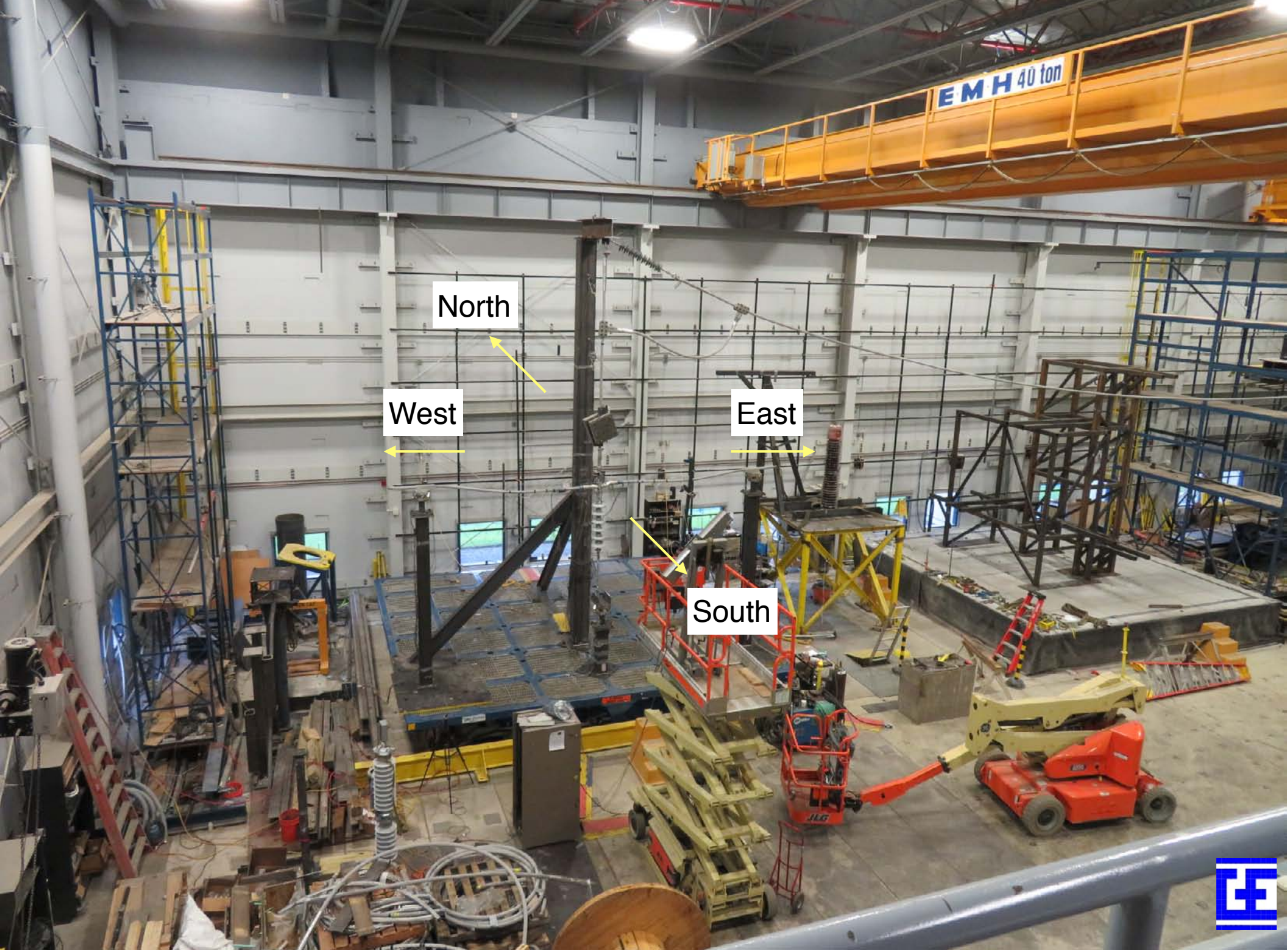
What is Happening that Still Causes Power Outages?

The Model

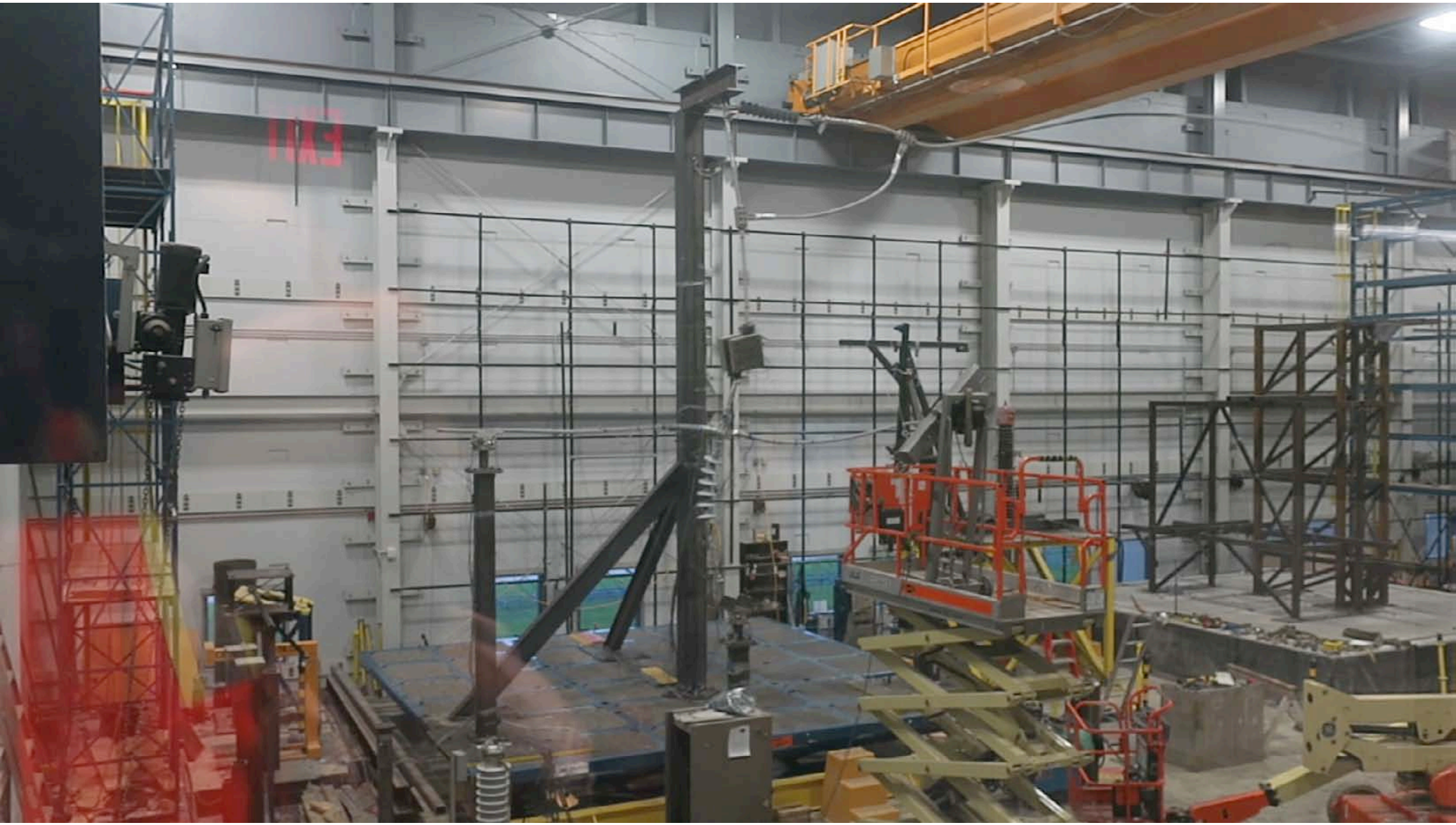
- SERA: risk model to quantify power outages at **substations**, **transmission towers** and the **distribution system**
- SDG&E, SCE, PG&E, PPL, BPA, BC Hydro (90% of the power grid from Mexico to the Yukon)
- Inventory includes every component at every substation; every transmission circuit; every transmission tower; every wood pole; every overhead and underground distribution feeder

The Issues

- Interactions between Equipment. Still a problem at many substations. A major problem in the distribution system.
- Fragility. Over 2 million "exposures" of equipment in actual earthquakes.
- Towers. Landslides present a significant risk (fault offset, liquefaction are relatively smaller risks).
- What is an "acceptable" power outage? Customer-Minutes (CM)
- Mitigation Benefits. If we can reduce CM, there is less economic impact. For California use $0.11 per CM outages.
- Cost. Rate payers want low cost / kilowatt-hour.
- Benefit. Present value of Mitigation Costs should be < Present value of future Benefits.

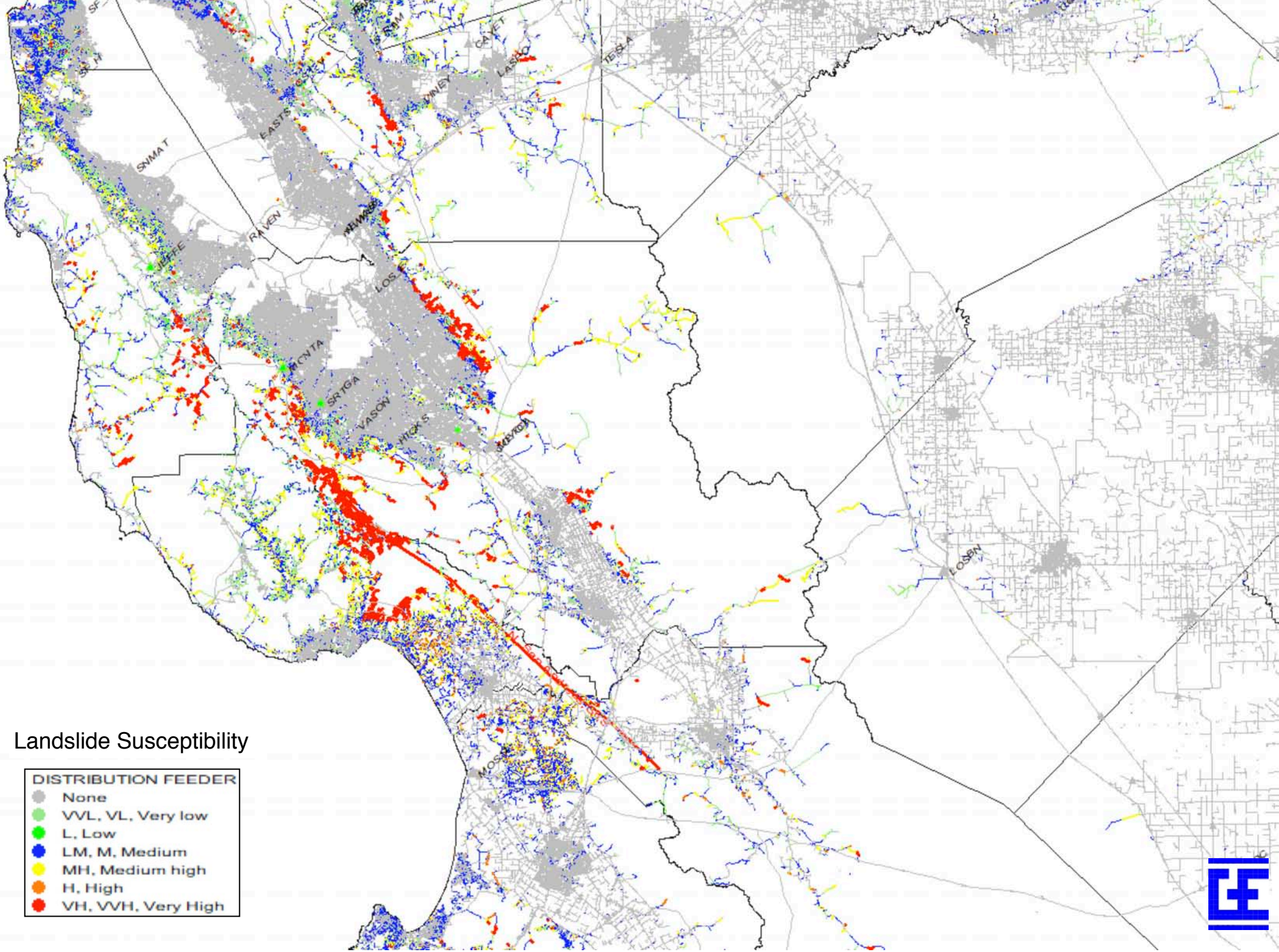

EMH 40 ton
North
West
East
South

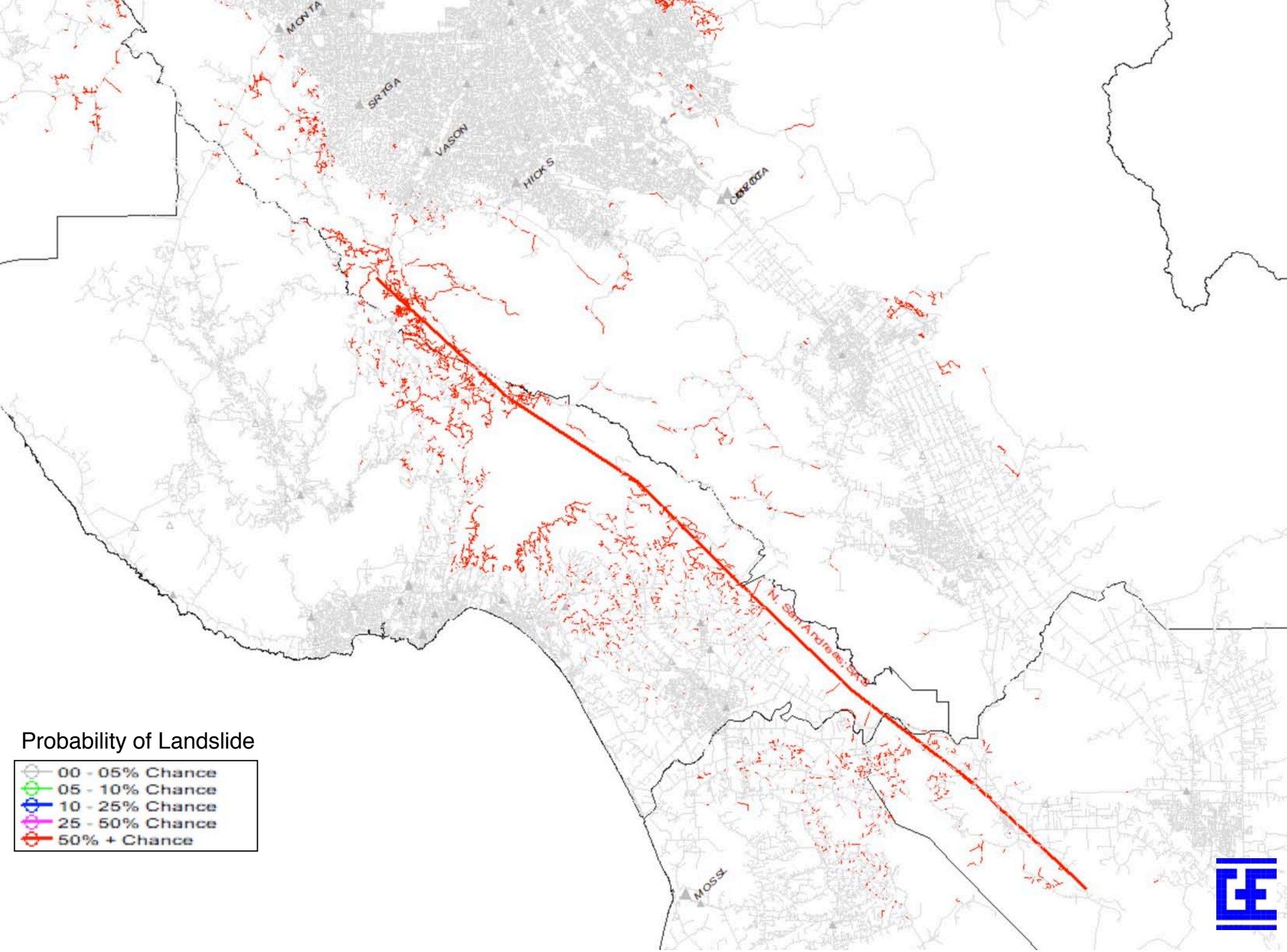

EMH 40 ton
20 TON
KONE CRANES
Transmission Line

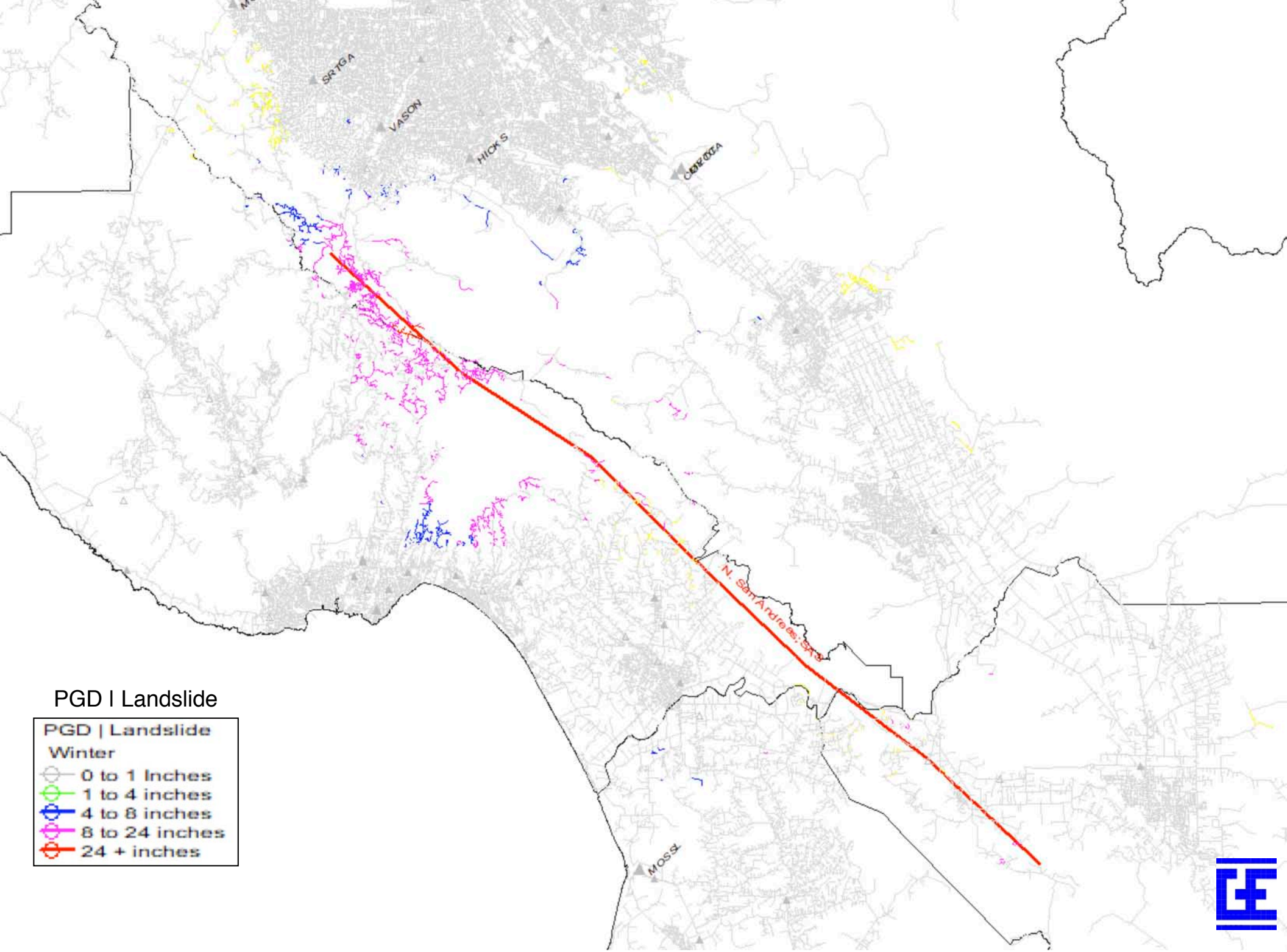


Test PGA = 1.00g, Broad Band, IEEE 693

Loma Prieta Power Outages

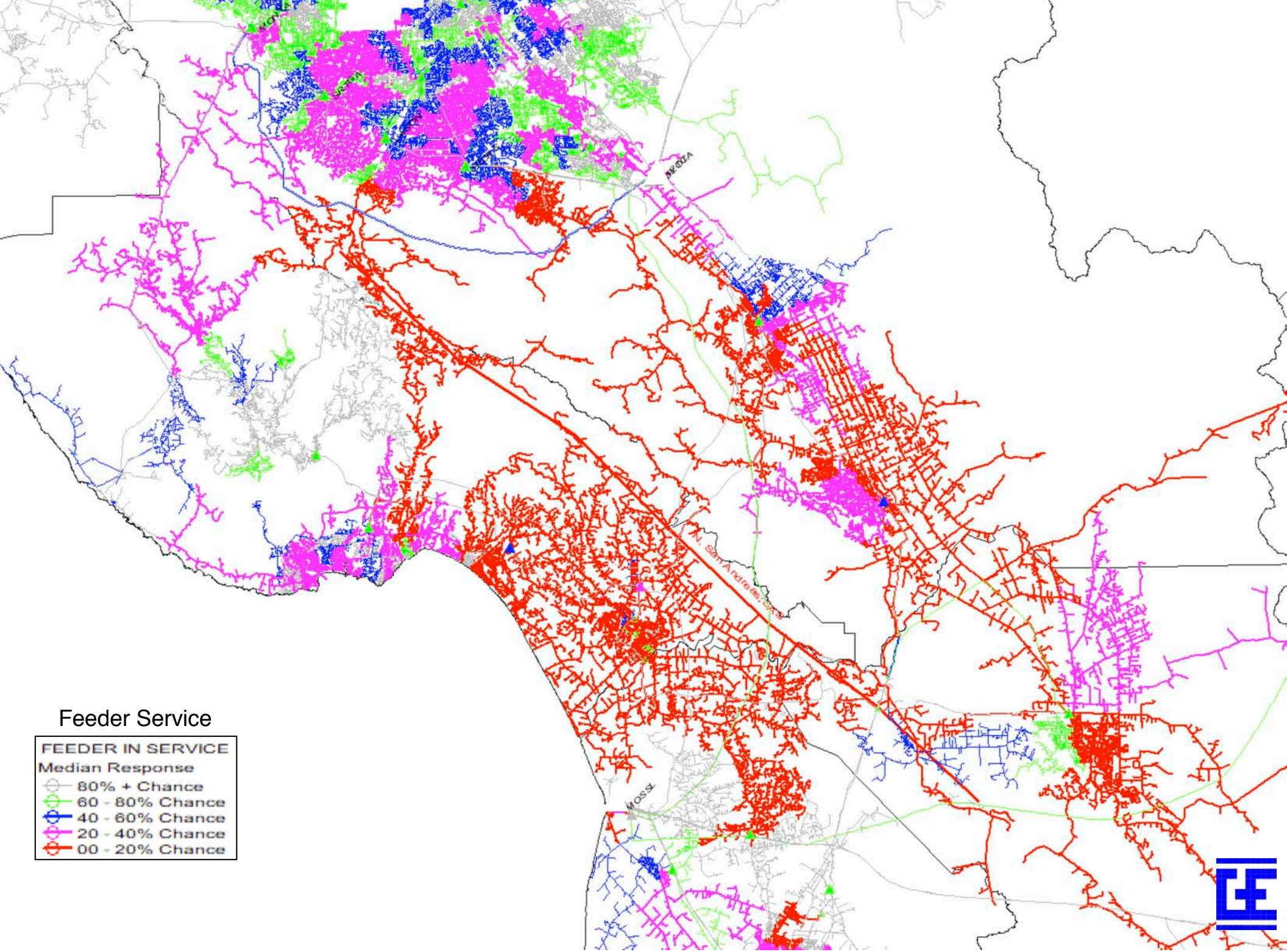

Landslide Susceptibility
DISTRIBUTION FEEDER
None
VVL, VL, Very low
L, Low
LM, M, Medium
MH, Medium high
H, High
VH, VVH, Very High


MONTA
SRTGA
VASON
HICKS
N. San Andreas, SAS
MOSS
Probability of Landslide
00 - 05% Chance
05 - 10% Chance
10 - 25% Chance
25 - 50% Chance
50% + Chance

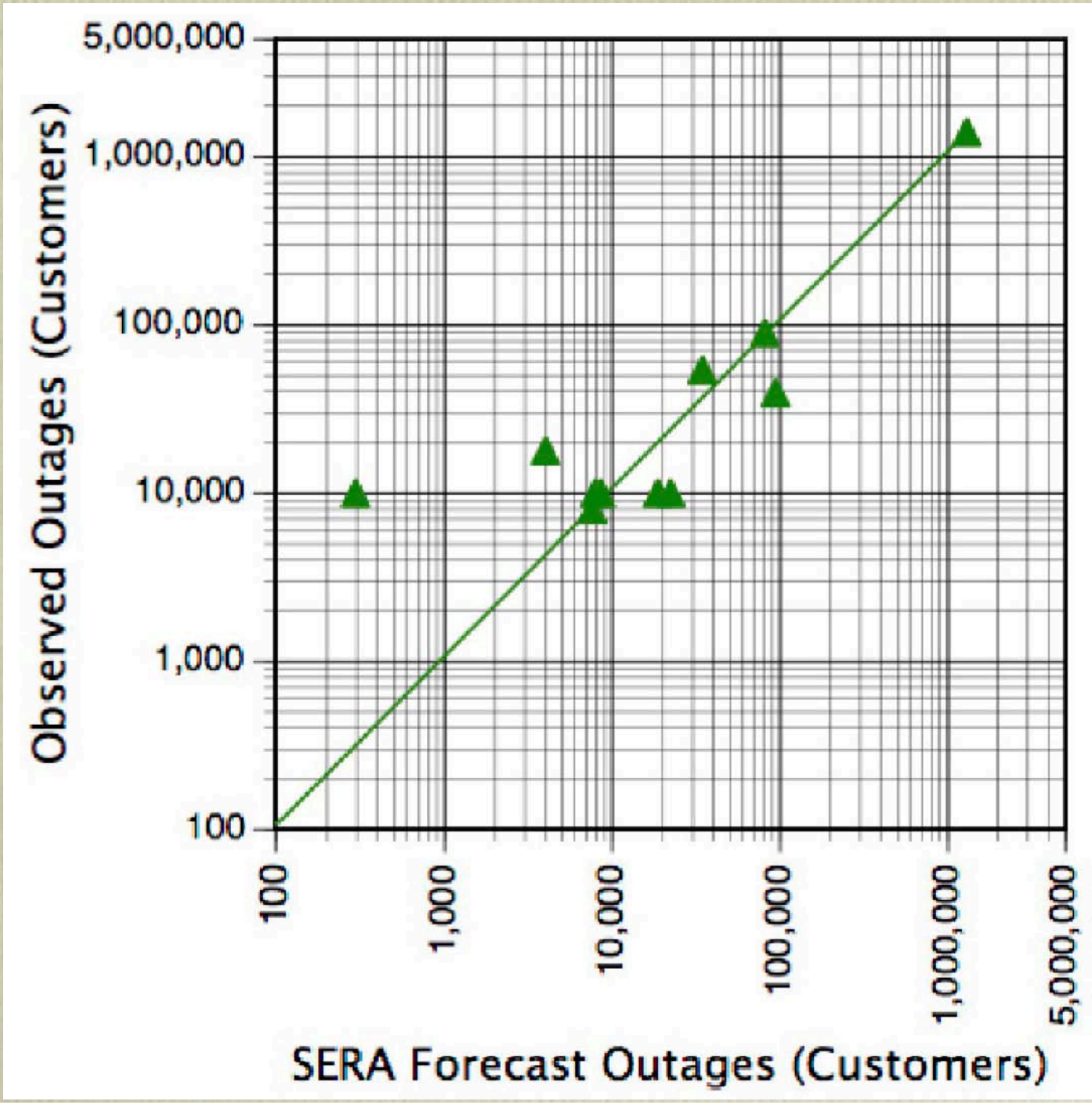


PGD | Landslide

PGD | Landslide
Winter
0 to 1 Inches
1 to 4 inches
4 to 8 inches
8 to 24 inches
24 + inches


Feeder Service
FEEDER IN SERVICE
Median Response
80% + Chance
60 - 80% Chance
40 - 60% Chance
20 - 40% Chance
00 - 20% Chance

SERA Forecasts vs 18 signiciant Earthquuakes, 1980 - 2017
Greenville 1980, Coalinga 1983, Morgan Hill 1984, Coalinga 1983, Loma Prieta 1989, Petrolia 1992, San Simeon 2003, Eureka 2010, etc.

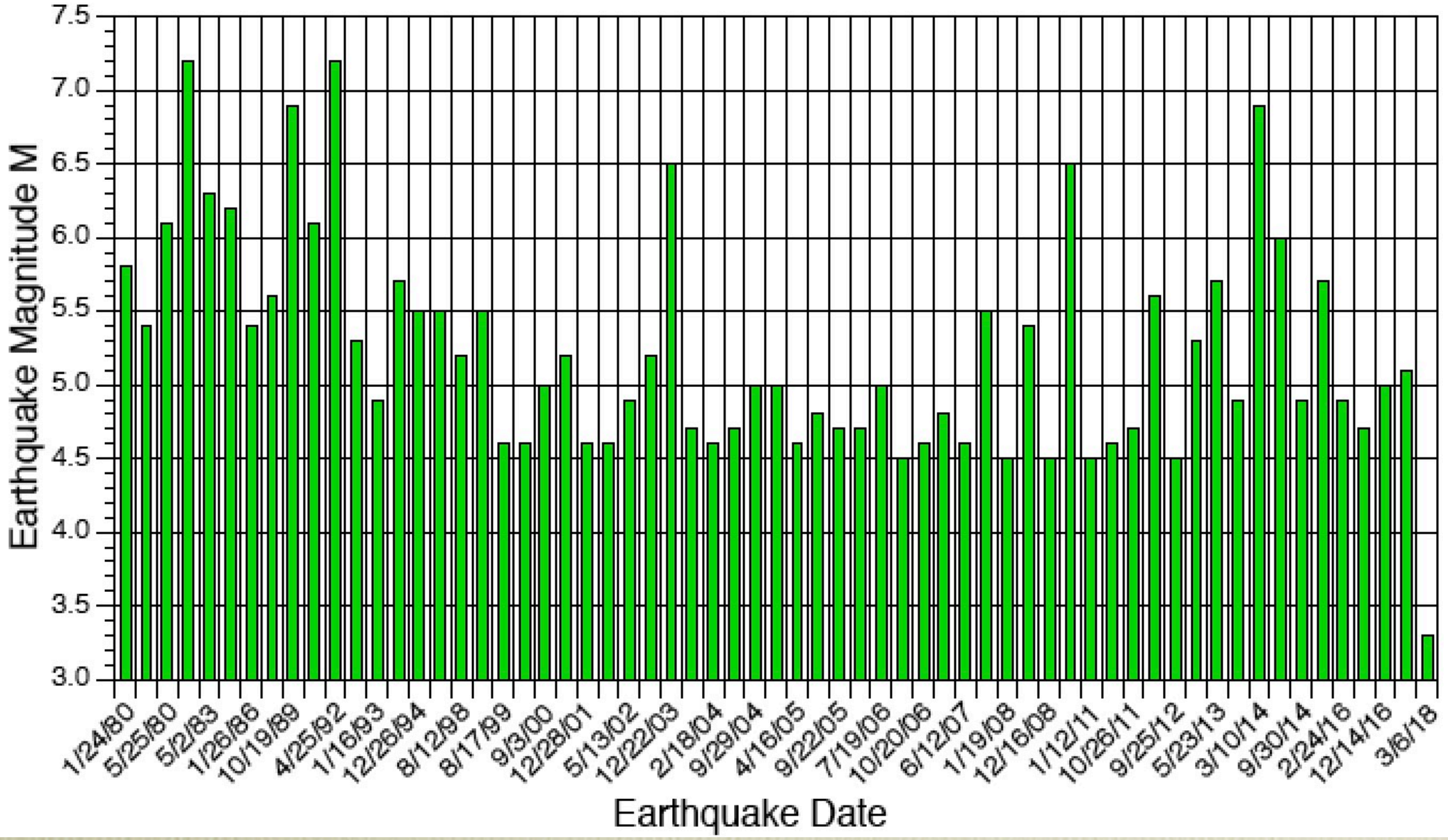


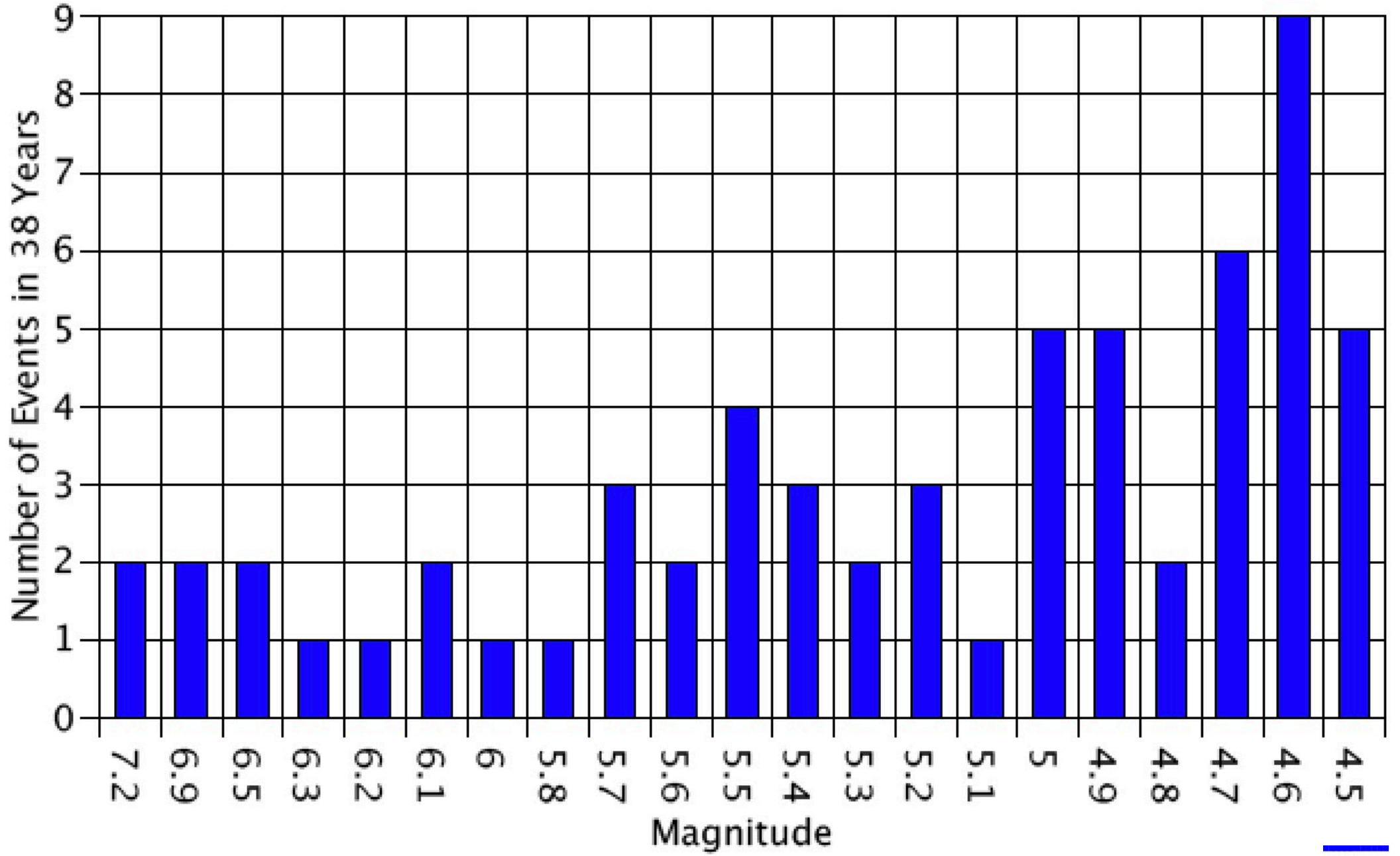
Equipment Performance in Historical Earthquakes

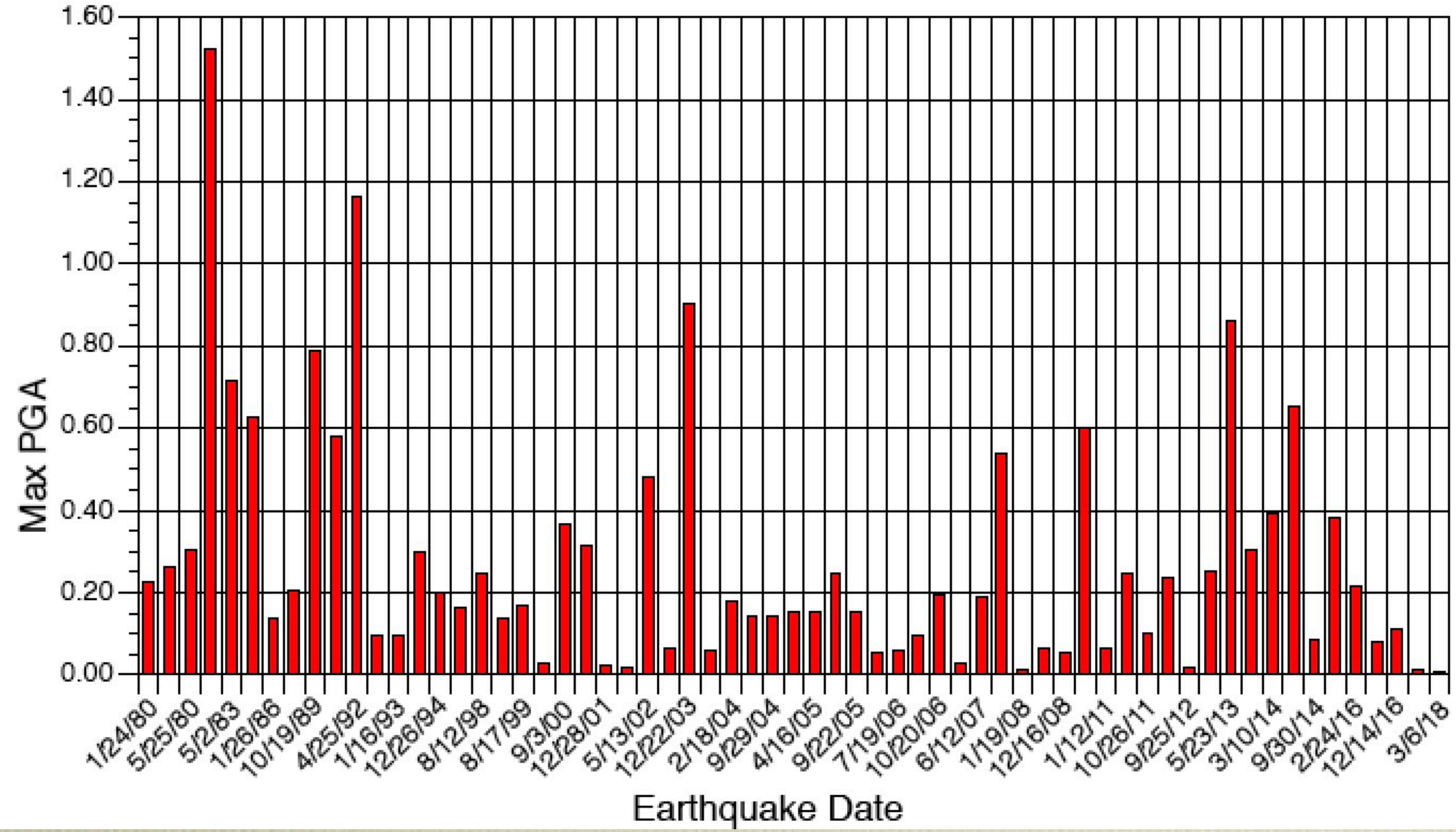
Epicenters of Historical Earthquakes in Northern California 1980 – 2018, M ≥ 5.0

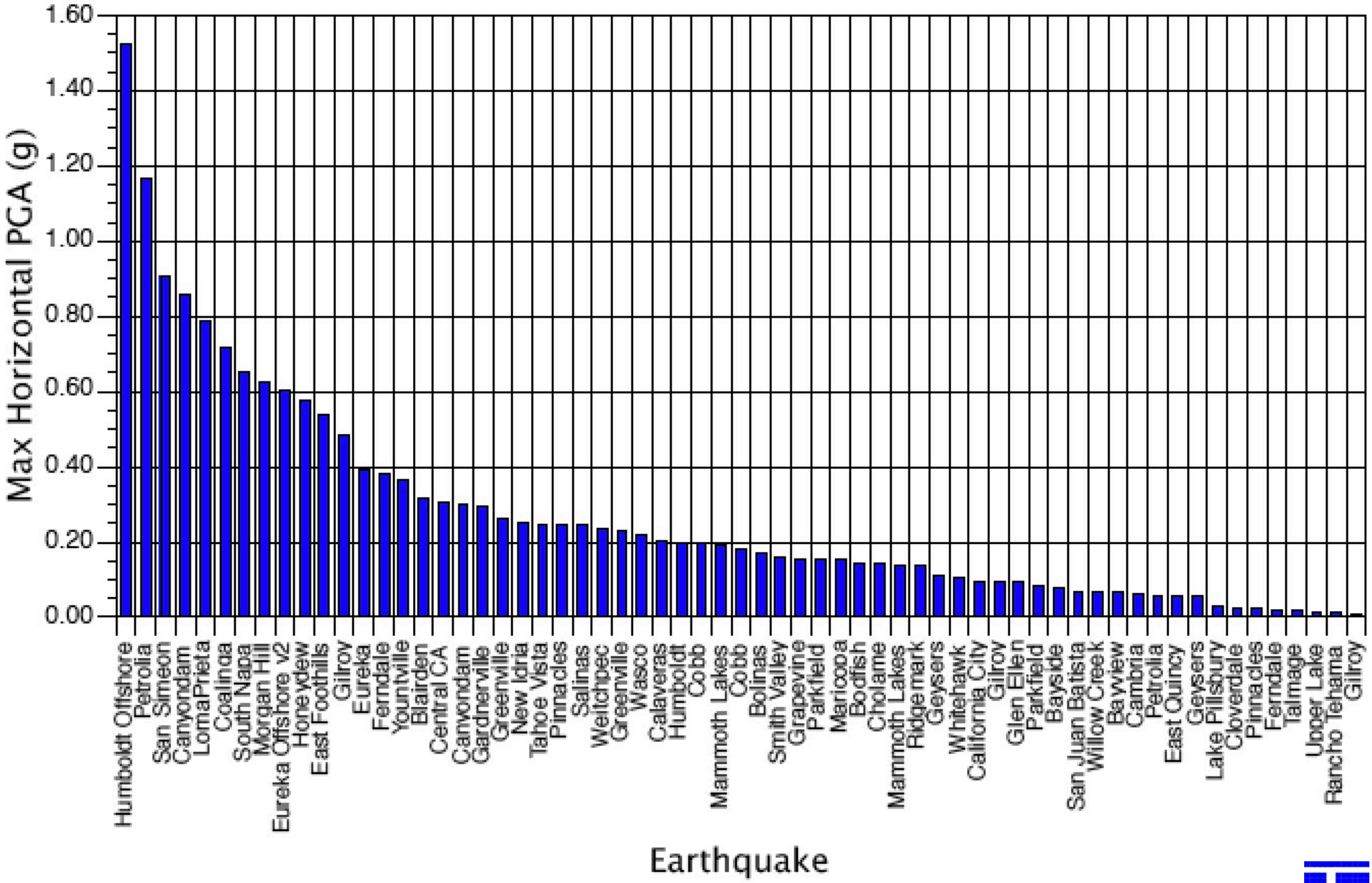
EQ	Name	M	Event Date	Max PGA, g	Event ID
1	Bayside	4.7	7.21.2016	0.0798	72664436
2	Bayview	5.2	6.17.2002	0.0652	21231051
3	Blairden	5.2	8.10.2001	0.3149	21188442
4	Bodfish (EQ 67)	5.0	9.29.2004	0.1443	14095626
5	Bolinas	4.6	8.17.1999	0.1696	21044694
6	California City	5.3	7.11.1992	0.0967	19920711181416
7	Cambria	4.7	12.23.2003	0.0598	21324051
8	Susanville (EQ 70)	5.7	5.23.2013	0.8594	71996906
9	Canyondam	4.9	5.24.2013	0.3019	71997821
10	Central CA	6.1	5.25.1980	0.3050	19800525163347
11	Cholame	4.7	9.28.2004	0.1411	21400461
12	Cloverdale	4.6	1.11.2000	0.0261	21076750
13	Cobb	4.6	2.18.2004	0.1814	21344222
14	Cobb	4.6	10.20.2006	0.1959	21543835
15	Alum Rock (EQ 68) (East Foothills)	5.5	10.31.2007	0.5381	40204625
16	East Quincy	4.5	12.16.2008	0.0568	51213957
17	Eureka	6.9	3.10.2014	0.3919	72182046
18	Eureka (EQ 69)	6.5	1.10.2010	0.6031	71338066
19	Ferndale	5.7	1.28.2015	0.3811	72387946
20	Ferndale	4.6	4.28.2002	0.0183	21223451
21	Gardnerville	5.7	9.12.1994	0.2976	19940912122343
22	Geysers	4.7	5.12.2006	0.0551	21516950
23	Geysers	5.0	12.14.2016	0.1124	72737985
24	Gilroy	4.9	1.16.1993	0.0959	19930116062934
25	Gilroy	3.3	3.6.2018	0.0099	72979736
26	Gilroy	4.9	5.13.2002	0.4831	21254601
27	Glen Ellen	4.5	8.2.2006	0.0958	21530368
28	Grapevine	4.7	9.22.2005	0.1539	14186612

EQ	Name	M	Event Date	Max PGA, g	Event ID
29	Greenville (EQ 54)	5.8	1.24.1980	0.2275	19800124190009
30	Greenville (EQ 55)	5.4	1.27.1980	0.2625	19800127023336
31	Honeydew	6.1	8.17.1991	0.5780	19910817192940
32	Eureka (EQ 63)	5.5	12.26.1994	0.1997	19941226141029
33	Trinidad (EQ 56) (Eureka)	7.2	11.8.1980	1.5237	19801108000000
34	Lake Pillsbury	4.8	4.18.2007	0.0273	40195779
35	Loma Prieta (EQ 61)	6.9	10.19.1989	0.7876	19891019000000
36	Mammoth Lakes	5.5	5.15.1999	0.1390	19990515132210
37	Mammoth Lakes	4.6	6.12.2007	0.1901	51182810
38	Maricopa	4.6	4.16.2005	0.1520	14138080
39	Morgan Hill (EQ 58)	6.2	4.24.1984	0.6277	19800424211520
40	New Idria	5.3	10.20.2012	0.2514	71883625
41	Parkfield	5.0	9.29.2004	0.1522	21401069
42	Parkfield	4.9	9.30.2014	0.0858	21401170
43	Petrolia (EQ 62)	7.2	4.25.1992	1.1658	269151
44	Petrolia	5.0	7.19.2006	0.0584	21527987
45	Pinnacles	4.6	8.27.2011	0.2464	71627835
46	Pinnacles	4.6	12.28.2001	0.0256	21207275
47	Rancho Tehama	4.5	1.19.2008	0.0126	51194914
48	Salinas (EQ 64)	5.2	8.12.1998	0.2451	19980812141026
49	San Juan Batista	4.5	1.12.2011	0.0663	71508850
50	San Simeon (EQ 66)	6.5	12.22.2003	0.9057	20031222191558
51	Smith Valley	5.5	12.28.1995	0.1617	19951228182759
52	South Napa (EQ 71)	6.0	8.24.2014	0.6512	72282711
53	Tahoe Vista	4.8	6.26.2005	0.2474	21465580
54	Talmage	4.5	9.25.2012	0.0169	71847715
55	Upper Lake	5.1	3.17.2017	0.0144	72672610
56	Wasco	4.9	2.24.2016	0.2184	37528064
57	Weitchpec	5.6	2.13.2012	0.2343	71734741
58	Whitehawk	4.7	10.26.2011	0.1035	71671059
59	Willow Creek	5.4	4.29.2008	0.0658	40216664
60	Yountville (EQ 65)	5.0	9.3.2000	0.3664	20000903083630
61	Coalinga (EQ 57)	6.3	5.2.1983	0.7161	19830502234237
62	Ridgemark	5.4	1.26.1986	0.1367	19860126192051
63	Calaveras	5.6	3.31.1986	0.2050	19860331115540

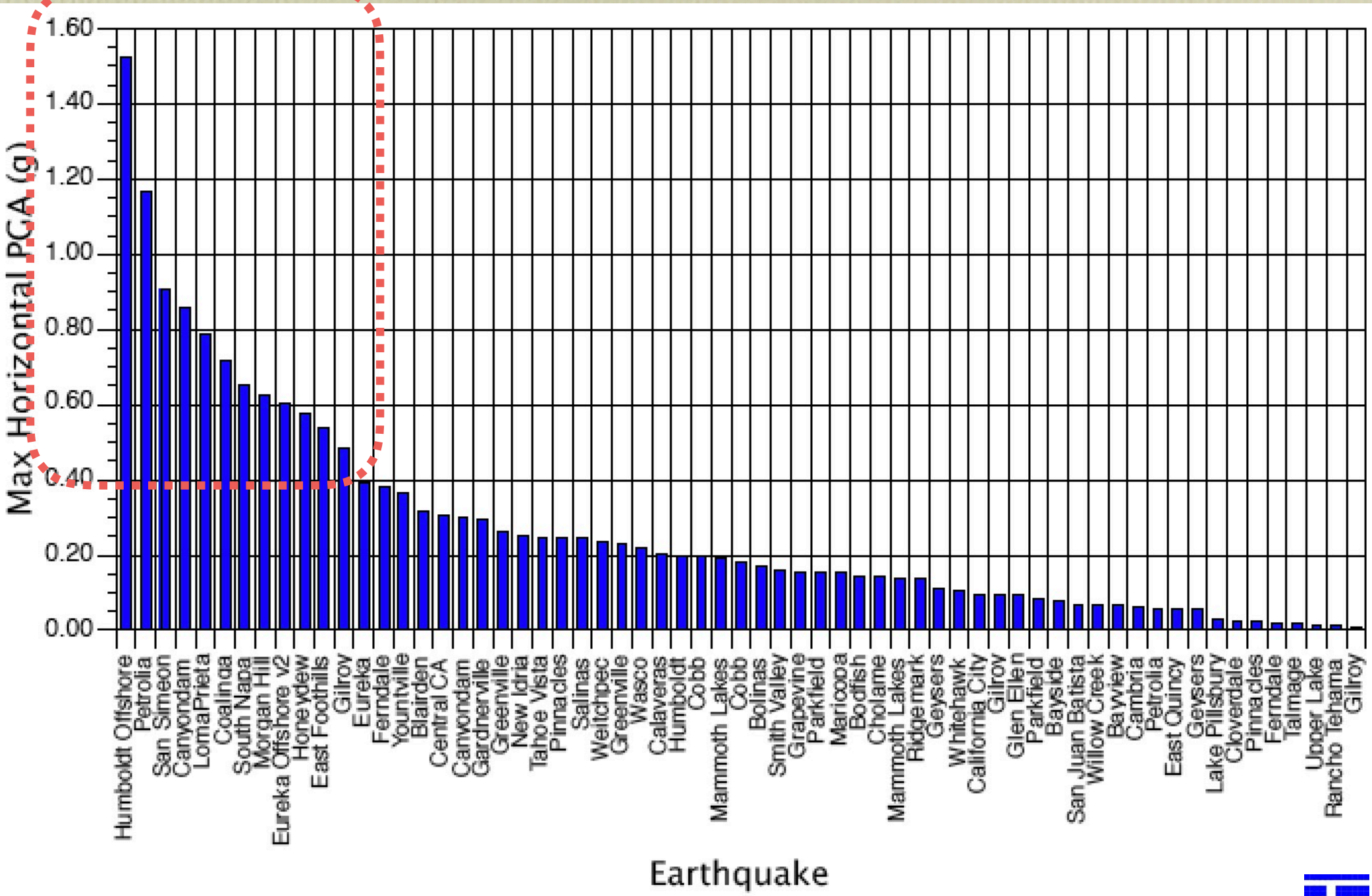

Earthquake Magnitude M
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
1/24/80
5/25/80
5/2/83
1/26/86
10/19/89
4/25/92
1/16/93
12/26/94
8/12/98
8/17/99
9/3/00
12/28/01
5/13/02
12/22/03
2/18/04
9/29/04
4/16/05
9/22/05
7/19/06
10/20/06
6/12/07
1/19/08
12/16/08
1/12/11
10/26/11
9/25/12
5/23/13
3/10/14
9/30/14
2/24/16
12/14/16
3/6/18
Earthquake Date


Number of Events in 38 Years
0
1
2
3
4
5
6
7
8
9
7.2
6.9
6.5
6.3
6.2
6.1
6
5.8
5.7
5.6
5.5
5.4
5.3
5.2
5.1
5
4.9
4.8
4.7
4.6
4.5
Magnitude


Max PGA
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
1/24/80
5/25/80
5/2/83
1/26/86
10/19/89
4/25/92
1/16/93
12/26/94
8/12/98
8/17/99
9/3/00
12/28/01
5/13/02
12/22/03
2/18/04
9/29/04
4/16/05
9/22/05
7/19/06
10/20/06
6/12/07
1/19/08
12/16/08
1/12/11
10/26/11
9/25/12
5/23/13
3/10/14
9/30/14
2/24/16
12/14/16
3/6/18
Earthquake Date

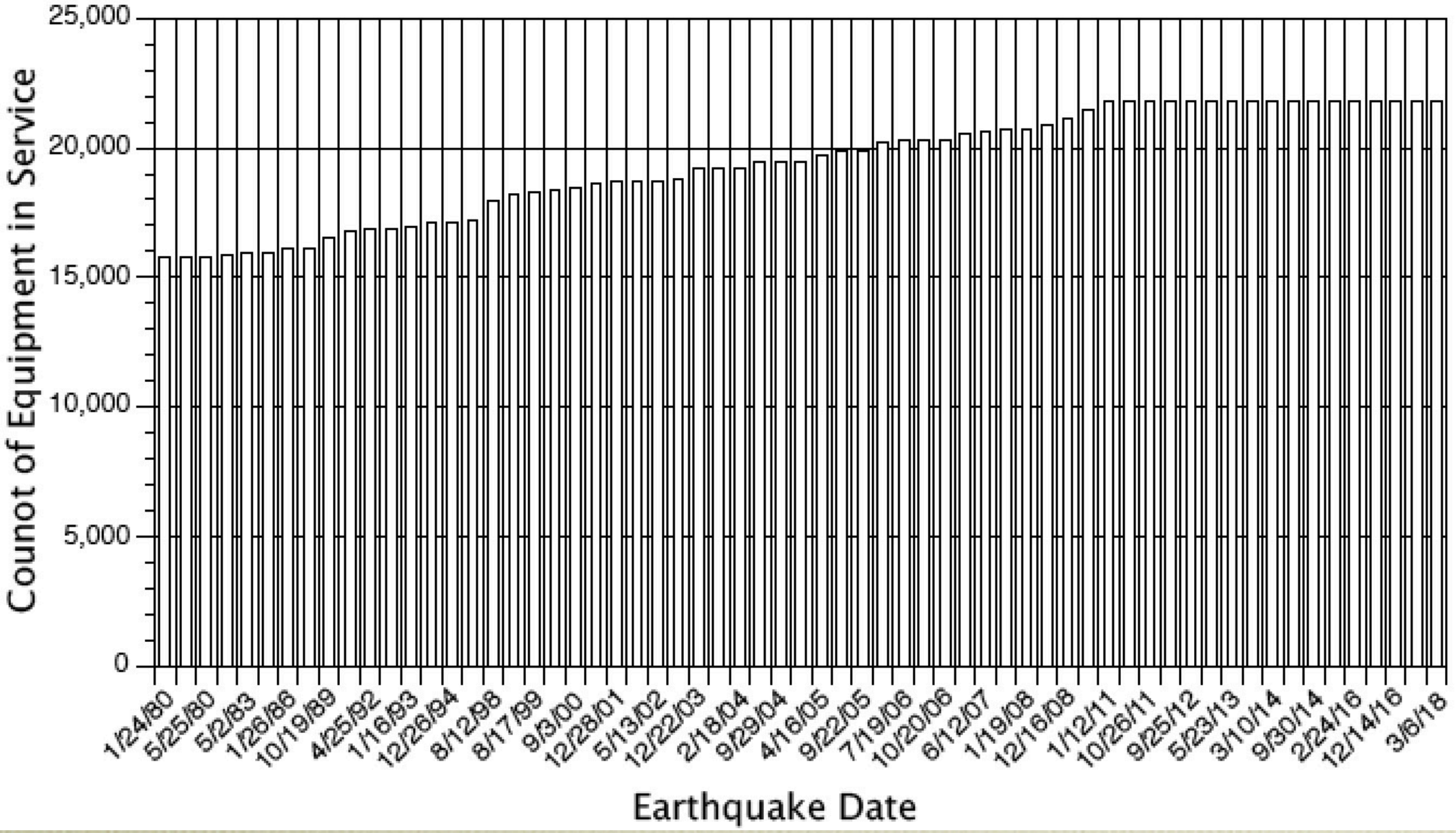

Max Horizontal PGA (g)
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Humboldt Offshore
Petrolia
San Simeon
Canyondam
LomaPrieta
Coalinga
South Napa
Morgan Hill
Eureka Offshore v2
Honeydew
East Foothills
Gilroy
Eureka
Ferndale
Yountville
Blairden
Central CA
Canyondam
Gardnerville
Greenville
New Idria
Tahoe Vista
Pinnacles
Salinas
Weitchpec
Greenville
Wasco
Calaveras
Humboldt
Cobb
Mammoth Lakes
Cobb
Bolinas
Smith Valley
Grapevine
Parkfield
Maricopa
Bodfish
Cholame
Mammoth Lakes
Ridgemark
Geysers
Whitehawk
California City
Gilroy
Glen Ellen
Parkfield
Bayside
San Juan Batista
Willow Creek
Bayview
Cambria
Petrolia
East Quincy
Geysers
Lake Pillsbury
Cloverdale
Pinnacles
Ferndale
Talmage
Upper Lake
Rancho Tehama
Gilroy
Earthquake

12 EQs with PGA > 0.40g in 38 Years (Return period is 3.2 years for the “475” year EQ)



9 EQs with PGA > 0.60g in 38 Years (Return period is 4.3 years for the “975” year EQ)

Fragility Exposures


Counot of Equipment in Service
25,000
20,000
15,000
10,000
5,000
0
1/24/80
5/25/80
5/2/83
1/26/86
10/19/89
4/25/92
1/16/93
12/26/94
8/12/98
8/17/99
9/3/00
12/28/01
5/13/02
12/22/03
2/18/04
9/29/04
4/16/05
9/22/05
7/19/06
10/20/06
6/12/07
1/19/08
12/16/08
1/12/11
10/26/11
9/25/12
5/23/13
3/10/14
9/30/14
2/24/16
12/14/16
3/6/18
Earthquake Date

Substation Equipment

20 Equipment Classes
(CB, TR, CT, DS, EG, etc.)

4 Voltage Ranges
500 kV
230 kV
115 kV
66 kV

Well anchored / installed
Marginal Installation
Poor Installation

Every Major
Equipment Vendor

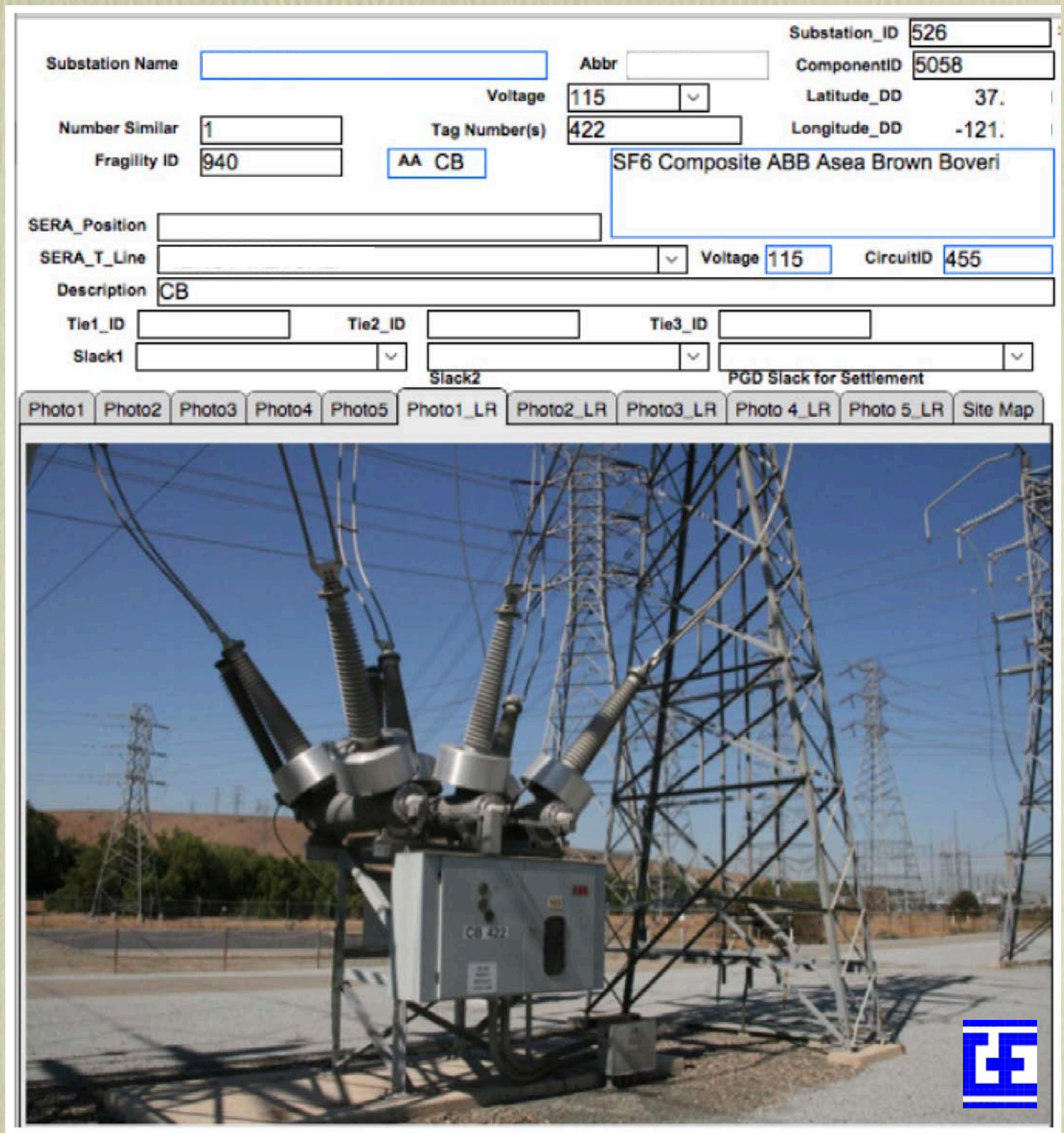
Over 70,000 Installations

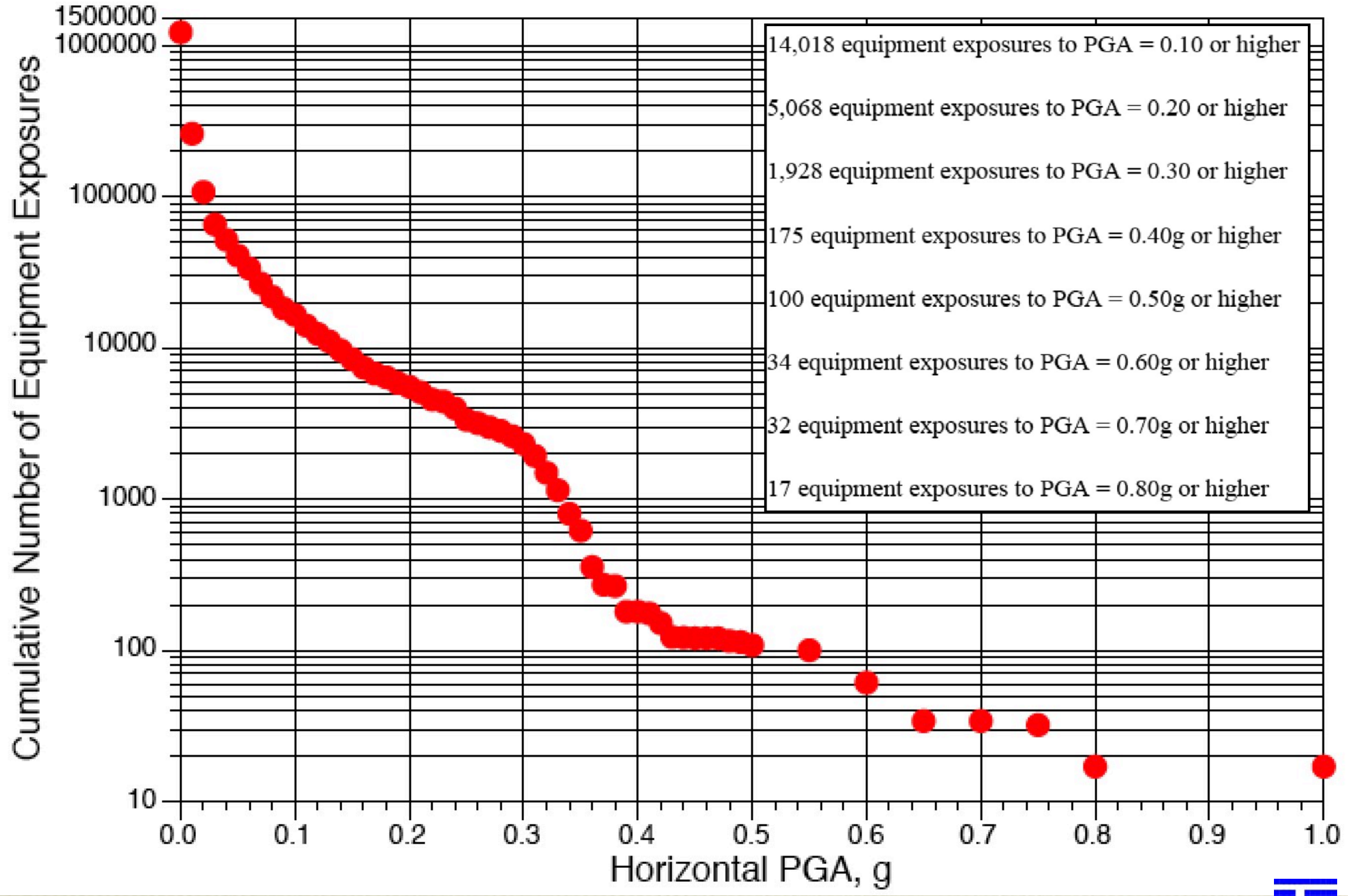
100s of Shake Table Tests

100s of Qualification Reports

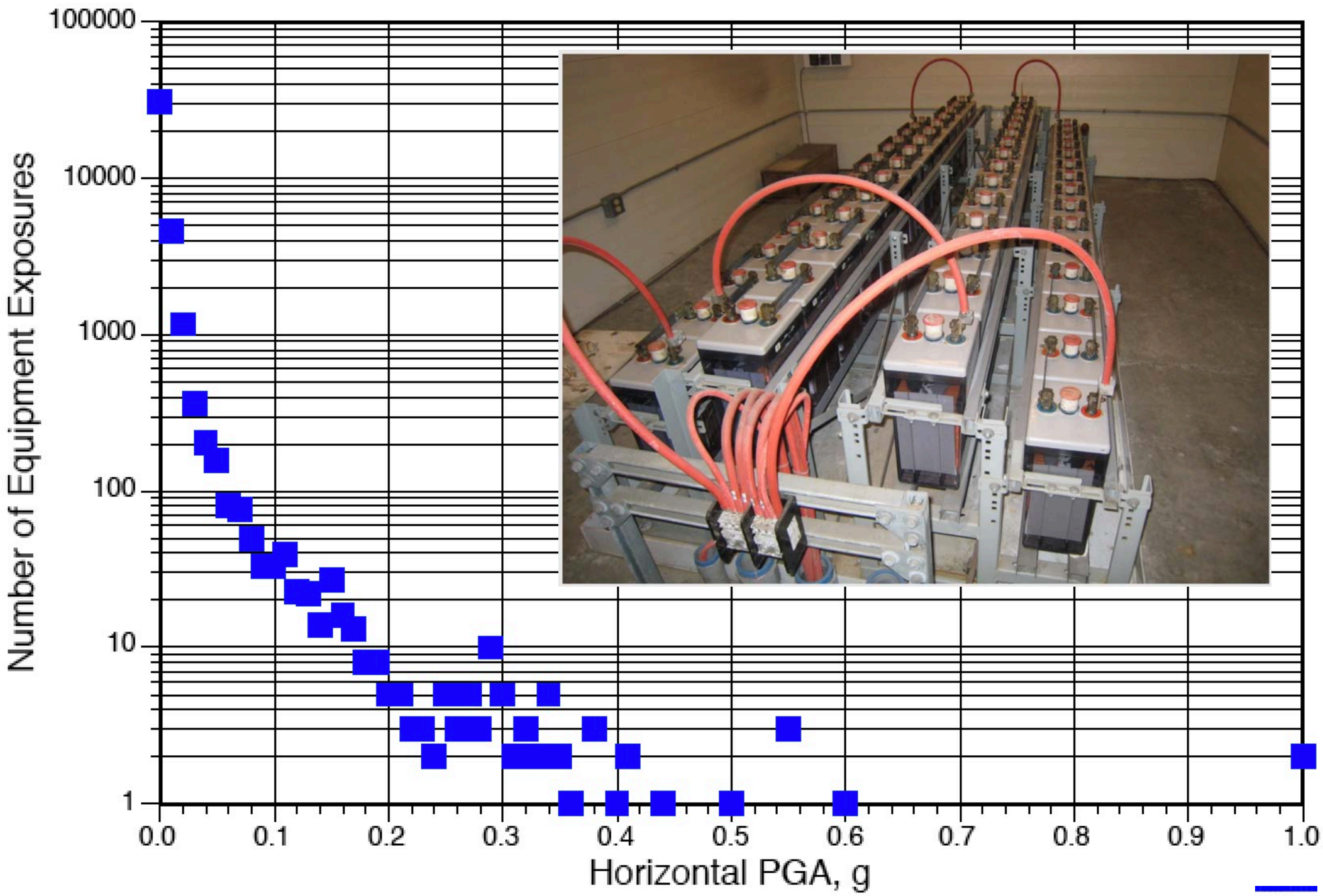
Component-Specific Slack

Over 2,200 Fragility Models

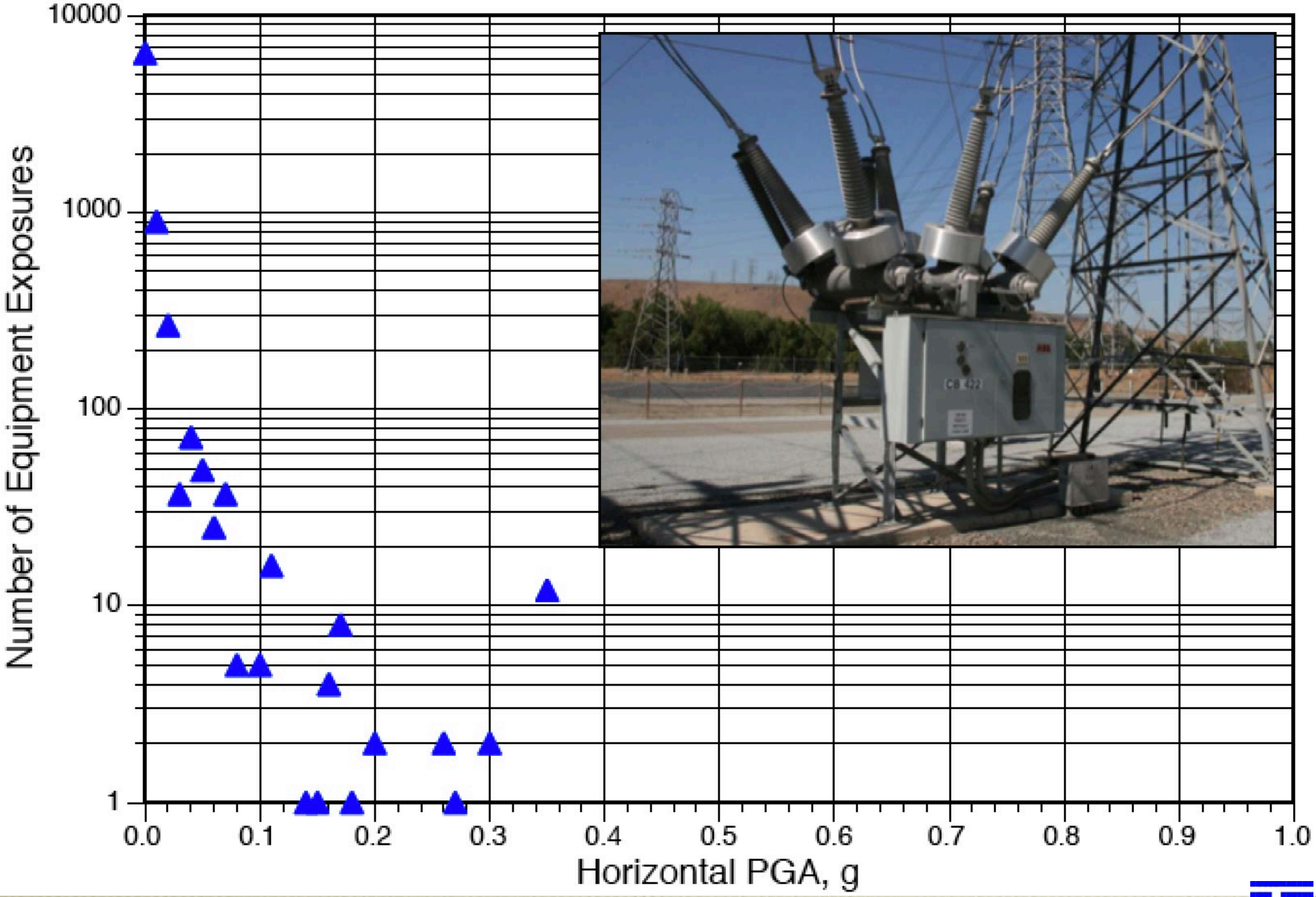




Cumulative Number of Exposures, 20 Equipment Classes



Number of Exposures, Seismic Battery Racks



Number of Exposures, 115 kV SF6 CB

Conclusions

- To forecast Power Outages, the SERA model needs to include all Substations, Transmission Towers, Distribution
- To get Restoration Times: Add up the damage, divide by the repair crew size
- How big a Repair Crew is ideally needed for “The Big One”? 1,000 people is “not enough”. 10,000 people is a better. 25,000 or more might be best.
- What is an acceptable power outage? 40 million customer-minutes should be “okay”. With 1,000 repair crew, “billions and billions of CM” is a possibility.

What to Do?

- Mitigation. Much of the "inertial" upgrades is already done at high voltage substations. (some fine-tuning, and old equipment replacements, Tuned Mass Dampers / bushing fixes, will solve the remainder). 10 more Years for California.
- Cable Slack: a big remaining vulnerability. With time and good installation practices, this too can be solved for substations. 10 Years for California if pursued aggressively.
- Towers. Landslides are an open item. At least 10 Years for selective relocations.
- Distribution. There are no seismic standards. Cable Slack is the biggest open issue. Undergrounding will help (50 Years). Big repair crews will help.

Questions?

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