Seismic Reliability of the Electric Grid

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PSU Course on Lifelines, Prof Yumei Wang
October 27 2022
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John Eidinger

- 1954 - 1971: A youth in Canada
- 1971 - 1975: B.S. MIT
- 1975 - 1982: M.Eng, M.S., MBA Berkeley
- 1978 - 1990: ABB
- 1991 - 2022: G&E
- P.E. S.E.

John Eidinger

- 100 water utilities
- 60 power plants
- 4,000 substations
- 4 Books
- 100 Papers
- Lifelines: Electric Power, Water, Wastewater, Natural Gas, Trains
- Many documents free at www.geEngineeringSystems.com

Agenda

- Some pictures and videos to give you an idea
- Is the Electric Grid Reliable?
- Why is the Electric Grid not Reliable After Earthquakes?

Today's Quizzes. Given CSZ M 9, how long will the power be out at your residence?

Person	Location	Forecast 1	Forecast 2
Student 1			
Student 2			
Student 3			
Student 4			
Student 5			
Student 6			
Lecturer 1			
Lecturer 2			
Lecturer 3			

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What You Should Take Away

- What's seismically weak in the electric grid
- Is it worthwhile to seismically upgrade the electric grid
- What are some potential "weak" spots in Oregon
- What should we (you) do about this?

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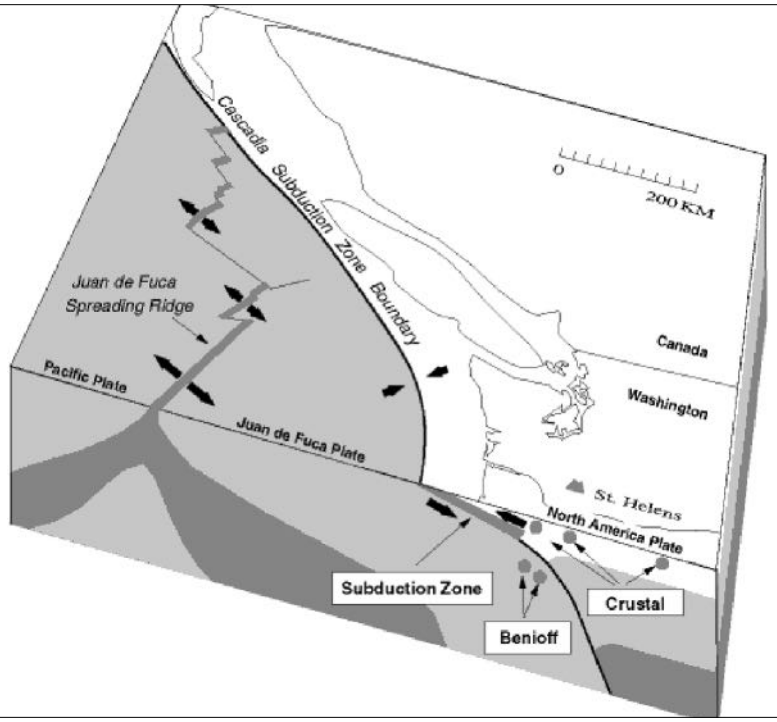
Are there Dinosaurs running the Electric Grid?

7



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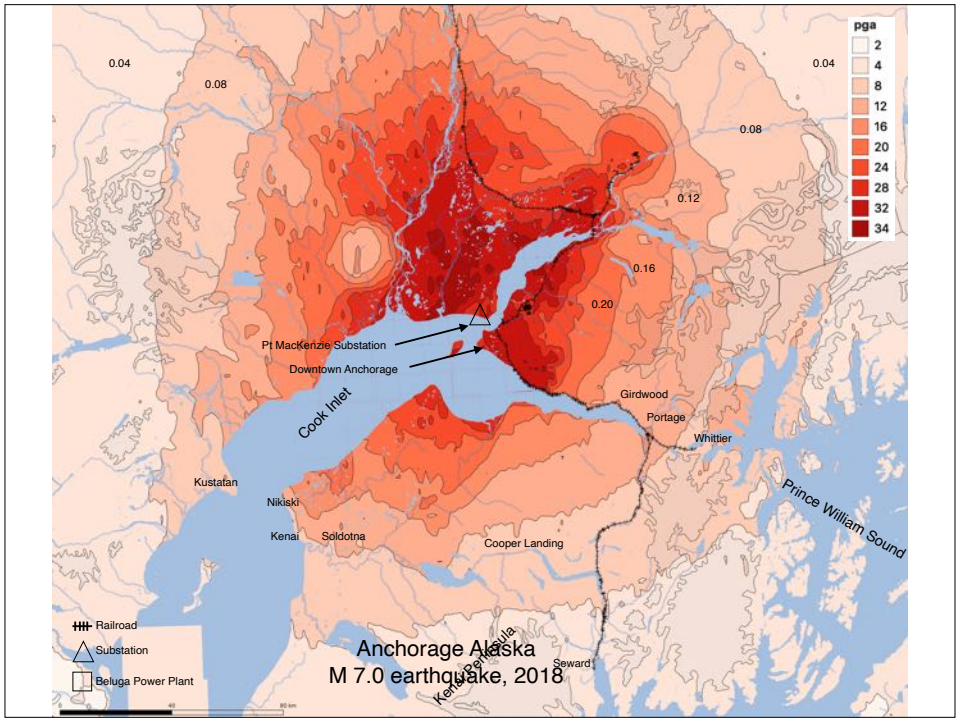
pga
2
4
8
12
16
20
24
28
32
34
0.04
0.08
0.12
0.16
0.20
Pt MacKenzie Substation
Downtown Anchorage
Cook Inlet
Girdwood
Portage
Whittier
Prince William Sound
Kustatan
Nikiski
Kenai
Soldotna
Cooper Landing
Seward
Railroad
Substation
Beluga Power Plant
Anchorage Alaska
M 7.0 earthquake, 2018

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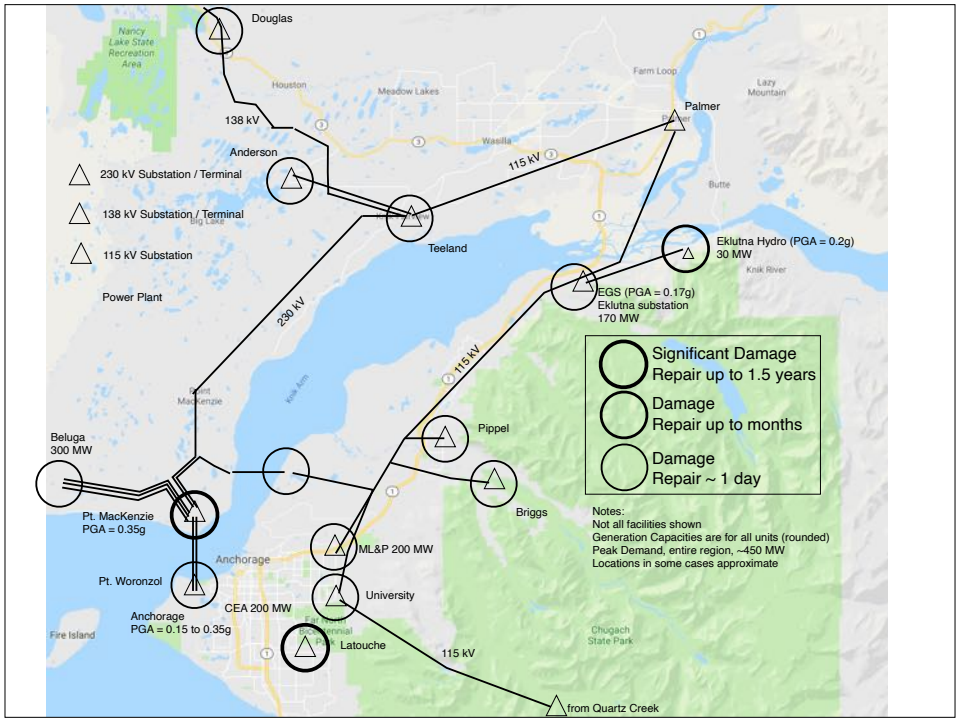
Douglas
Palmer
Anderson
Teeland
138 kV
115 kV
230 kV Substation / Terminal
138 kV Substation / Terminal
115 kV Substation
Power Plant
Eklutna Hydro (PGA = 0.2g)
30 MW
EGS (PGA = 0.17g)
Eklutna substation
170 MW
230 kV
115 kV
Significant Damage
Repair up to 1.5 years
Damage
Repair up to months
Damage
Repair ~ 1 day
Beluga
300 MW
Pt. MacKenzie
PGA = 0.35g
Pippel
Briggs
Notes:
Not all facilities shown
Generation Capacities are for all units (rounded)
Peak Demand, entire region, ~450 MW
Locations in some cases approximate
ML&P 200 MW
Pt. Woronzol
CEA 200 MW
University
Anchorage
PGA = 0.15 to 0.35g
Latouche
115 kV
from Quartz Creek

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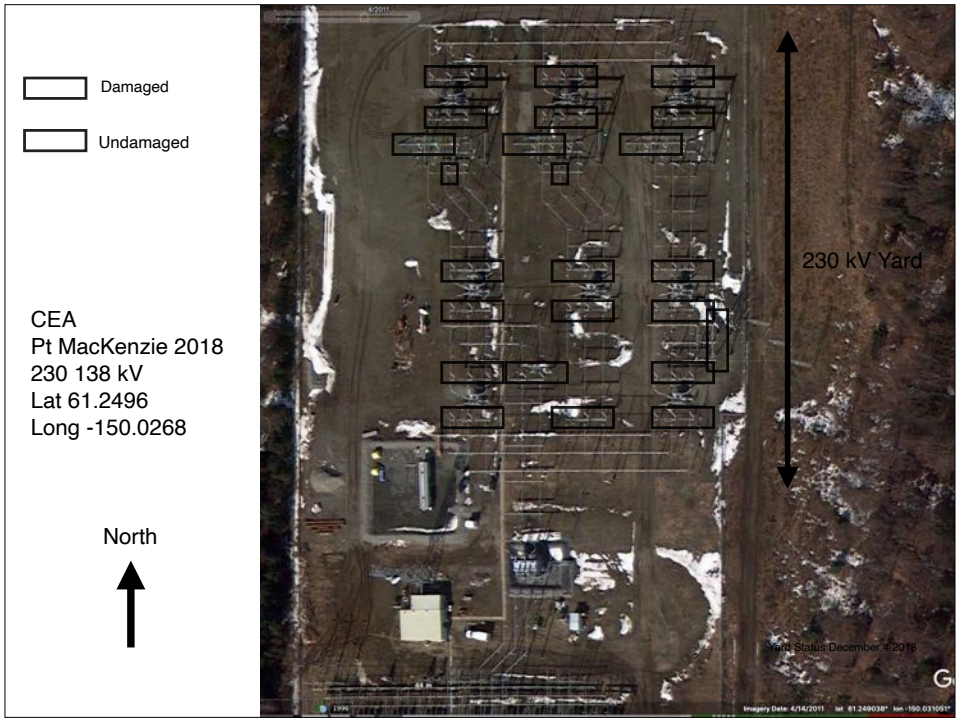
Damaged
Undamaged
CEA
Pt MacKenzie 2018
230 138 kV
Lat 61.2496
Long -150.0268
North
230 kV Yard

11

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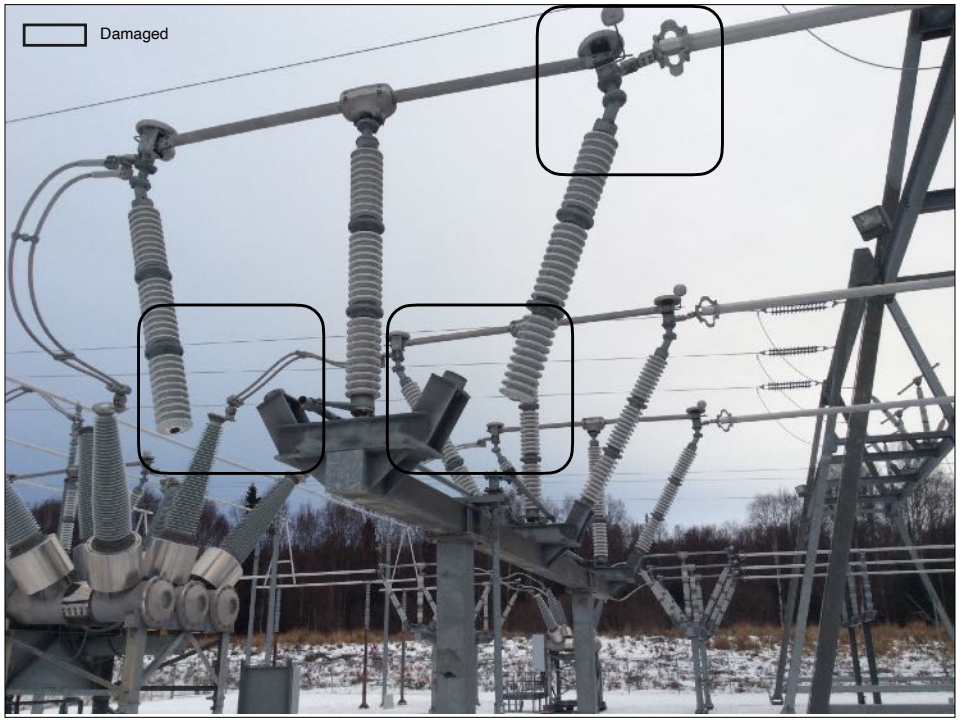

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MEA Briggs Substation

Rigid Bus. Surge Arrestors. Transformer slid, breaking 2 bushings.+ 2 SAs.
PGA ~ 0.30g

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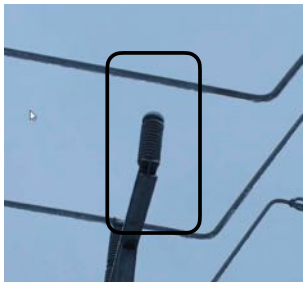
MEA Douglas Substation

Rigid Bus Expansion Joints, Bus Supports. PGA ~ 0.30g



Excessive differential movements leads to failures
Switch streel structures and bus supports
use I-beams, low frequencies,
twisting / torsion. All this is readily computed.
Suitable connectors are available.
Do utilities (and their A/Es) turn a blind eye?
Sunshine will expose the weaknesses.
CEA, ML&P and MEA all have work to do.

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MEA Anderson Substation

Surge Arrestors. Circuit Switchers (candlestick breakers)
PGA ~ 0.30g

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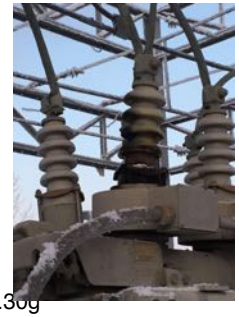
MEA Pippel Substation







Candlestick Breaker. Surge Arrestors. Bus. 115 kV DS + CB. PGA ~ 0.30g

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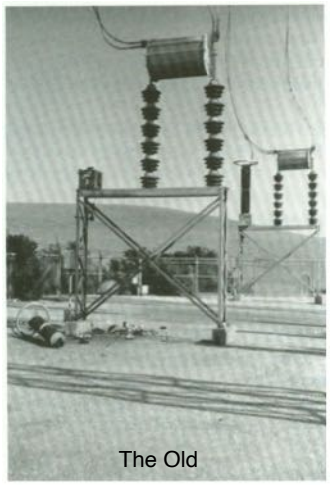
1989 Loma Prieta Earthquake
230 - 500 kV Wave Trap, CCVTs



The CCVTs failed at PGA ~ 0.35g, but the WTs did not

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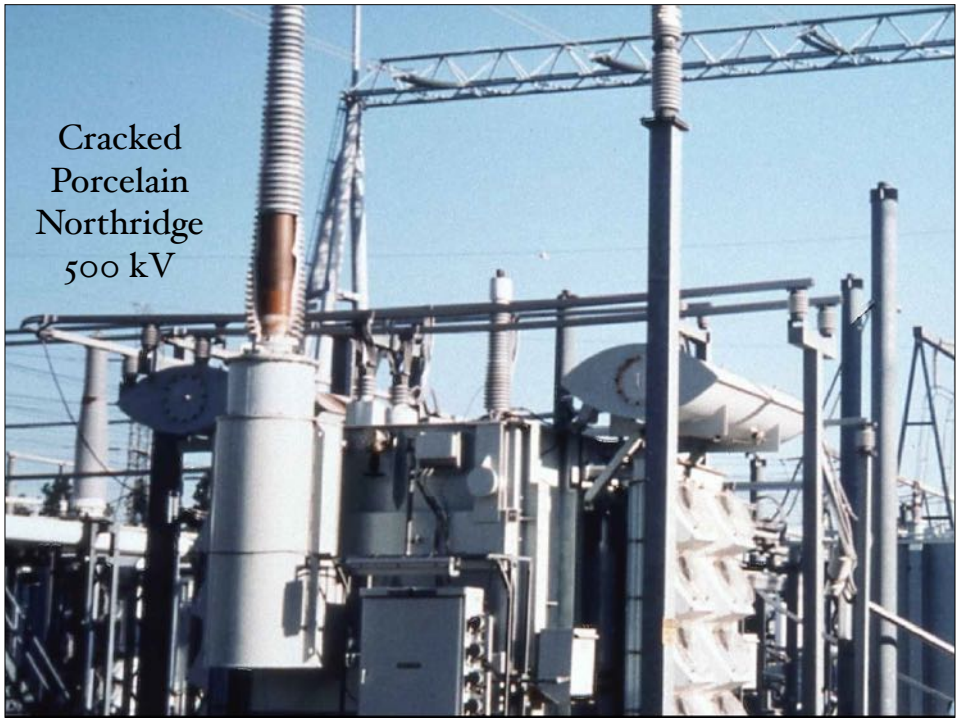

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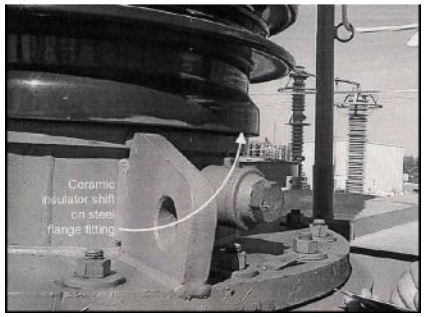
Displaced



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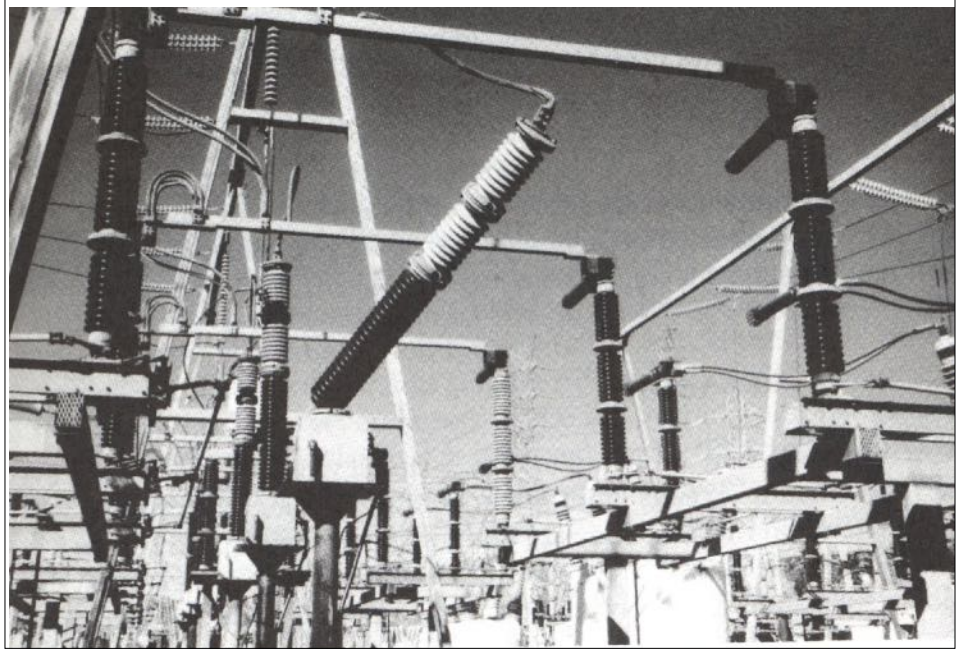
1997 Cap Rouge
m_N 5.1
735 kV Reactor at
Jacques Cartier

21

2008 M 8 Sichuan China

22

PT failed, likely due to inertial loads



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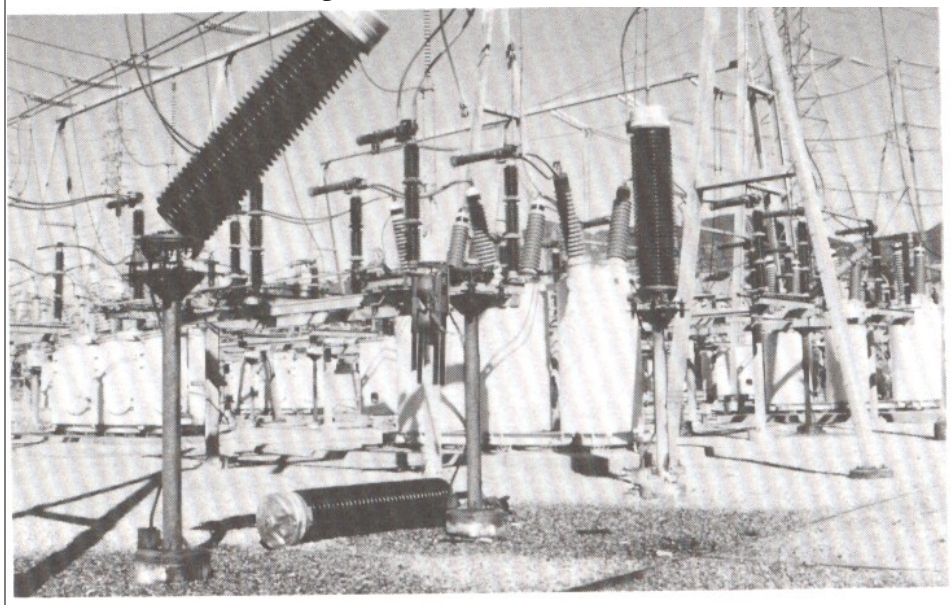
Northridge - Potential Transformers



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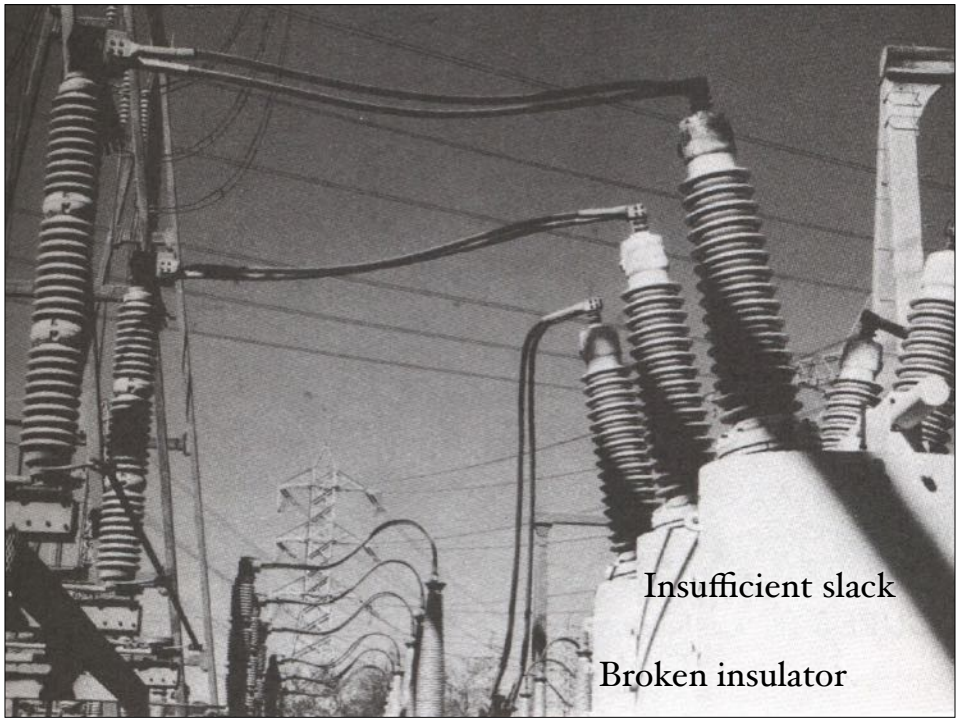
Insufficient slack
Broken insulator

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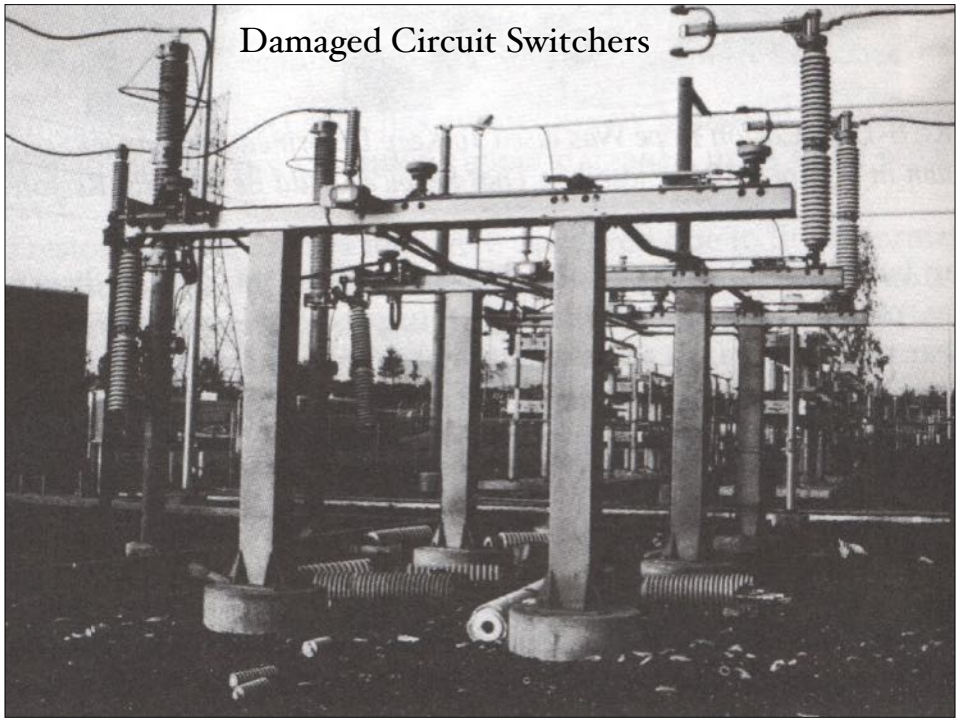
Damaged Circuit Switchers

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Iko Power Plant, Peru M8.3 2001

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Equipment Abbreviation CB | Equipment Number 1 | Voltage 735 | Photo Number 0993 Boucherville | Fragility ID 2

Equipment Description Areva

Comments Pneumatic. PK 8D Built 1970 2500 amps 765 kV mass 23640 kg (lb?). F1 about 1 hertz.

Example 1

Example 2

Will these 735 kV Live Tank CBs survive PGA = 0.5g?

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2019 Ridgecrest M 7.1

3 Transformer Frames: High W, Low Frequency, High Wire “snapping” forces,
High Torsion = high displacement demand on drop wires

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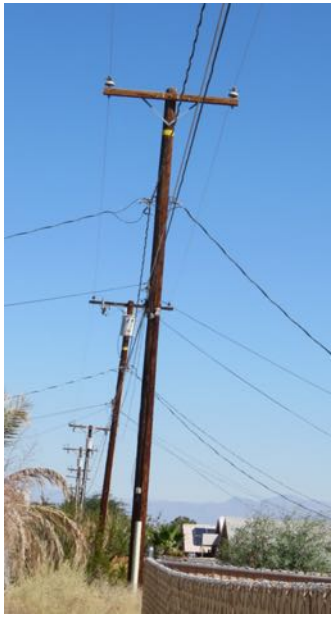
Tilted Poles



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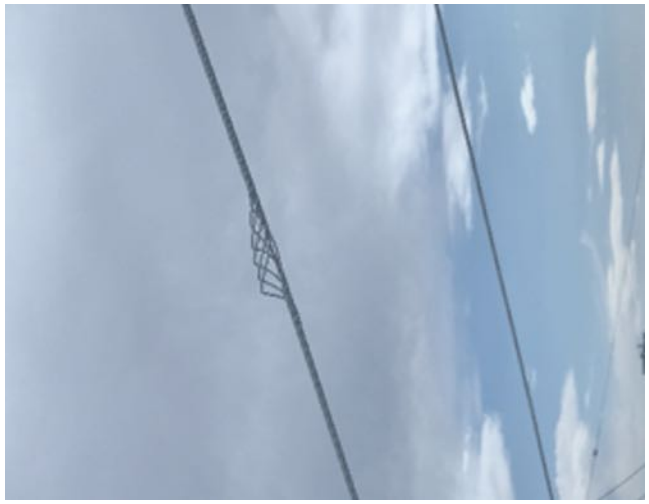
Birdcaging



Why: high curvature. What causes the high curvature: cable galloping dynamics

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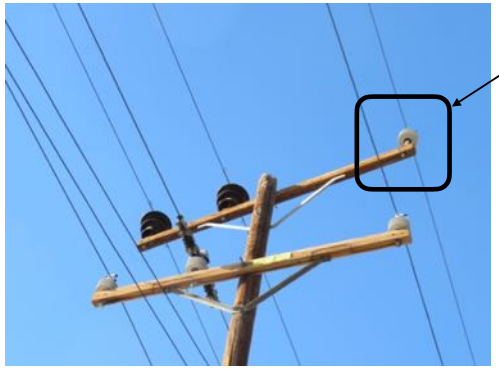
Insulators



Why: high conductor forces. If copper wires, wires can break.
If ASCR wires (aluminum with steel core), the conductor is so strong, the insulator breaks.
Or, sometimes the cross arm breaks.

Root cause: no seismic design to determine forces in wires and limit forces to allowables

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Street Lights

Replaced

Not Replaced

Located < 100 meters away

Inertial loading. Why? ShakeMap shows PGA 0.28g constant for both these poles.
Most likley, this was not the case, and PGA (spectra) was >> 0.28g.
(or, did local Dogs weaken these poles?). Corrosion is KING

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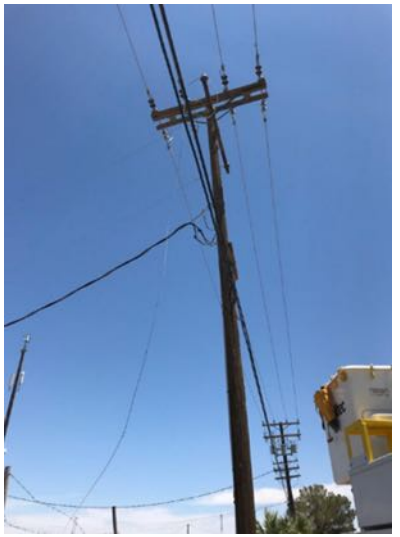
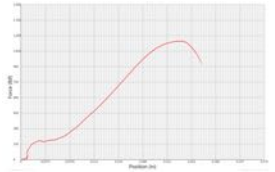
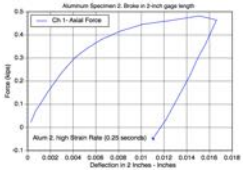
Wire Down



Wire Test Data





Copper Wires: Break forces around 1,200 pounds. Non-ductile, Strain at failure ~ 2%
Aluminum wires: Non-ductile if using electrical-grade aluminum

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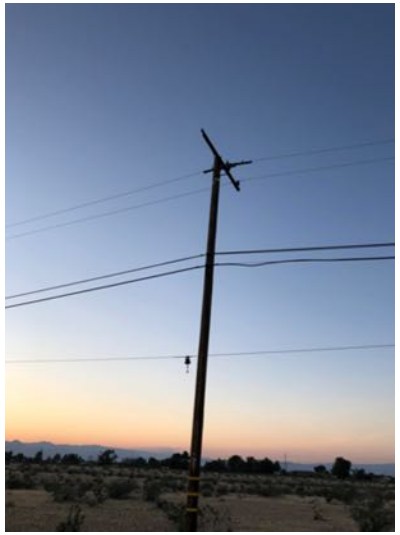
Cross Arms



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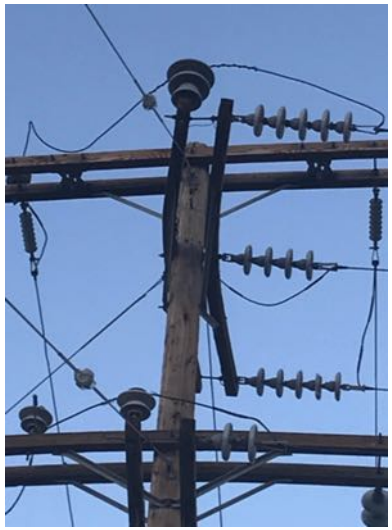
Cross Arms



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Older Transformers hooked onto Cross Arms
Not many of these left....

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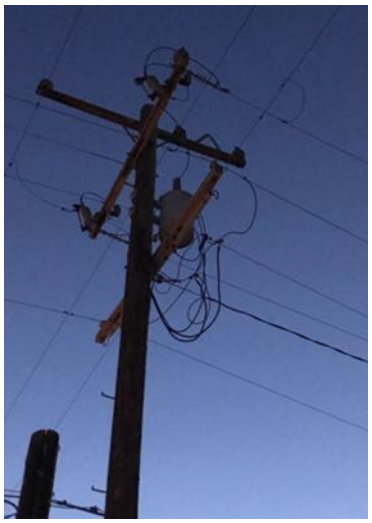
Wrapped Wires



Secondary neutral wrapped around an energized phase leading to burn down.

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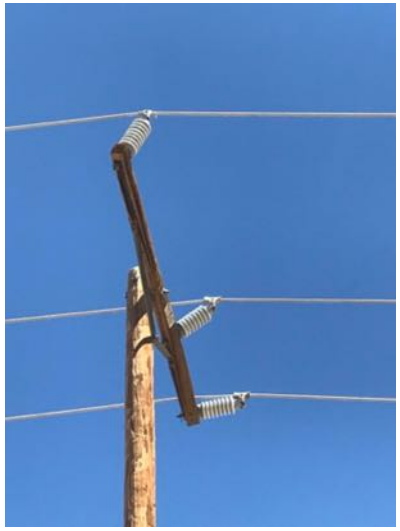
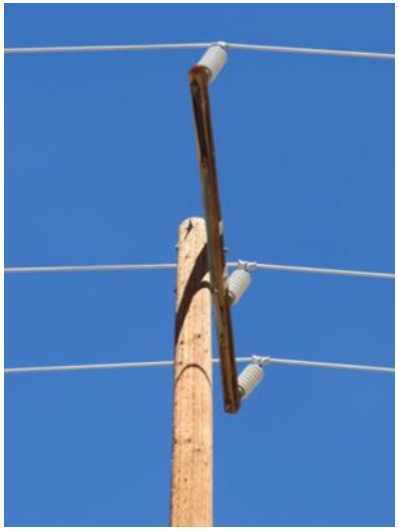
Cable / Pole Snapping Forces





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115 kV Yingshiao Substation

- Abandoned (weeds allowed to grow)
- In portion of town with nearly 100% destruction, so power need is zero
- Supply from 220 kV substation is priority
- No repair work 159 days after earthquake

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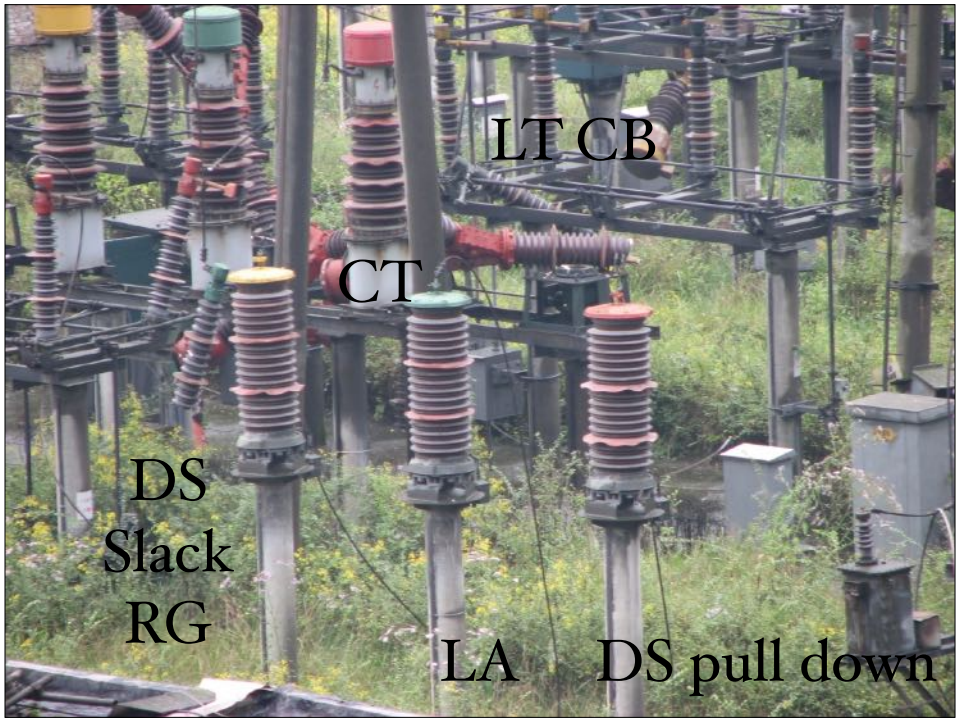

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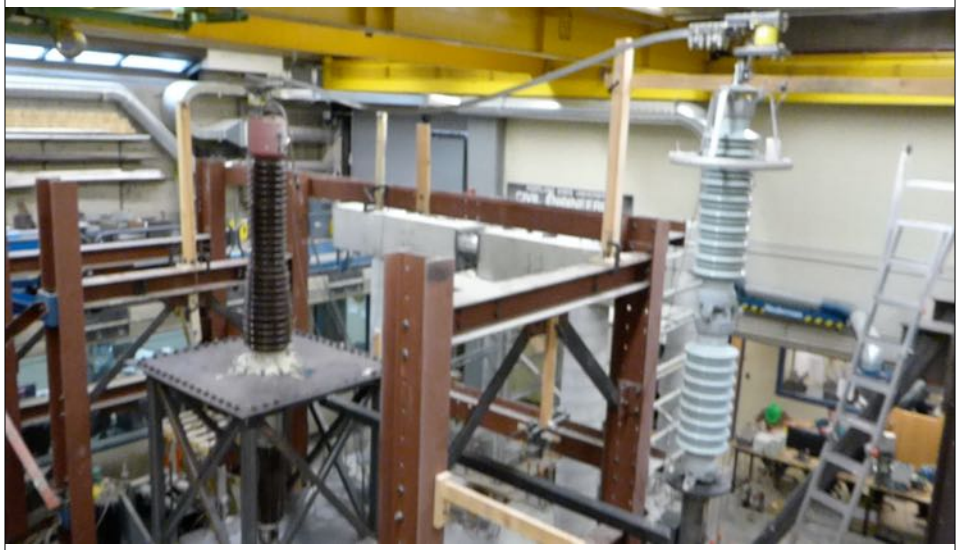
Medium Slack (2%) 1.00g RRS test, 6.8 Hertz + 6 hertz, Cowslip Conductor



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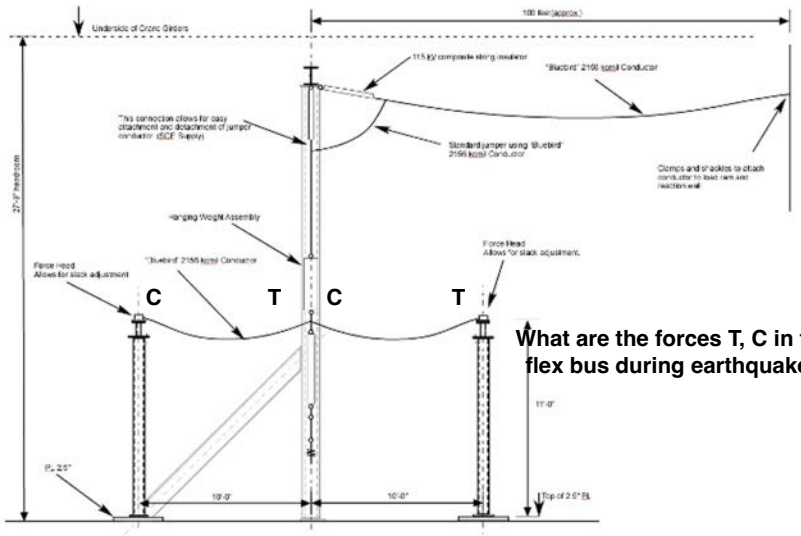
Quantifying Bus Forces



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What is the Fragility Level for this 220 kV DS?

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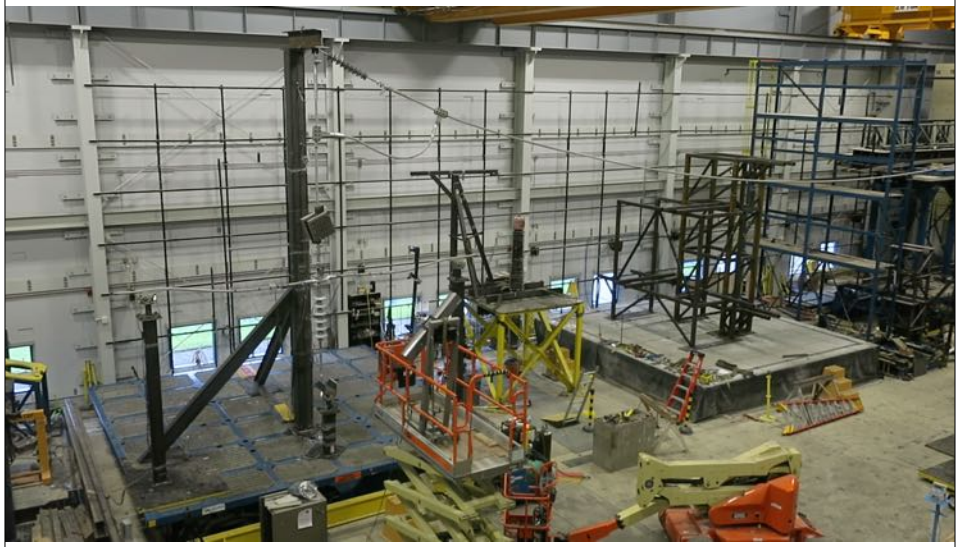

Test S18. PGA = 1.00g. Artificial. No Weights. Tight Slack Porcelain String.

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Snapshot during Test

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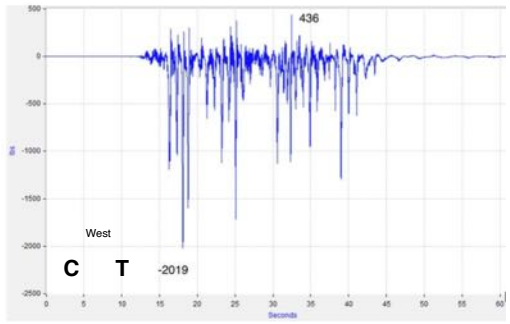

Conductor: Bluebird 2156 kcmil
Steel core
Aluminum strands

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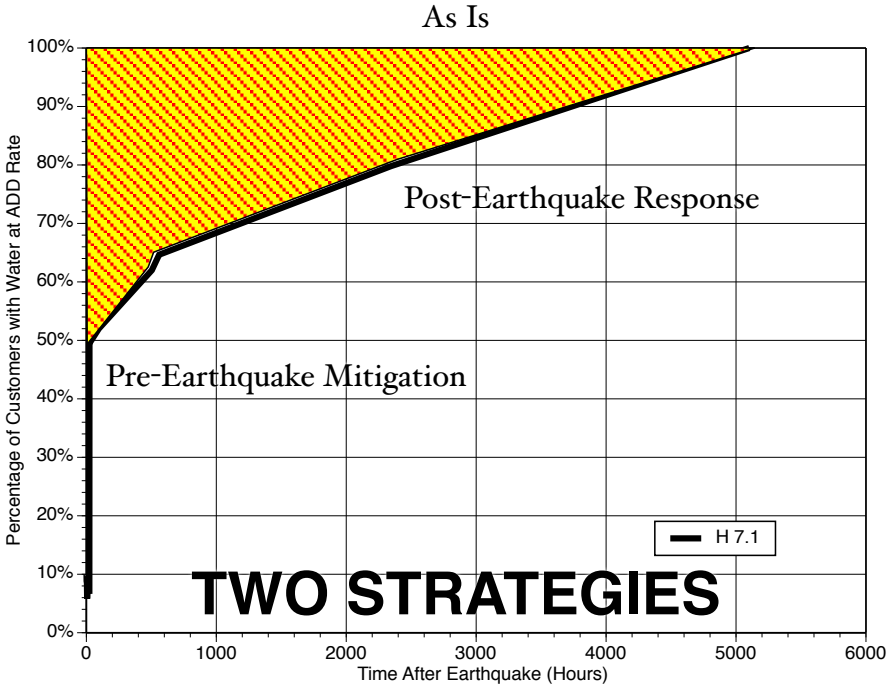

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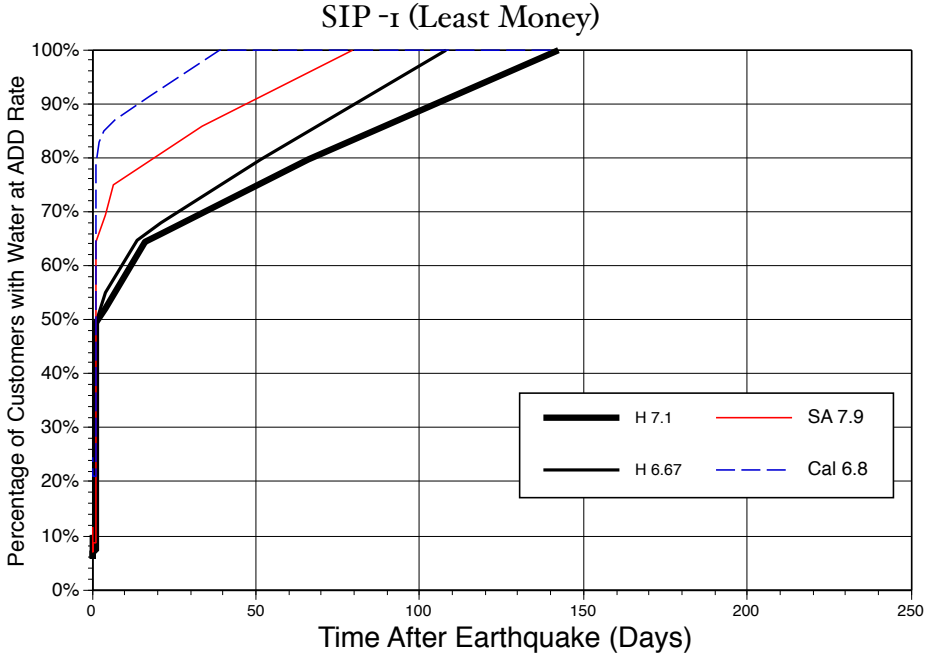

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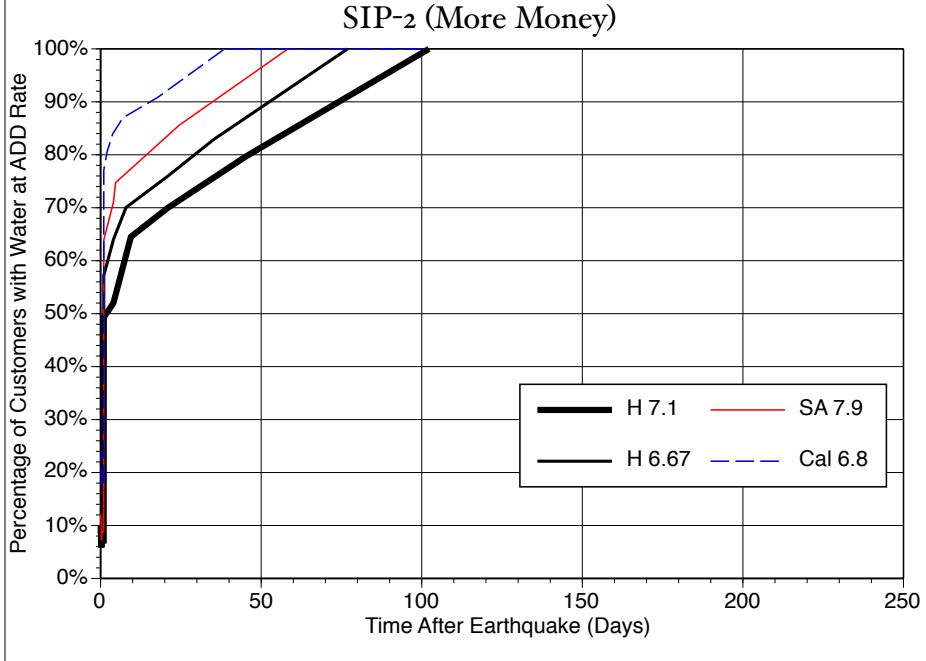

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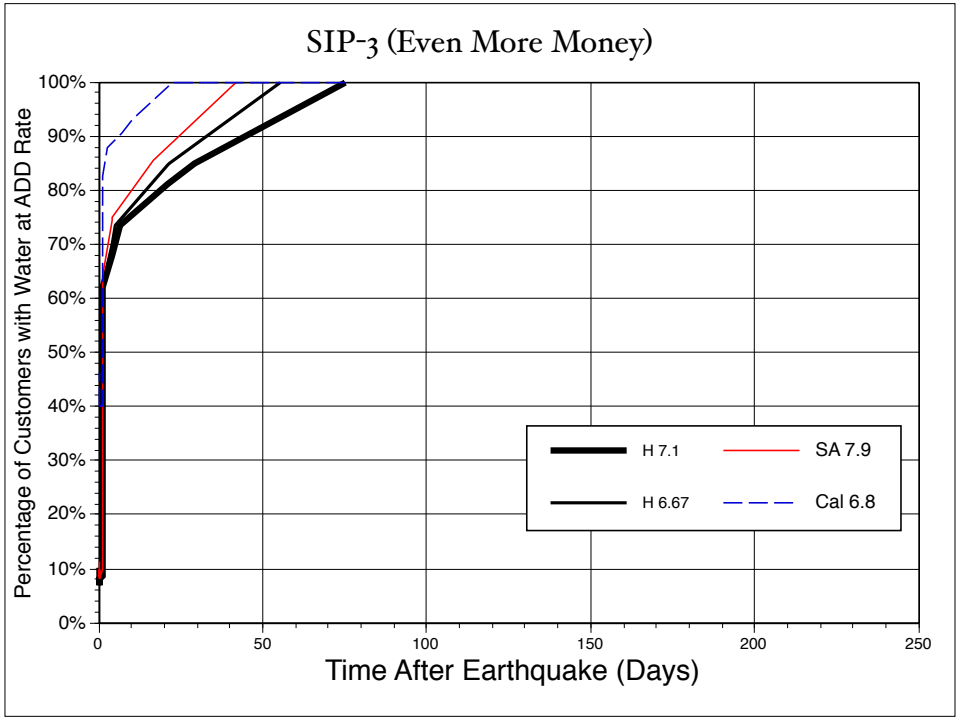

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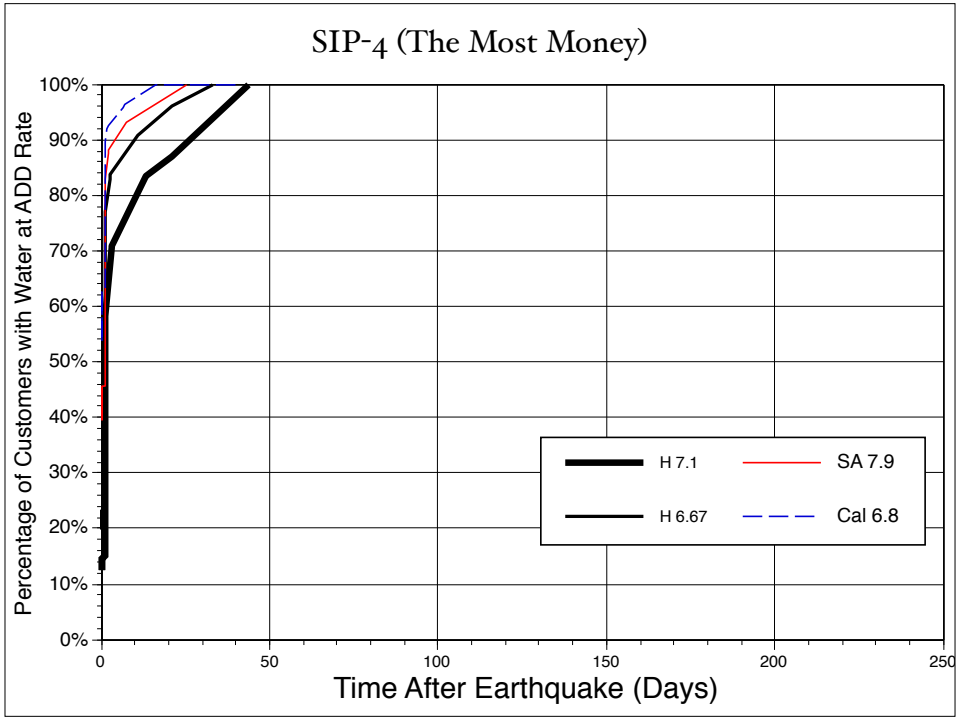

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Disciplines

- Structural Engineering
- Geotechnical Engineering
- Economics
- Geology
- Climate Science
- Political Science

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Disciplines

- Structural Engineering.... Reasonably accurate
- Geotechnical Engineering... sometimes accurate
- Economics... liars, damned liars, and economists
- Geologic Hazards... wild ass guesses over 10,000 year horizon
- Climate Science... you want proof?
- Political Science... wealth creation and income redistribution

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So?

- We have something for everyone today
- By the end of today's lecture, you should either be:
  - Excited and ready for a lifetime's work to solve this riddle in a cost effective way
  - Totally bored and let the lawyers sue if you don't like the outcome

What is Electricity Worth (I)?

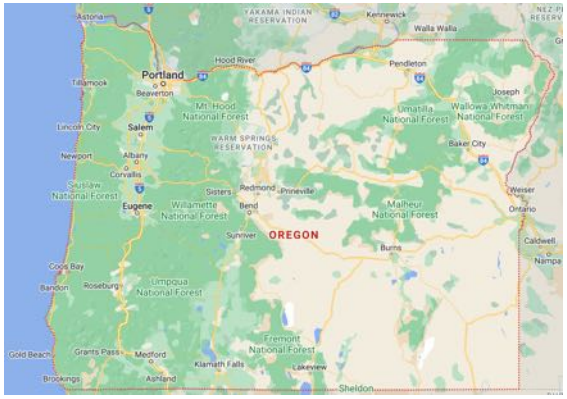
- Single family residence, California, no air conditioning. Monthly usage: 500 kWh. $0.45 / kWh. $225 / month
- Single family residence, Portland, no air conditioning. Monthly usage: 800 kWh. $0.12 / kWh. $96 / month
- These rates per kWh are averages over 24-hours. Time of use rates can vary substantially (lower 1 am to 5 am, higher 3 pm to 9 pm).

What is Electricity Worth (II)?

- US Economy GDP = $22.99 trillion
- US Population = 331 million
- Per capita GDP = $69,184 ($2021) per year, $189 per day.
- Drop in GDP/ day = 80% if there is a power outage, or $152 / day, or $4,612 per month

What is Electricity Worth (III)?

- What we pay: $89 to $225 per month
- What it is worth if we don't have it: $4,612 per month
- Portland vs. Gold Beach vs. Baker City



Grid Reliability

- What makes the Grid Reliable?
- Portland (major urban areas). Common power outage per year = 100 minutes. 99.98%
- Rural areas (Coastal range, Cascades). Common power outage per year = 1,000 minutes. 99.81%
- Includes common winter storms, maintenance issues, cars hitting power poles, etc.
- Excludes earthquakes, rare storms

Back Up Power

- Emergency Generators (Honda, Generac, etc.) Commonly 1 kW, $1,000 to $2,000. Runs on gasoline (smaller) or diesel (larger).
- For pump stations, commonly 100 kW to 500 kW, $500,000, could run on diesel or propane.
- If you want reliability after an earthquake, this is a way to go. Adoption is 10X higher in rural areas.

Back Up Power

- Solar household. Commonly 7 kW, $20,000. Add $20,000 for battery storage for 48 hours (40 - 60 kWh).
- An EV automobile with 250 mile range will have about 80 kWh of battery storage.

Economics

- Goal. Make the grid more reliable. Add seismically qualified equipment. Toughen power plants. Add redundant transmission lines. Underground local distribution lines. Etc.
- Figure a way to to this for under $0.0001 to $0.001± per kWh. This will fly.
- OPM. Other People's Money. If you can get a grant from FEMA (US Federal Government), it's free! (Not).
- If the Benefit / Cost Analysis shows Benefits < Costs, DON'T DO IT.

Our Government (I)

- Should Elected Officials set Reliability Goals?
- Should Unelected Functionaries set Reliability Goals?
- Should the Electric Utilities set Reliability Goals?
- Who do you trust?

Our Government (II)

- Should Elected Officials set Reliability Goals? Least technical knowledge, most political.
- Should Unelected Functionaries set Reliability Goals? More technical knowledge. Some have agendas.
- Should the Electric Utilities set Reliability Goals? The most technical knowledge, most keen on cost effective strategies.
- Who do you trust? Are IOUs more (less) trustworthy than public-owned utilities?

Code Committees

- Should the ICC set the Reliability Goal for Electricity after Earthquakes?
- ICC = International Code Council
- Example 1: Mandate that Power Must be Restored to all Essential Facilities within 24 hours after any Earthquake
- Example 2: Mandate that all Power Plants (including solar) that serve the public be designed for 2,475 year Earthquake (I = 1.5)

Why the ICC might be Corrupt

- Who is the ICC? A bunch of engineers who design parking lots and hospitals and the like
- What does the ICC know about the electric grid? Often, zilch. Maybe they should take this course!

What about IEEE?

- Who is the IEEE? A bunch of engineers who design and operate the electric grid
- What does the IEEE know about the electric grid? A huge amount.
- IEEE 693: Current world-wide guideline for seismic design of high voltage equipment. Created by Utilities (leadership by IOUs and BPA)
- Who do you trust? IEEE or ICC or politicians in Salem or Washington?

What about Your Local Utility?

- Who is your local Utility?
- Are they integrated (generation + transmission + distribution)?
- Who owns the generation?
- Who owns the transmission?
- Who owns the distribution?
- Are the PUDs in Oregon up to the task? Where to start?

Generation

- California uses 50 GW on a hot summer day (peak usage)
- California has 90 GW of power plants
- From an Earthquake point of view, does it matter if California loses 3 large power plants (2± GW) due to earthquake damage?
- Should power plants be designed for 475 year or 2,475 year earthquakes? (I = 1.0 or I = 1.5)? Who should decide?

Generation

- Puerto Rico uses 4± GW on a hot summer day
- Puerto Rico has 6± GW of power plants, but 2± GW are "semi-permanently broken"
- PR grid is not reliable on a day-to-day basis
- PR's power utility went bankrupt.
- Is it a surprise that power outages after hurricanes / earthquakes are long in PR?

Redundancy - Water

- In 2005, an industry committee for water utilities created a guideline for post-earthquake performance.
- Why a "guideline" and not a "mandated standard"?
- The 10 of us (4 water utility engineers, 2 professors, 4 consultants) didn't think we had the perfect answer. So, we created the guideline to be used for 10-20 years, see how it goes, and only then establish an industry wide "standard"

Water Pipelines

Pipe Function Class	Seismic Importance	Description
I	Very low to None	Pipelines that represent very low hazard to human life in the event of failure. Not needed for post earthquake system performance, response, or recovery. Widespread damage resulting in long restoration times (weeks or longer) will not materially harm the economic well being of the community.
II	Ordinary, normal	Normal and ordinary pipeline use, common pipelines in most water systems. All pipes not identified as Function I, III, or IV.
III	Critical	Critical pipelines serving large numbers of customers and present significant economic impact to the community or a substantial hazard to human life and property in the event of failure.
IV	Essential	Essential pipelines required for post-earthquake response and recovery and intended to remain functional and operational during and following a design earthquake.

Table 3-1. Pipe Function Classes

Water Pipelines

Pipe Function Class	Probability of Exceedance P in 50 years	Return Period T (years)
I	100%	Undefined
II	10%	475
III	5%	975
IV	2%	2,475

Table 3-2. Earthquake Hazard Return Period for each Pipe Function Class

Water Pipelines

Pipelines meeting the above requirements may have their Functions reclassified as shown in Table 3-3 in terms of the level of redundancy L_R. There is no redundancy at L_R=0. For one redundant pipeline, L_R=1. For two or more redundant pipelines, L_R=2.

Pipe Function	$L_R = 0$	$L_R = 1$	$L_R = 2$
I	I	I	I
II	II	II	II
III	III	II	II
IV	IV	III	II

Table 3-3. Function reclassification for redundant pipes.

Redundancy - Power

- In 2022, a single Structural Engineer proposed to ICC to set I = 1.5 (Return Period 2,475 years) for every power plant in the USA that delivers power to the public (nearly all of them). That Structural Engineer admits he is not an expert in the electric power business.
- 12 / 12 industry engineers wrote to ICC to protest I = 1.5.
- What will ICC do?
- What should ICC do?

Redundancy - Power

- The Structural Engineer is a colleague
- He says: "Power is essential after earthquakes"
- He says: "Hospitals are essential after earthquakes"
- Codes: I = 1.5 for Hospitals (and has been for > 20 years)
- But, does this make sense for power plants?

After an Earthquake

- Demand for Hospitals: goes up
- Demand for Power: goes down

So... How to Improve Post-Earthquake Power Reliability?

- If you are on an Island with only 1 power plant.... Get another power plant. Better... get multiple power plants so that if you lose 50% of them, you can still run the grid
- If you are in Portland....
  - Harden the high voltage substations
  - Get more people available to fix busted low voltage distribution

So... How to Improve Post-Earthquake Power Reliability?

- If you are in Gold Beach....
  - Harden the high voltage substations
  - Get a reliable transmission line (better, get 2 reliable transmission lines)
  - Get more people available to fix busted low voltage distribution
  - Everybody buy a Honda generator?
  - Build a power plant near Gold Beach

What are Big Outages?

- California (population 40 million)
  - 1,000,000 CM (typical daily outages)
  - 40,000,000 CM (Napa 2014 EQ, customers satisfied)
  - 100,000,000 CM (~ 5 times per winter)
  - 500,000,000 CM (2011 wind storm, customers angry)
  - 1,000,000,000 CM (Loma Prieta 1989 M 7, customers forgiving)
  - 10,000,000,000 CM (future San Andreas M 8). Will customers be satisfied?

The Future

- Over time, technology and fuels change
- The key to a reliable grid: redundancy + repair crews
- The key to short outages: a large workforce for common storms (less than 10,000,000 customer-minutes outages for Oregon, less than 50,000,000 CM in California)
- The keys to prevent long outages in rare earthquakes in Oregon: mitigate seismically-weak items cheaply ($); underground overhead distribution ($$$$); seismic design for overhead distribution ($$); be able to ramp up to (at least) 2,000 work crew within ~ 1 day ($); and solve the coastal transmission / generation issue ($$$).

The Abyss

- Legislate 1 day restoration of service to critical customers.
  - Potentially huge cost and impossible to achieve. Lawyers will love this. Will your utility go bankrupt?
- Seismic retrofit Generation with I = 1.5.
  - High cost, IPPs and the Army / Bureau will be impacted. Won't be of much benefit except to consultants and contractors.

Thank you!
Quiz Part 2
Questions?