Puebla M 7.1 Earthquake of Sept 19 2017
Impact to Water and Power

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The TCLEE Team

- The Council of Lifeline Earthquake Engineering
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- Document (TCLEE #3) at www.geEngineeringSystems.com (free).

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Key points

- Water System: 1,500 Pipe Repairs. Aqueduct Failures. Basin Effect issue. No seismic design.
- Power System: 37 damaged substations. 4.78 million people lose power. “Limited” seismic design.
- Codes and Standards:
  - ALA (2005) will solve most water pipe seismic design issues (should be updated for basin effects). www.americanlifelinesalliance.com, www.geEngineeringSystems.com (free)
  - IEEE 693 (2018) will solve most substation issues (including cable slack issues). http://ieeexplore.ieee.org (fee)
- Remaining implementation time for California: Water: 50 years. Power: 10 years.

CFE
Commision Federal de Electricidad
“la comision”

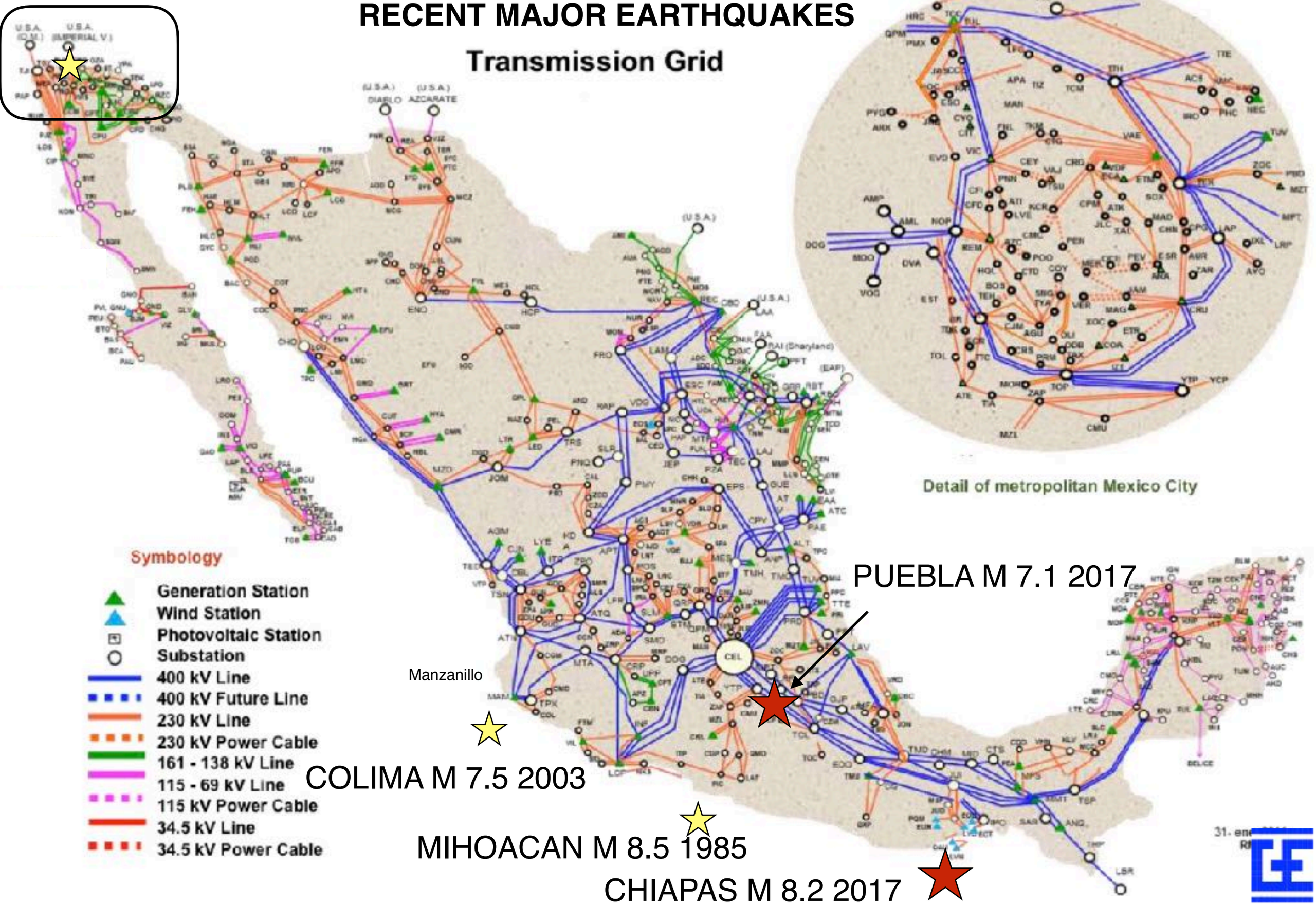
- CFE is the power transmission company for all of Mexico.
- Transmission voltages are 400 kV, 230 kV

LAGUNA SALADA M 7.1 2010

Interconnected with SDG&E

RECENT MAJOR EARTHQUAKES

Transmission Grid



Chiapas M 8.2 (Sept 7 2017)

- Shaking level: PGA ~ 0.5g±.
- Near the Pacific coast, so seismic design for newer equipment (PGA = 0.5g).
- Juchitan Dos (Toppled 230 kV transformer, broken 230 kV CT, broken 230 kV CB, 230 kV DS)
- Ixtepec, Matias Romero, Oaxaca Substations
- Total Damage ~ $126 million pesos (~$7 Million USD)

Puebla M 7.1 Sept 19 2017

- Intraplate. Inland, ~100 km SE of Mexico City, ~70 km SW of Puebla.
- 37 substations with damage.
- 6 Transmission steel lattice towers with damage.
- 1 High voltage cable with damage.
- Moderate or Low shaking (PGA ~ 0.08g to 0.25g at the damaged substations)

M 7.1 Puebla Earthquake

- Sept 19. Power outages: Peak at 4.78 million customers, over 7 states. ~35% of all CFE customers lost power in Central Mexico, at least temporarily.
- Sept 20. Power outages: 95% restored.
- Sept 23. Power outages: 99% restored.
- Restoration effort: 3,072 CFE workers. Distribution: 74 portable generators, 1 helicopter, 920 trucks, 468 cranes.
- Transmission: widespread equipment failures at 1 substation (400 kV), some equipment failures (400 kV and 230 kV) at 6 substations (400 kV and 230 kV)

Note: damage (mostly minor) to 29 additional lower voltage substations not shown in this schematic

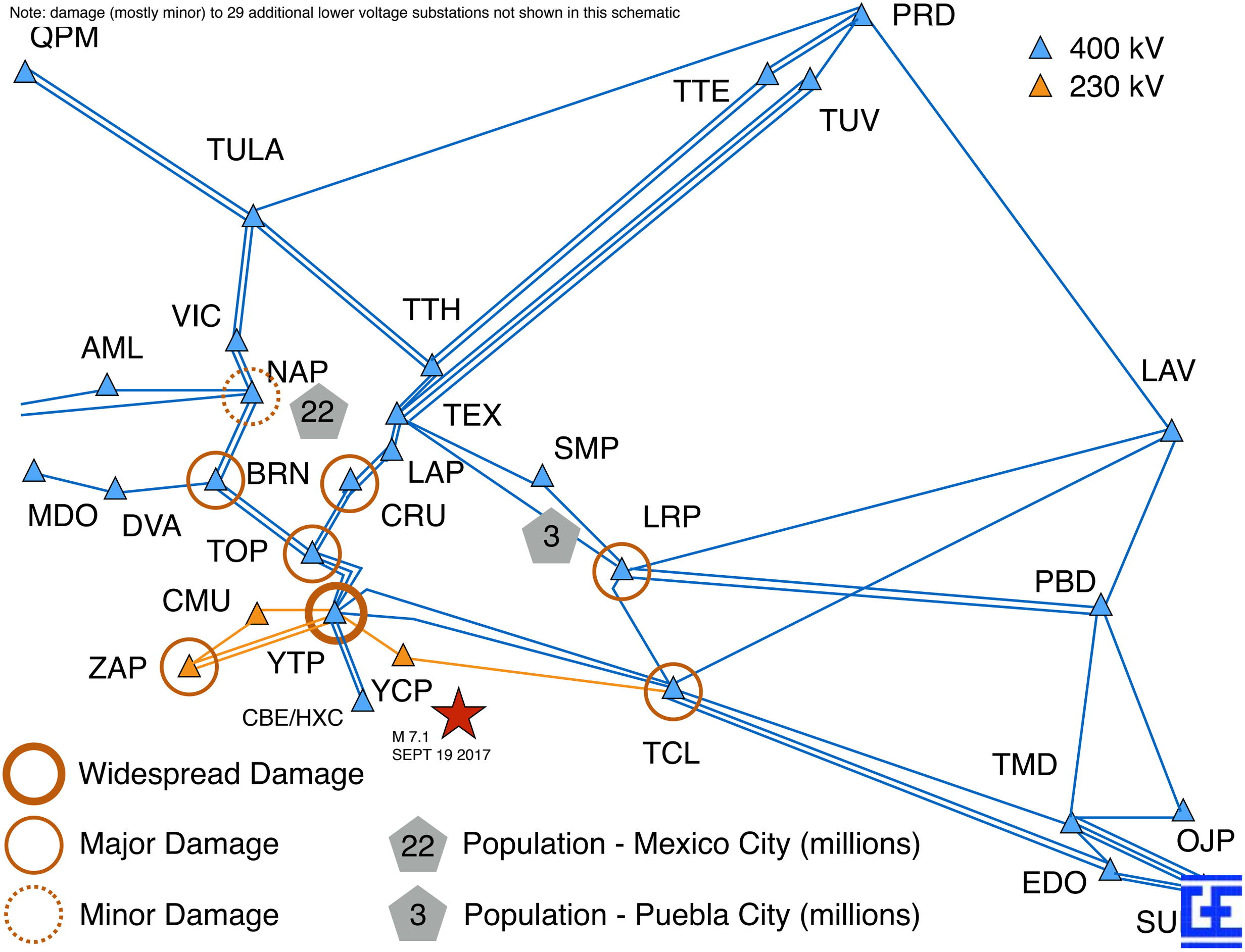
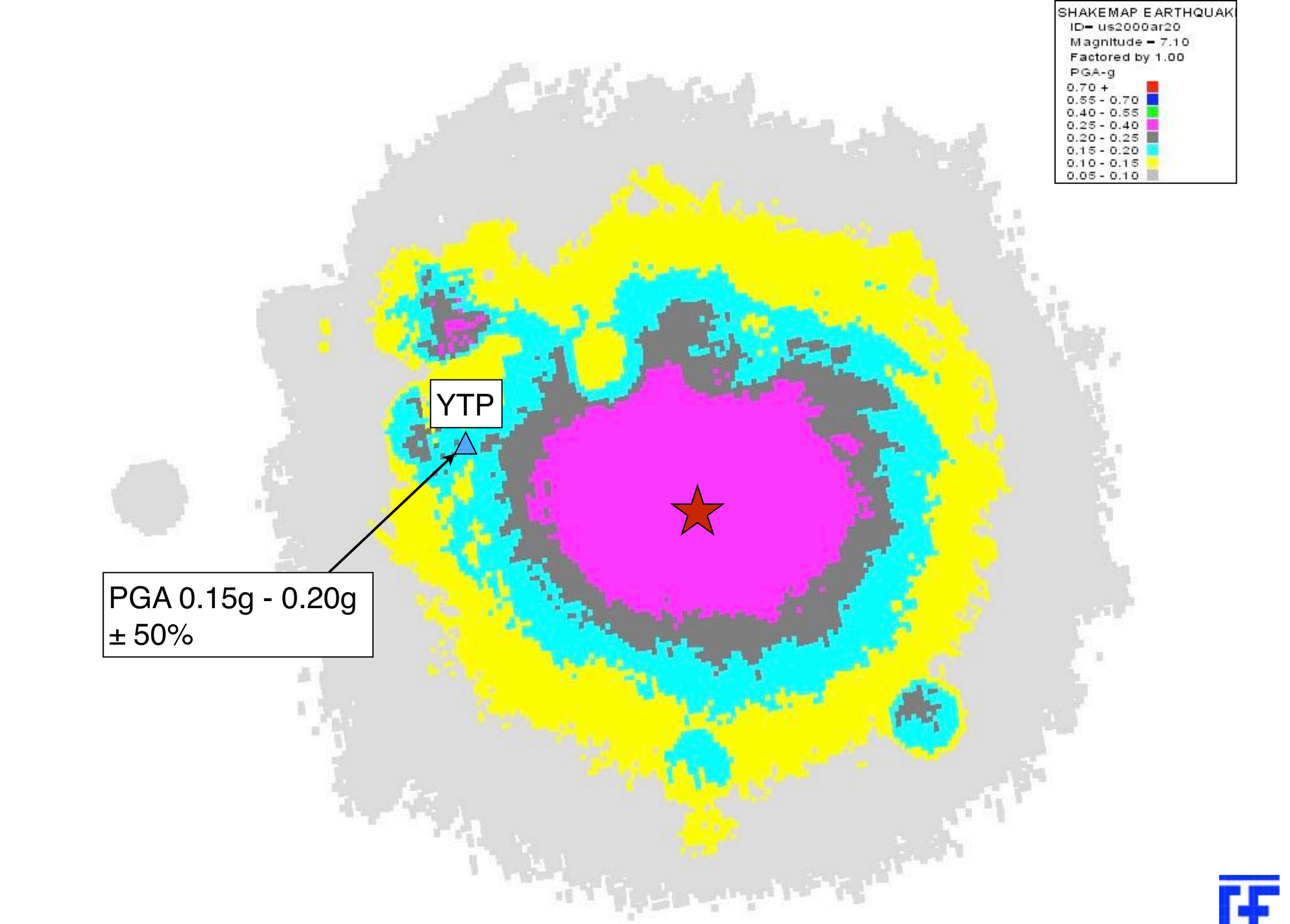


Photo Credit: Google Maps (2018)


SHAKEMAP EARTHQUAK
ID= us2000ar20
Magnitude = 7.10
Factored by 1.00
PGA-g
0.70 +
0.55 - 0.70
0.40 - 0.55
0.25 - 0.40
0.20 - 0.25
0.15 - 0.20
0.10 - 0.15
0.05 - 0.10
YTP
PGA 0.15g - 0.20g
± 50%

Damage at YTP
(Most Heavily Damaged Substation)

Item Damaged by Earthquake - Replaced

Circuit Breaker

Disconnect Switch

Wave Trap

Surge Arrestor

CCVT

TOP-1

TOP-2

TOP-3

TCL-1

TCL-2

B, C

400 South Bus

400 North Bus

1/3

Bank 2
400-230

Bank 4
400-230

1/4

Bank 3
400-115

1/4 400 Bushings

Cable

To 115 kV Yard

B

C

HXC-1

B, C

HXC-2

230 North Bus

230 South Bus

Transformer

Pot Head

Connection

400 kV Transformers (11) (4 x 400-115; 7 x 400-230)
All unanchored
1 slid ~7 inches
1 slid ~2 inches
9 showed ~0 to 1 inch sliding
Many control cables deformed, none reported damaged


sliding


7 Inches of sliding

Control Cables Deformed due to Sliding

4 x 400 - 115 kV Transformers

Broken 400 kV bushing

Broken 400 kV Surge Arrestor

400 kV Bushings (1 / 10 with damage)

400 kV TR Bushing

Low Voltage
TR Bushing

400 kV TR Bushing

LV kV Bushings (1 / 14 with damage)


OHIO BRASS

Older 230 kV DS (Scissor Switch) (6) - 3 / 6 collapsed

230 kV
Scissor Switch

230 kV CBs 3 / 6 collapsed. May have been aggraveted by collapse of adjacent Scissor Switches, note the tight slack

DS

CB

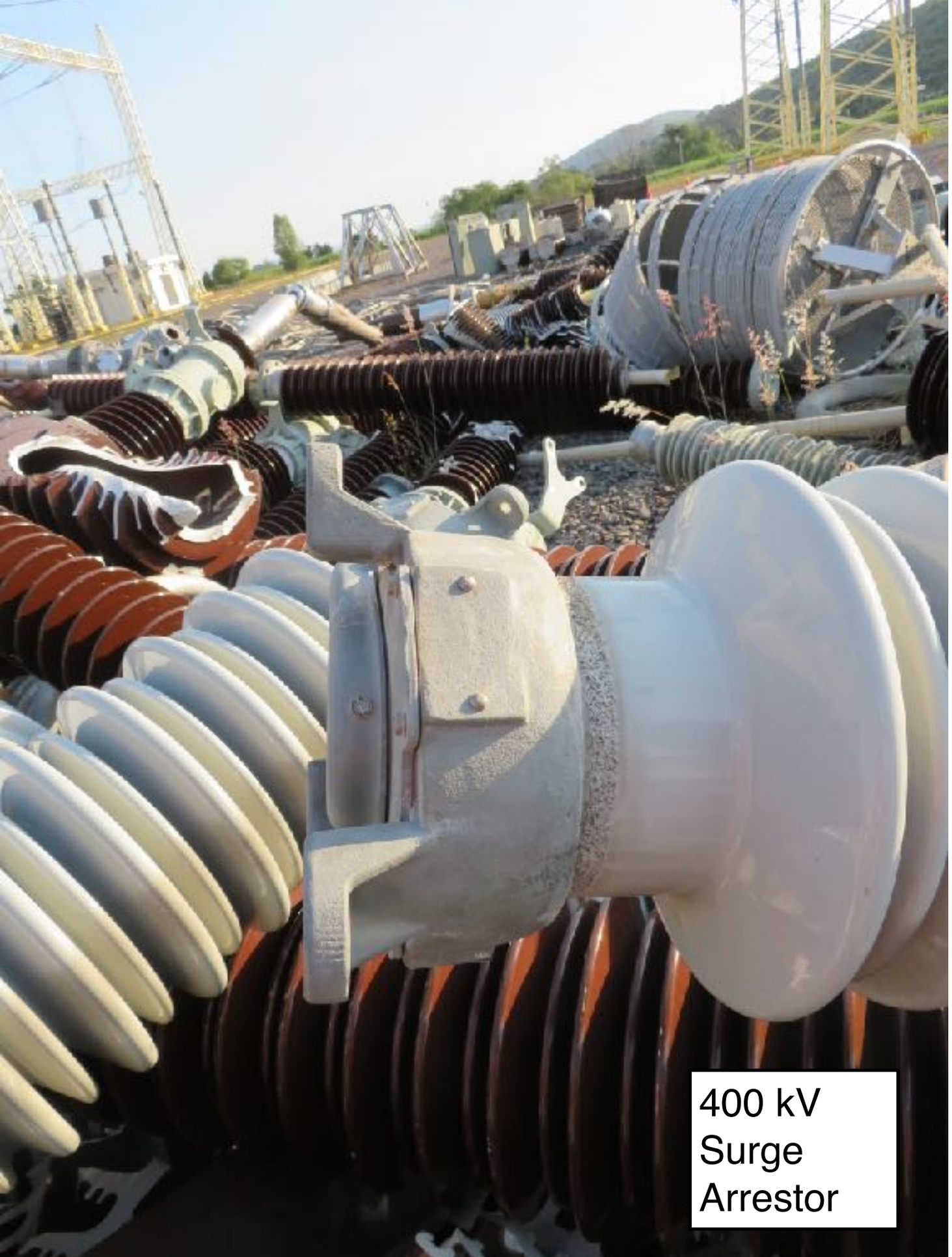
CT

Newer 400 kV CB (12) - 0 / 12 damaged
Newer 400 kV DS (30) - 0 / 30 damaged
Newer 400 kV CT (12) - 0 / 12 damaged

The Bone Yard


400 kV CB
Seismic “Qualified” for PGA = 0.2g

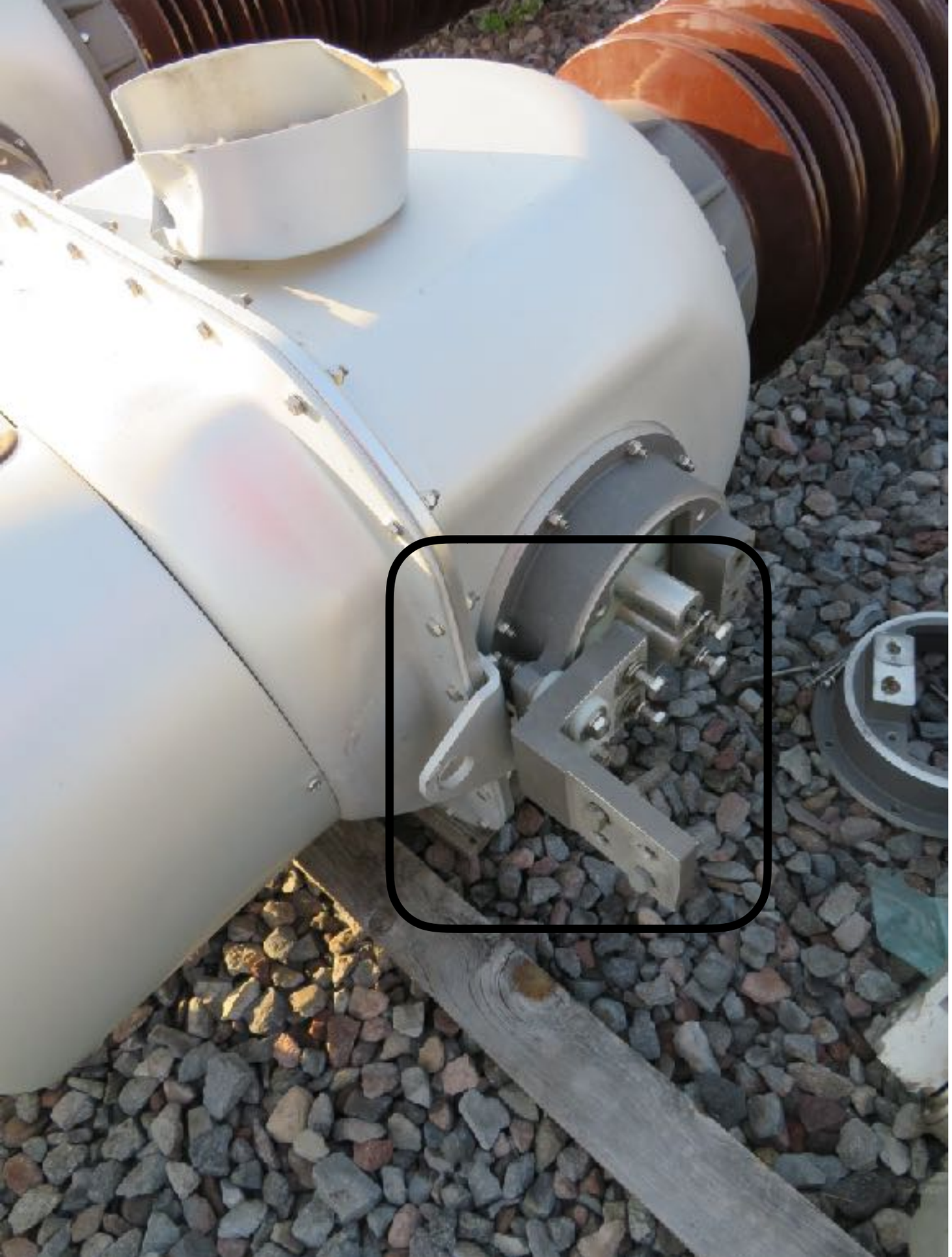
400 kV CB


400 kV
Surge
Arrestor

400 kV
Wave Trap


230 kV CB
400 kV CT
Older
400 kV CT
Newer

400 kV CT
Failure is non-ductile failure of cast aluminum bracket.
Likely due to insufficient slack



400 kV CT
Non-ductile failure of
cast aluminum bracket.
Likely due to insufficient slack

400 kV CT
Non-ductile faiure of
cast aluminum bracket.
Likely due to insufficient slack

400 kV CB
Newer
12 / 12 no damage

Older 400 kV CT
3 failures

Older 400 kV CB
19 / 36 failures

Replacements

400 kV CB
60 Hz
2000 Amps
W = 3200 Kg (per pole)
Fabricated December 2000
Seismic Qualification = 0.20g

Control Building

Batteries

No seismic design!
(how can this be?)

Rocking starts at PGA > 0.1g.

1 cell toppled.

Remaining cells
manually moved.

Evidence suggests
that PGA was likely < 0.3g.

Damage to Mexico City's Water System (King of Broken Segmented Large Diameter Concrete Pipes)

Historical Earthquakes

Year	M	Water System Damage
1818 May 31		Broken arches in aqueducts in Mexico City
1820 May 4		Damage to above ground aqueducts in Mexico City
1835 Jan 6		Damage to above ground aqueducts in Mexico City
1864 Oct 3		Damage to buried clay pipes in Mexico City
1882 July 19		Damage to buried clay pipes in Mexico City
1907 April 14	8.2	Damage to buried clay pipes in Mexico City
1932 June 3	8.4	Extensive damage to buried pipelines in Mexico City
1973 June 30	7.5	Damage to buried main aqueducts (20 locations) in Orizaba and Cordoba (Orizaba EQ)
1979 March 14	7.6	Damage to a buried aqueduct in Mexico City (Guerrero EQ)
1985 Sept 19	8.1	Extensive damage to buried pipelines and buried aqueducts in Mexico City (Mihoacan EQ)
2017 Sept 17	7.1	More damage to aqueducts in Mexico City (Puebla EQ)

M 7.1 Puebla Earthquke (Sept 19 2017)

- 1,500 leaks
- Tlahuac - Mixqui - Santa Catarina
    - 48” diameter segmented concrete pipe
    - 26 leaks in 22 kilometers
    - Why? Answer: Not related to PGD, Yes, related to PGV, but mostly related to Basin effects (how to select “c”)
    - ALA (2005): 7 * V/c might not be enough for basin effects. “7” might need to be increased to about 15 for PGV = 25 inches / second (median) in basin-effect zones; or segmented pipes not allowed in zones subject to basin effects; or site-specific design required.
    - V/c is NEVER recommended for segmented pipes.

Photo Credit: Conaqua

Bar Wrap Pipe Leak

Photo Credit: Conaqua

Photo Credit: Conaqua

Santa Catarina

48” diameter
26 leaks in 22 km

Replaced 192 meters of pipe that were so badly damaged that they could not be quickly repaired

Photo Credit: Conaqua

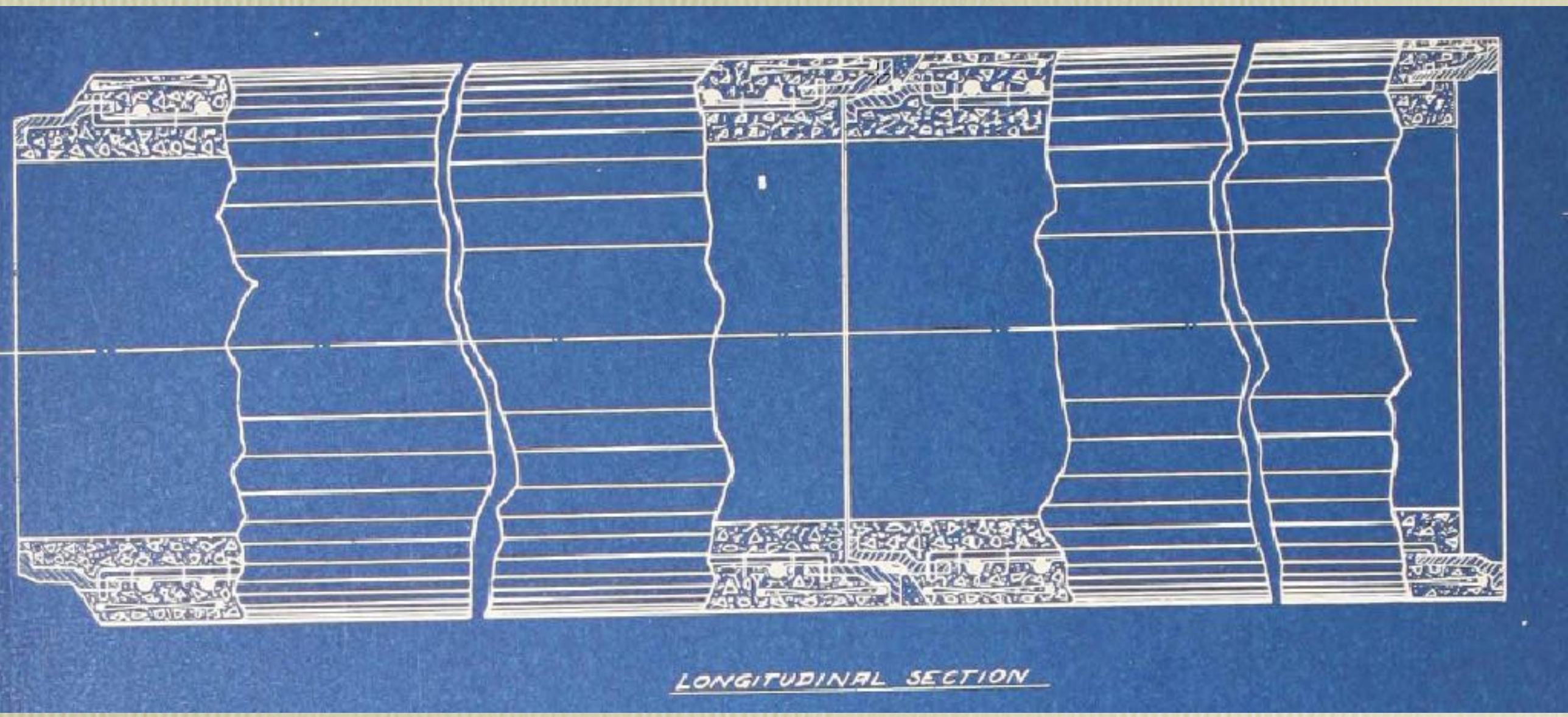
Distribution of Potable Water System

more than 1,500 leaks had been found in the distribution network

besides the east of the Iztapalapa delagacion and a part of the delegation Tlahuac, in the City of Mexico

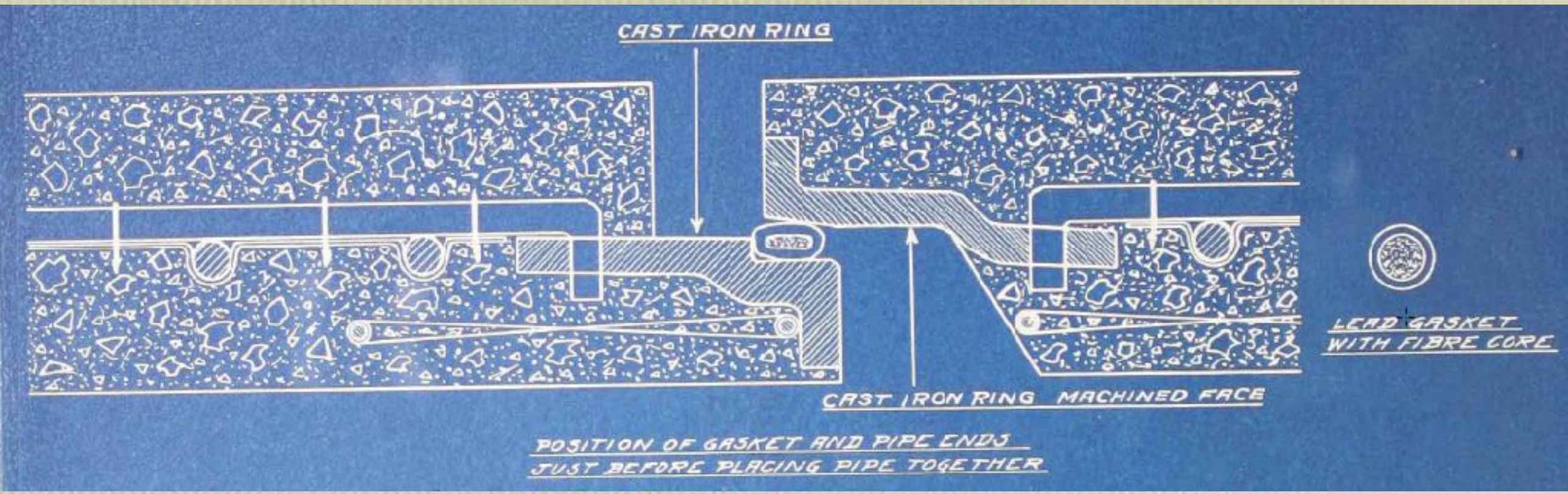
Photo Credit: Conaqua

Lock Joint Reinforced Concrete Pipe

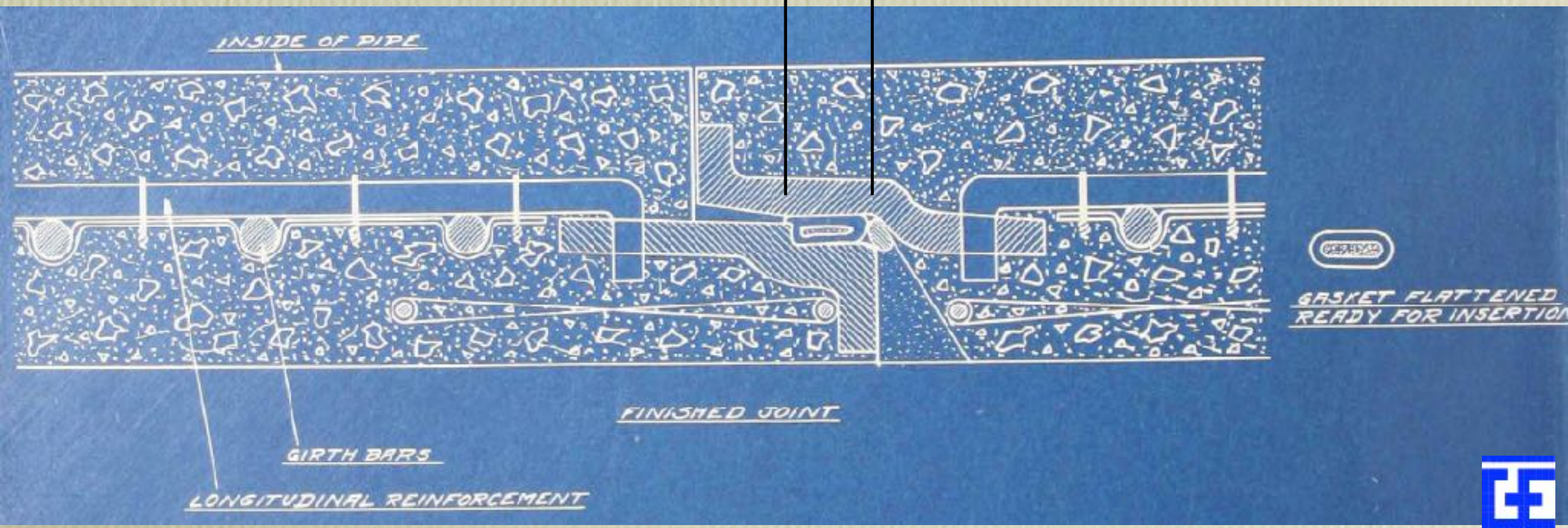


Lock Joint Pipe Company, New York
Manufacturerd Locally Near the Job Site

Pressure pipes, 8-inches to 108-inches



Capacity ~ 1.0 inches



Lock Joint Reinforced Concrete Pipe

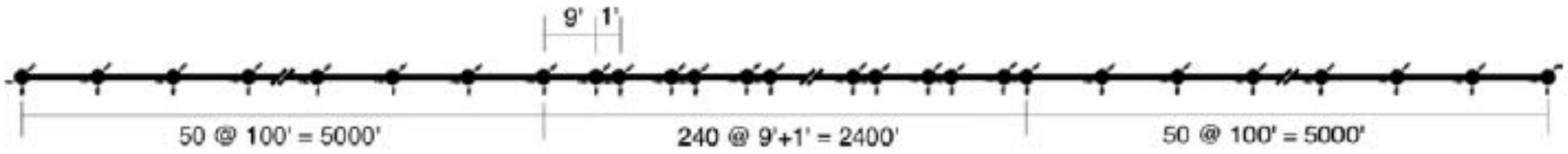
45 to 95 feet head, 48-inch and 66-inch pipe being manuafactured

Why do segmented pipes break in shaking?

- S Waves (vertically propagating shear waves) or R Waves (horizotnally propagating surface waves) ?
- S waves are the historically commonly accepted phenomena. Remains valid in soil zones located away from mountains
- Slow moving waves are becoming more recognized. Pulses, Directivity. Basin Effects.
    - Basins in California (Los Angeles, Pasadena, etc.) can be exposed to significant Basin effects

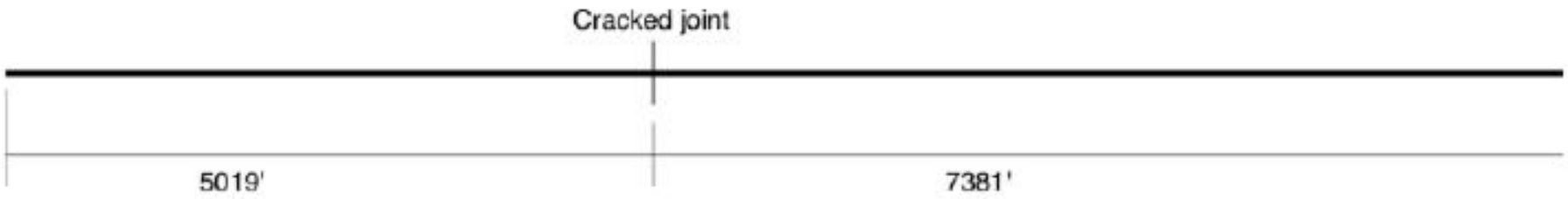
Case	Pipe M (kip-inch)	Joint Force (kips)	Joint opening (inch)
A	1260	~0	0 (restrained)
B	2980	2,040	1.35” peak

Case A

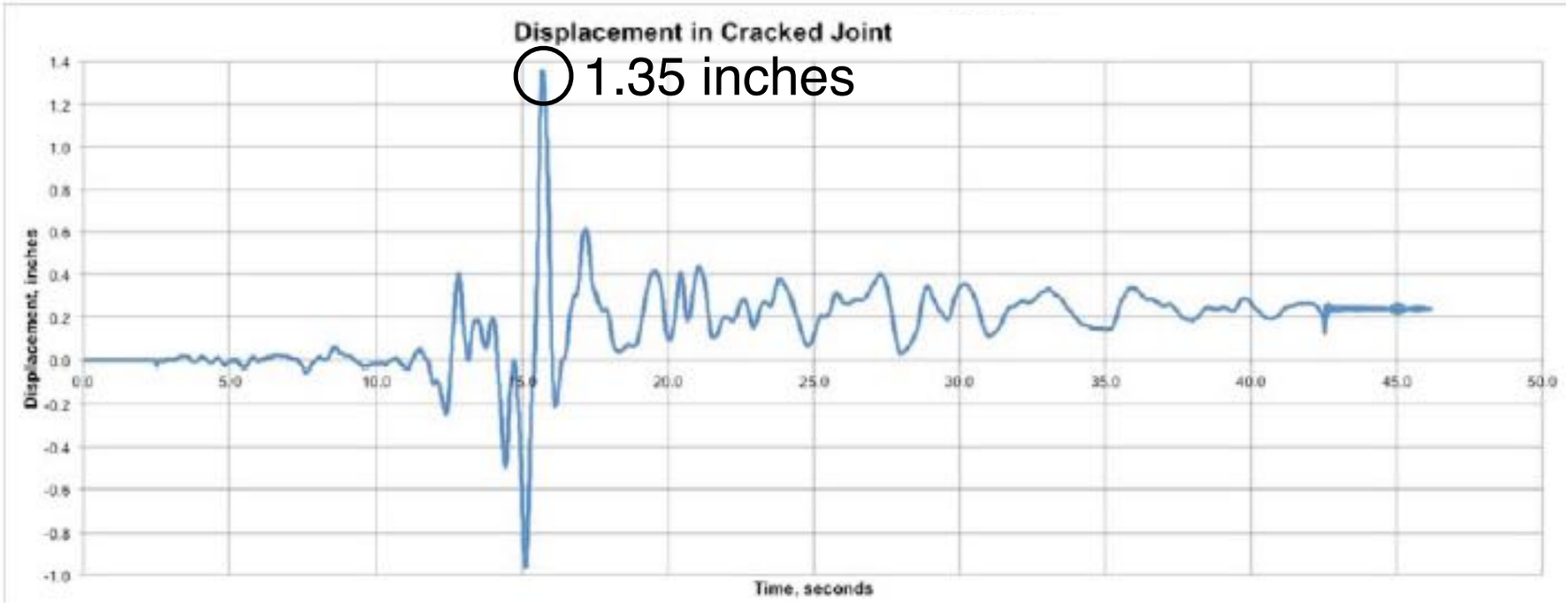


S Wave

Case B



R Wave



Case B
R Wave

Joint Opening Capacity ~ 1.0 inches

Case B Variations:
Increase surface wave speed to 10,000 feet/sec. Result: joint opening 0.29 inches
Increase surface wave speed to 20,000 feet/sec. Result: joint opening 0.16 inches

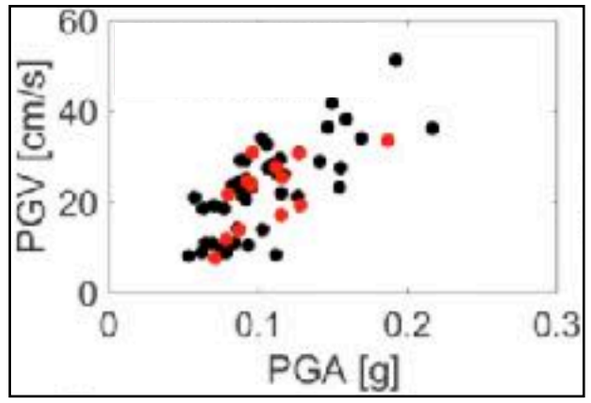
Observations

- Joints will open when there is a single pre-cracked joint after a long reach of continuous pipes
- Joints will open if there are slow moving travelling waves.
- Joints will open if there if a major stiffness discontinuity (vault, elbow) viz.
- Basin effects, pulses, directivity all make this worse

What to do?

- No segmented critical pipe. Solves the issue.
- Chained ductile iron pipe (eg. Kubota, US Pipe, etc.). Solves the issue.
- Continuous pipe (eg. welded steel, HDPE, etc.) Solves the issue.
- Long throw joints (6”+) can solve the issue.

Distribution Repairs



Instrumental Recordings in Mexico City

- Ground Motions. Mexico City “rock”. PGA = 0.05 to 0.10g. PGV = 10 cm / second. (1/5 of inventory)
- Ground Motions. Mexico City “lake and transition”. PGA = 0.07 to 0.2g, PGV = 28 cm / second. (4/5 of inventory)
- About 20,000 km of pipe (all types)
- Very few PGD zones (handfull, perhaps dozens of repairs)
- RR = k1 * 0.00187 * PGV (RR in repairs / 1000 feet, PGV in inches / second, k1 varies based on pipe type) (see ALA 2001, Eidinger, Maison et al, for derivation of this pipe damage model)

Distribution Repairs

- Total pipeline inventory might be about 20,000 km for 22 million people. “average” PGV = 24.5 cm/sec = 9.6 inch/sec
- Forecast repairs = 0.00187 * 9.6 * (20,000 * 3.30) (assuming k1 = 1.0)
- Forecast repairs ~ 1,185
- Actual repairs ~ 1,500
- Pipeline inventory is known to have severe leakage (pre-earthquake losses ~30% or more), is aged, much might be in hot soils, PGV might be > 24.5 cm/sec for oldest and weakest pipes, many pipes have undergone distorations due to 1 to 3 inches of subsidence per year over 100 year time frame, length of pipe might be more or less than 20,000 km.
- Considering these issues, the first-order prediction (1,185), with further adjustments, might be within ballpark of actual (1,500). Or, Mexico k = 1.27.

Questions