Nor Any Drop To Drink

Seismic Analysis of the Cedar River Pipeline System

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BEFORE WE BEGIN….

- What is liquefaction?
  - Per the United States Geological Survey:

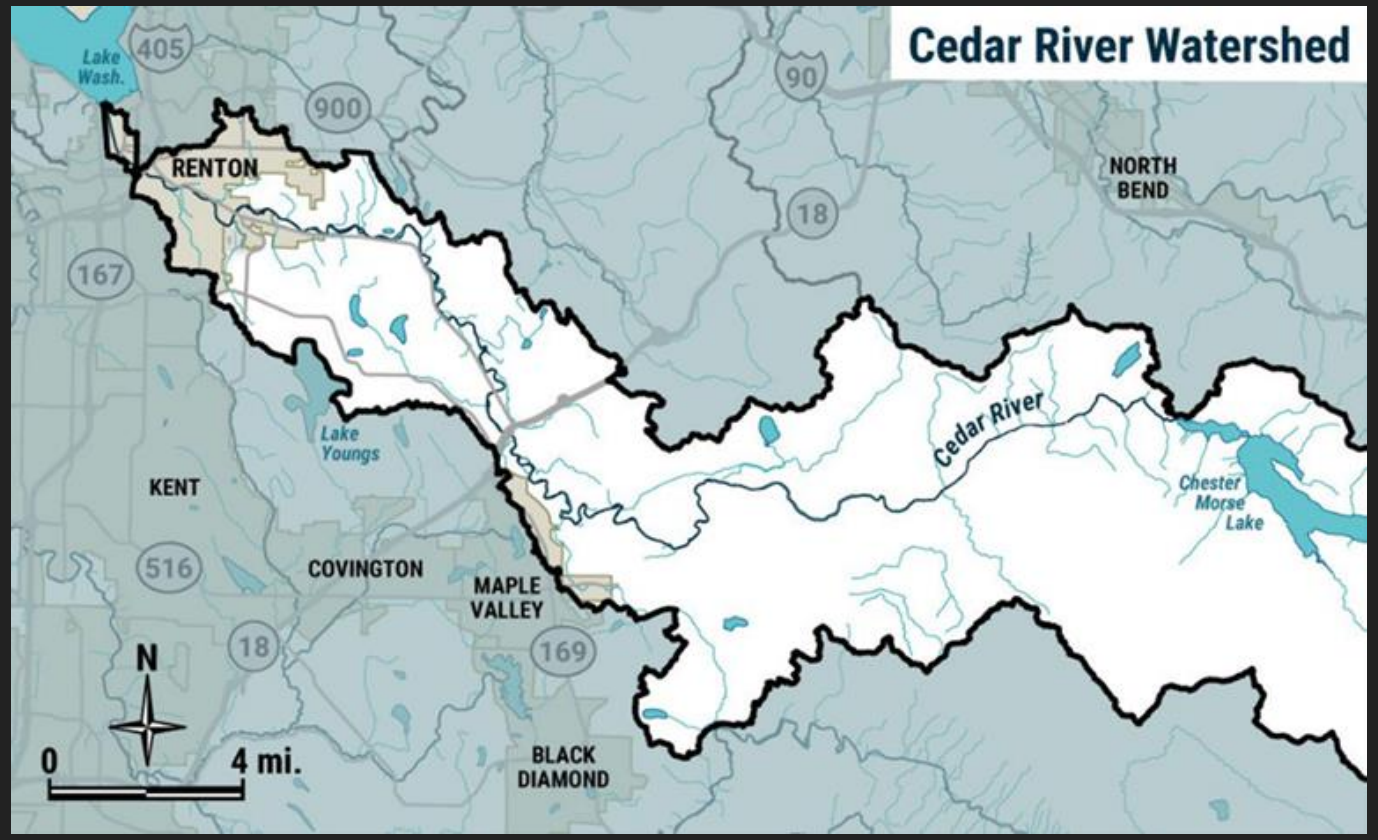
    “Liquefaction takes place when loosely packed, water-logged sediments at or near the ground surface lose their strength in response to strong ground shaking.”
- Areas most susceptible to liquefaction:
  - High groundwater
  - Infilled land
  - Locations adjacent to bodies of water (marshes, riverbeds, etc)



Liquefaction from the 2001 Nisqually Earthquake (source: Washington Department of Natural Resources)

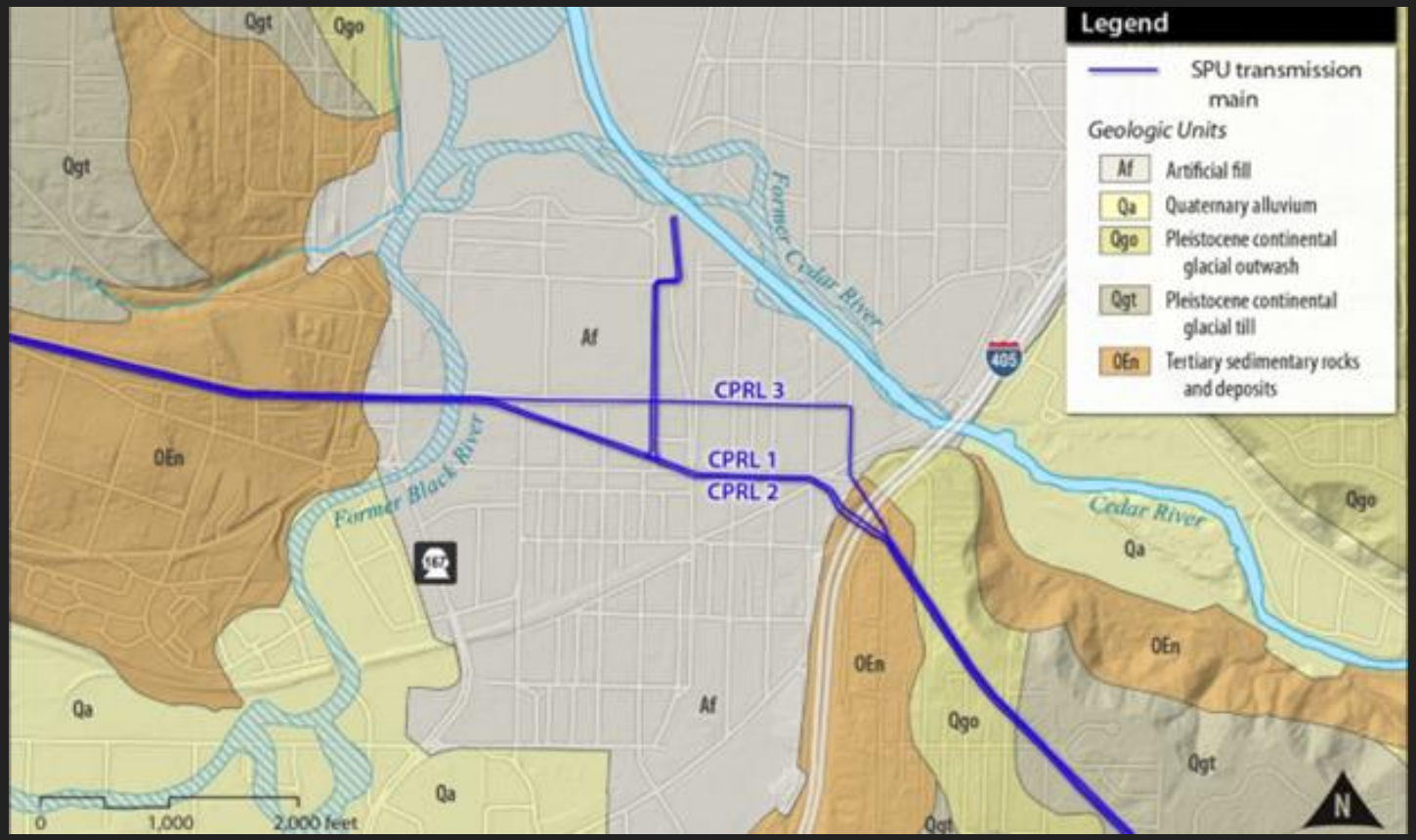
BACKGROUND

- The Cedar River Watershed (managed by Seattle Public Utilities) conveys water to approximately 1.6 million people in the Seattle metro area
- Water is conveyed via gravity-fed transmission mains from the Chester Morse Reservoir in the Cascade Range
- Near downtown Renton, the Cedar River Pipeline system (CRPL) consists of (3) riveted steel pipelines:
  - CRPL 1: 66-inch diameter, constructed circa 1920
  - CRPL 2: 51.5-inch diameter, constructed circa 1920
  - CRPL 3: 66-inch diameter, constructed circa 1930



Cedar River Watershed (source: kingcounty.gov)

PIPELINE DESCRIPTION

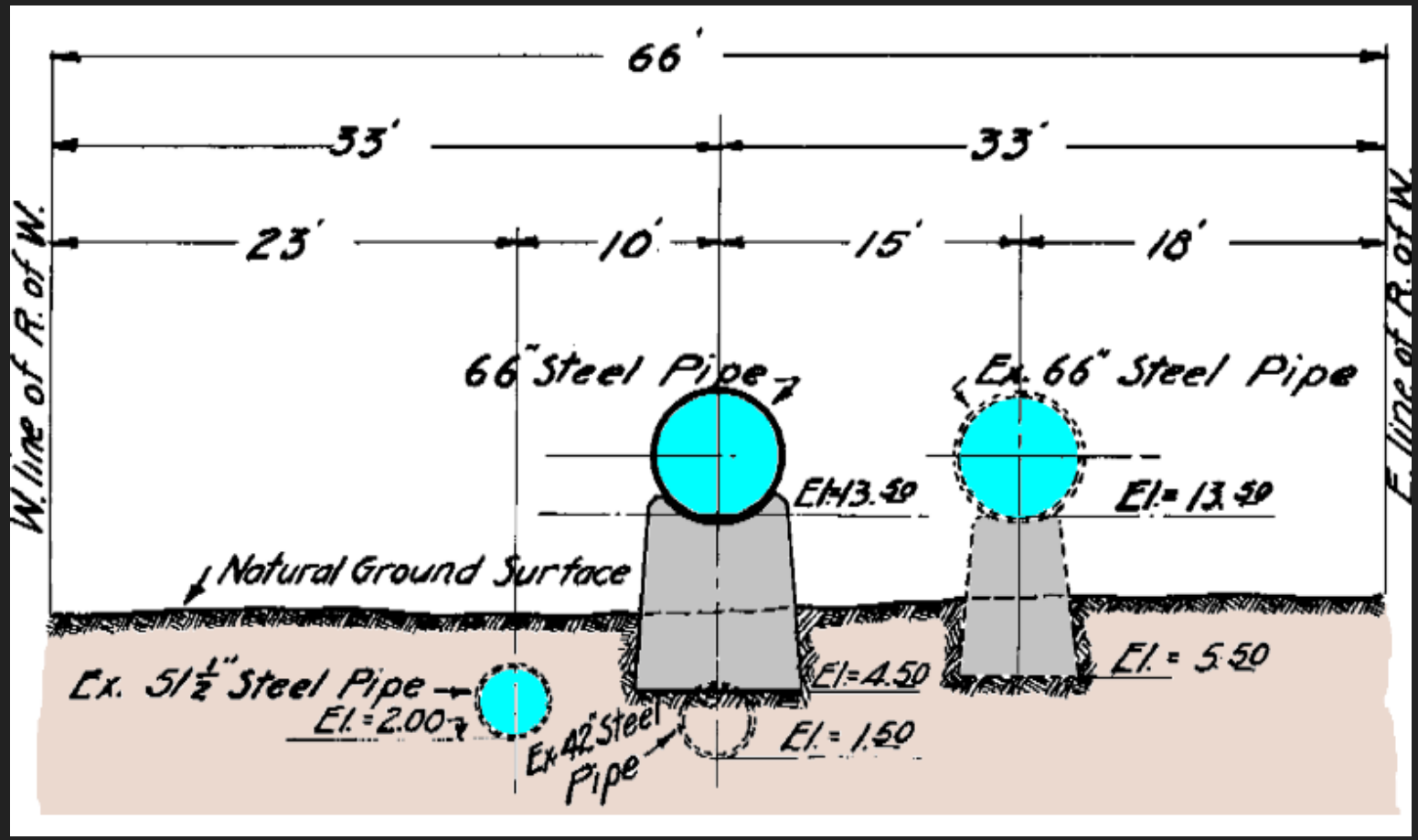


Cedar River Pipeline (CRPL) Alignment In Downtown Renton (source: SPU)

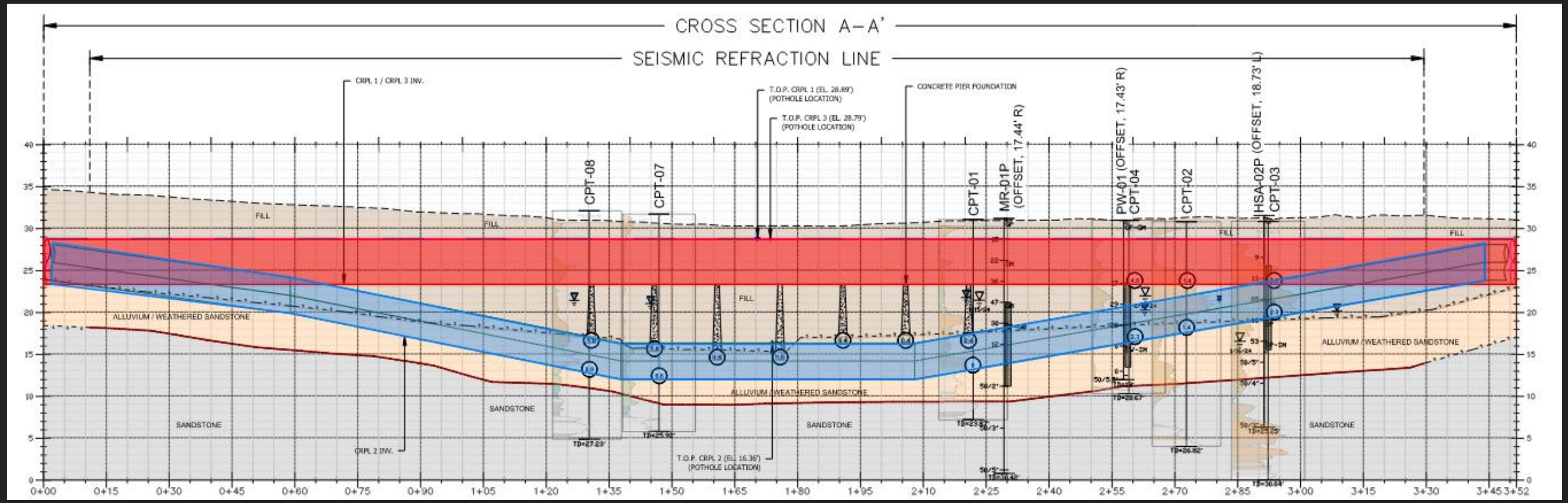
- In the early 20th century, the Lake Washington Ship Canal was constructed, connecting Lake Washington to Puget Sound....
- ....which permanently lowered the lake level....
- ....causing the Black River to dry out.
- The CRPL alignment was constructed over the former Black River channel, which was then backfilled.

PIPELINE DESCRIPTION

- Riveted steel pipe
  - Barrels connected by single line of rivets at girth joints
  - Spacing unknown
- CRPL 1 & 3 are pier-supported across the length of the Black River Channel
  - Fill depth: approx. 2 feet
  - Pier spacing: 15 feet
  - Pier depth: unknown
- CRPL 2 was installed before CRPL 1 and 3 and is directly buried below the former Black River channel
  - Fill depth: approx. 10-15 feet
- Pier depths are unknown; may rest upon liquefiable soils (alluvial fill) OR extend into bedrock (Renton Formation)



CRPL 1, 2, & 3 Cross-Section at Black River Channel



CRPL 1, 2, & 3 Profile at Black River Channel (source: Seattle Public Utilities)

ANALYSIS

ANALYSIS

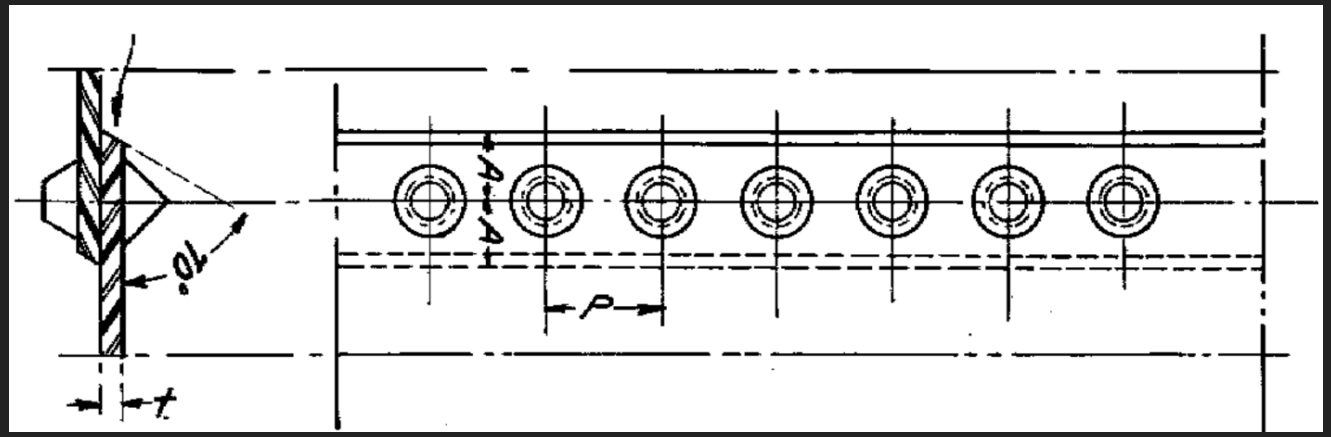
- SPU hired Stantec to perform a 3D finite element analysis of the CRPL pipelines to confirm the risk of liquefaction-induced failure
- Model was constructed using SAP2000 structural analysis software
- Per American Lifelines Alliance (ALA guidelines, non-linear analysis is not appropriate for riveted pipelines
    - If the pipes experience longitudinal loading that exceeds the rivet strength....
    - ....the rivets will fail before the pipe barrel yields.



CRPL 2 Girth Joint Test Sample (source: SPU)

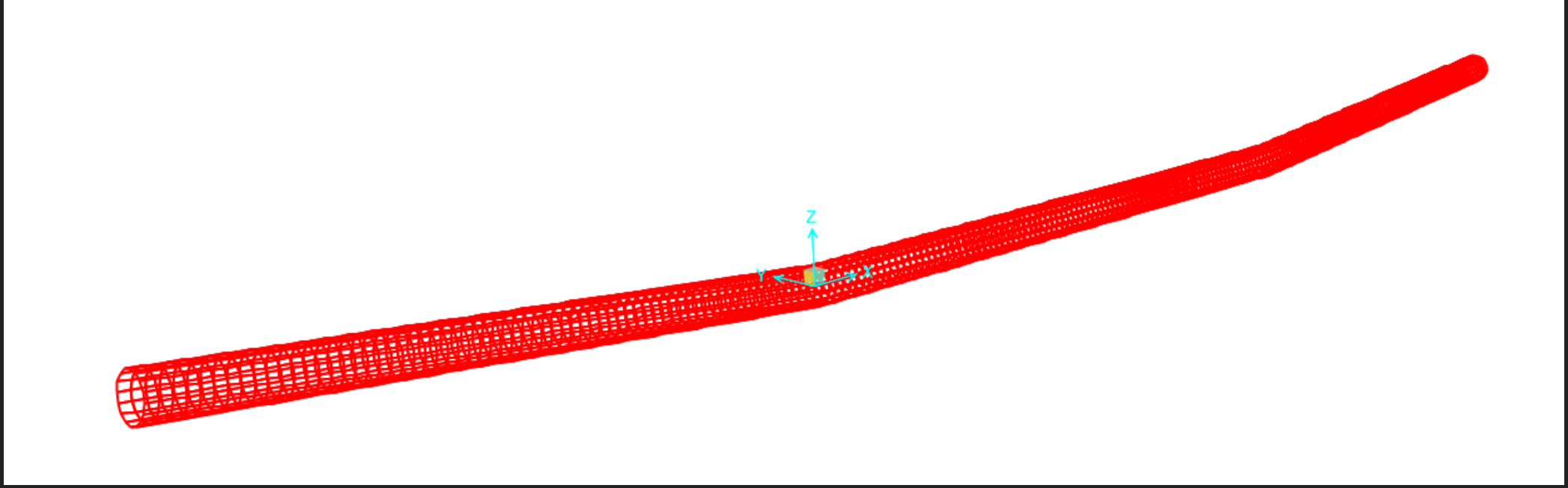
LIMITING CRITERIA

- Per ALA guidelines, non-linear analysis (aka analyzing forces within a structure beyond the plastic limit) is not appropriate for riveted pipelines
    - In other words: the rivets are expected to fail before the pipe barrel yields
- Therefore, a linear analysis was performed with the results checked according to the following limit criteria:
    - Strain at failure = 0.145%
    - Limit based upon destructive testing of rivet sample from CRPL 2
    - Location of girth joints is UNKNOWN



Girth Joint Layout for CRPL 1, 2, & 3 (source: SPU)

MODELING ASSUMPTIONS

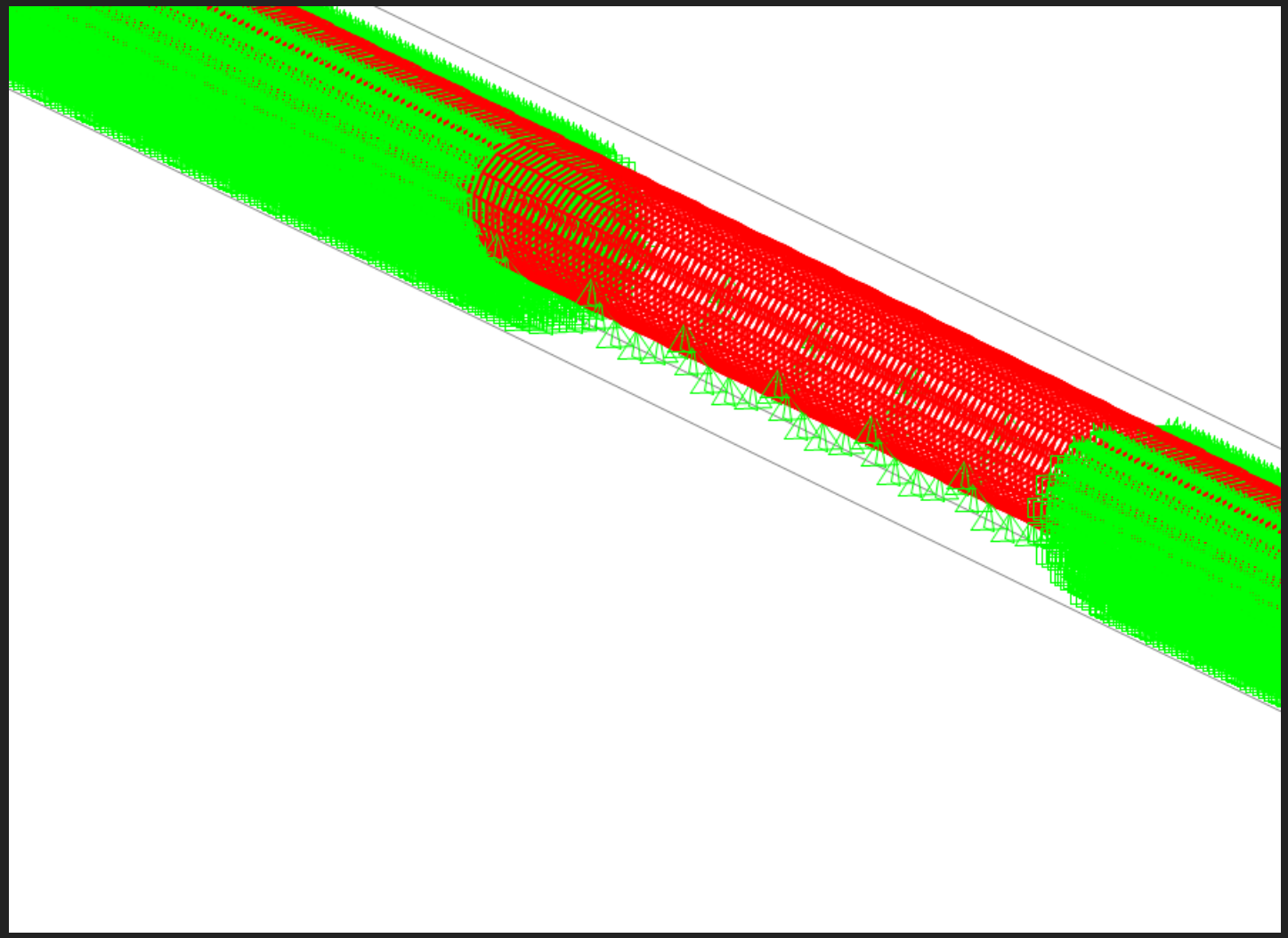


CRPL 2 Pipe Profile Analyzed in SAP2000

- 300 feet of each pipeline was analyzed
  - 100 ft upstream, downstream of Black River Channel
  - 100 ft within Black River Channel
- Multi-linear spring elements used to model soil supports
- Pin supports at pier locations

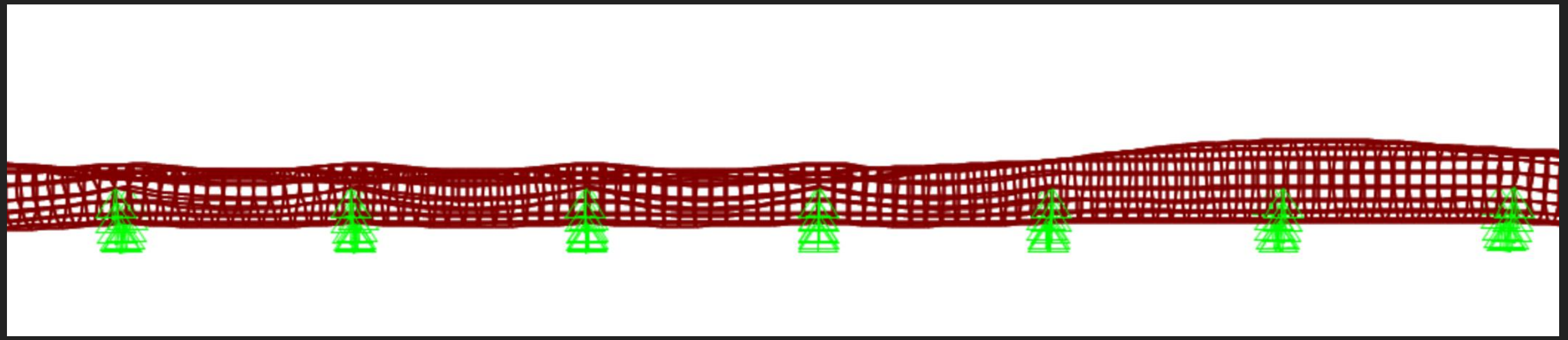
MODELING ASSUMPTIONS

- Mesh size:
  - 1’ x 1’ (approximate) shell elements
  - Thickness: 9/16”
- Boundary conditions:
  - Rotationally-restrained
  - Vertically-free
  - Springs consist of axial, transverse, and longitudinal soil link supports
  - Spring stiffness calculated according to ALA guidelines
  - Estimated displacement applied to each soil node



CRPL 1 & 3 Pipe Profile Analyzed in SAP2000 (soil springs in Black River Channel not shown for visual clarity)

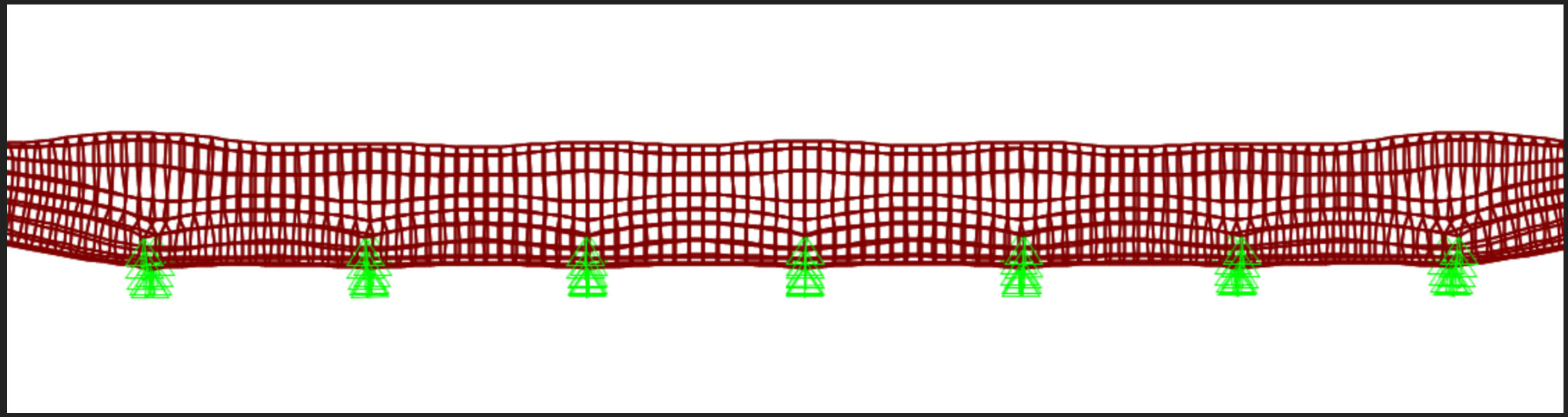
SETTLEMENT CONDITIONS



Model 1: Deformed Pipe Shape

- Model 1: Assumes the pipe is supported by piers that extend below the liquefiable layer into the Renton Formation
    - Piers do NOT displace, only the soil surrounding the pipe

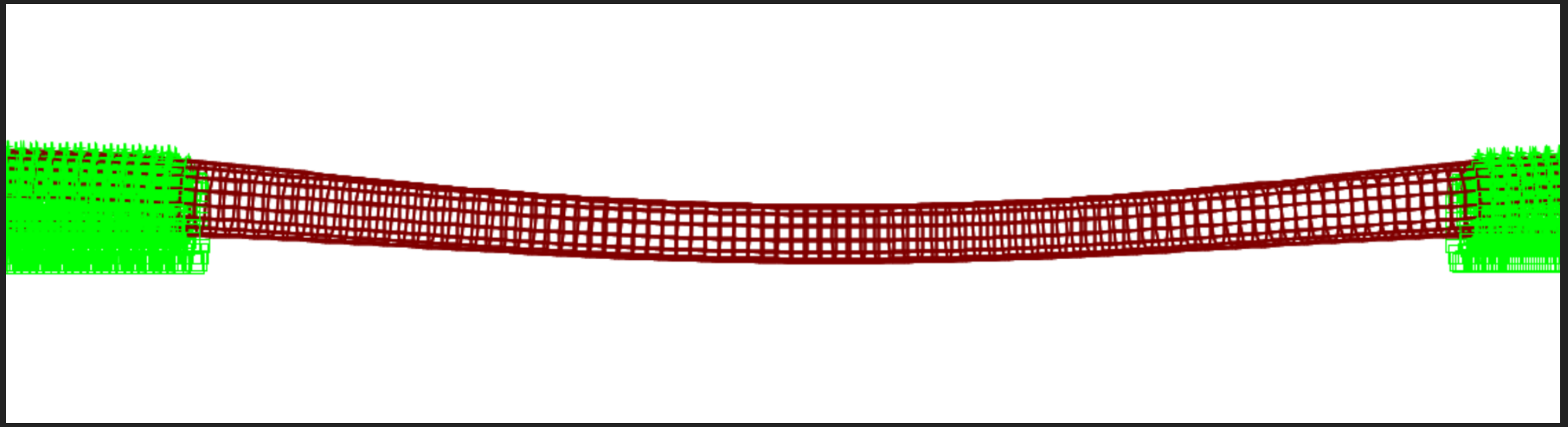
SETTLEMENT CONDITIONS



Model 2: Deformed Pipe Shape

- Model 2: Assumes the pipe is supported by piers that do not extend below the liquefiable layer and instead rest upon native alluvium soils
    - Piers and pipe displace concurrently; pipe and pier remain in contact post-seismic

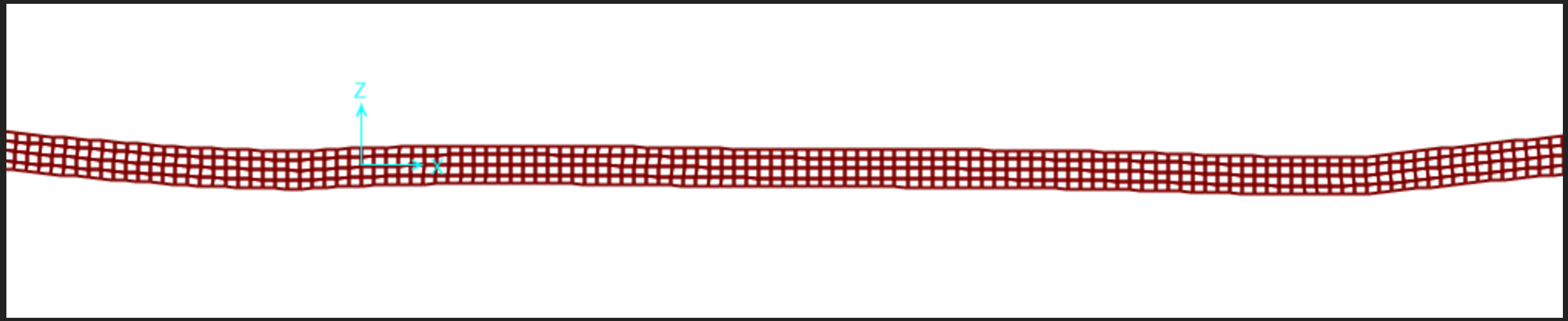
SETTLEMENT CONDITIONS



Model 3: Deformed Pipe Shape

- Model 3: Assumes the pipe is supported by piers that do not extend below the liquefiable layer and instead rest upon native alluvium soils, however….
  - Piers and pipe do NOT displace concurrently, with the pier experiencing greater degree of settlement than the pipe
  - Pipe loses contact with piers; void forms underneath the buried pipe

SETTLEMENT CONDITIONS

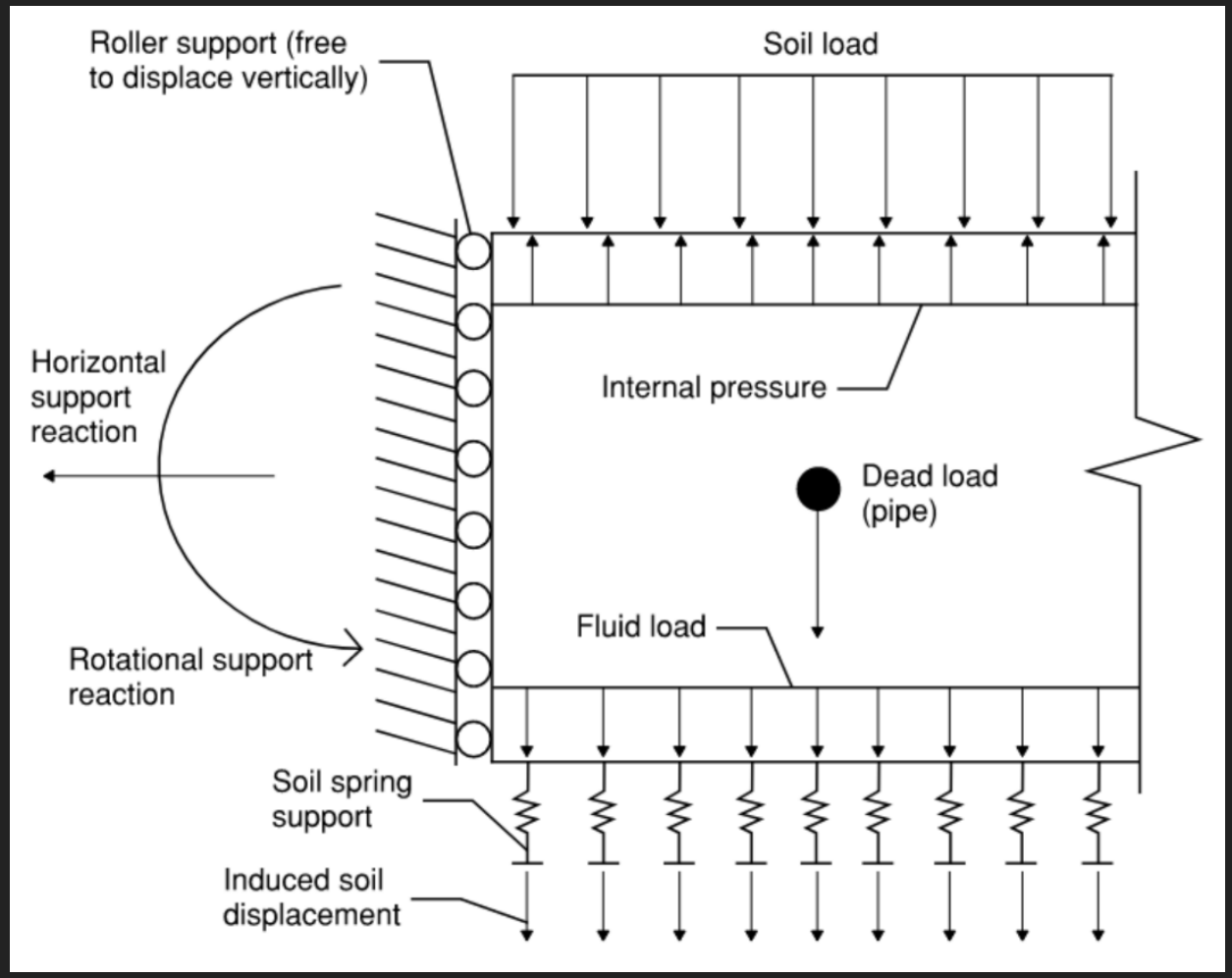


Model 4: Deformed Pipe Shape

- Model 4: Assumes the pipe is supported solely by the soil, and therefore experiences settlement equal to that of the surrounding soil layers
    - Applies only to CRPL 2 (no pier supports)

LOADING CRITERIA

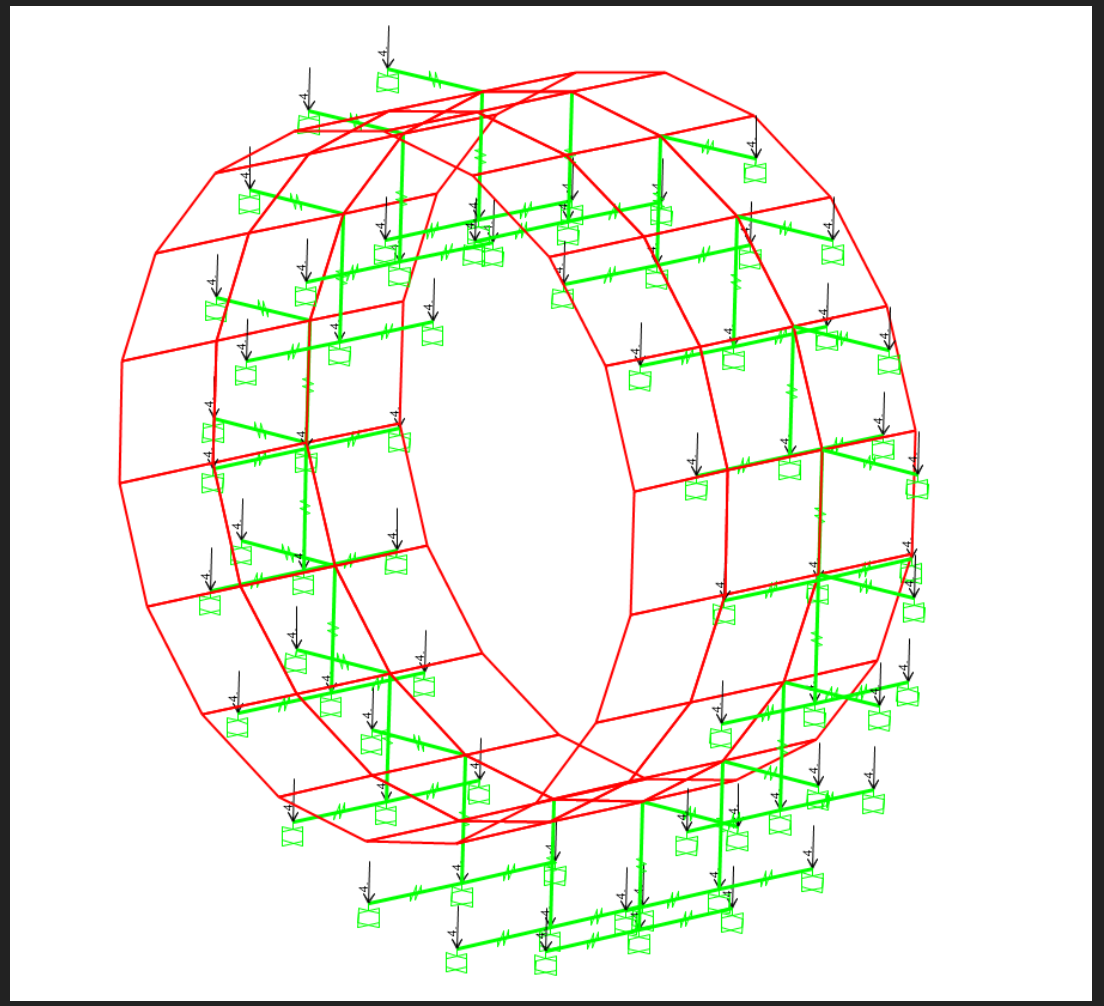
- Dead Load (self-weight)
- Soil Load: vertical soil pressure over pipe
- Fluid Load: weight of water within pipe
- Internal pressure: 200 psi (service conditions)
- No load factors!



Section of Analyzed Pipe with Loads and Boundary Conditions

DISPLACEMENT MAGNITUDES

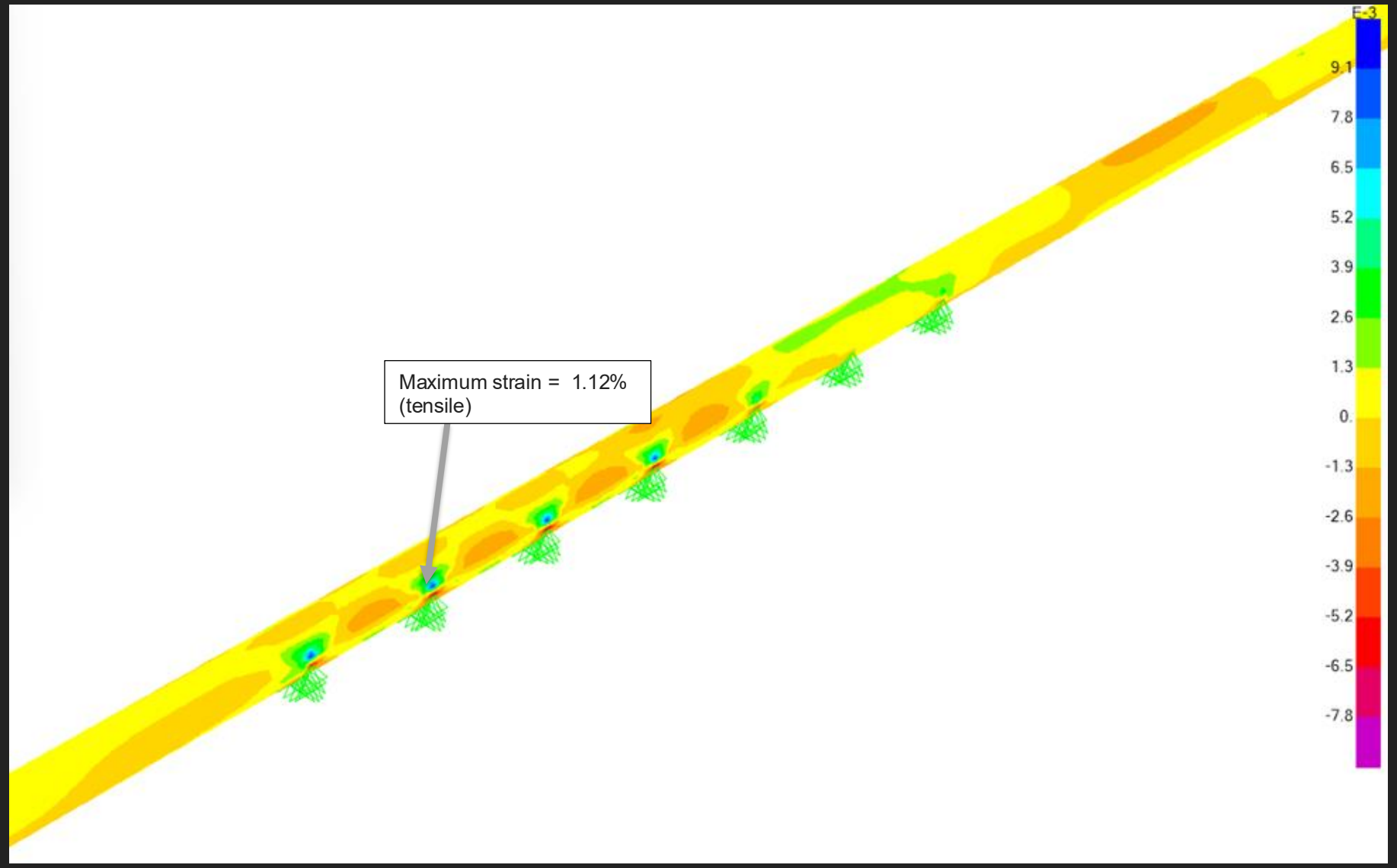
- Displacements based upon geotechnical borings taken by HWA in 2025
    - Magnitudes range from 0.4 inches to over 4 inches
- Problem: liquefaction is highly difficult to predict with accuracy!
- Solution: (3) settlement cases were analyzed in each model
    - Case 1: Uniform Settlement
        - Soil around pipe experiences the same displacement throughout the model
    - Case 2: Differential Settlement, Boring Locations
        - Soil displacements applied to soil nodes in model based on relative location to borings
    - Case 3: Differential Settlements
        - Displacement magnitudes applied to maximize strain at critical pipe locations
        - Example: at CRPL 1 & 3, soil displacements of 4.0 inches applied within Black River Channel, decreasing to 0.4 inches outside channel



SAP2000 Model of CRPL Mesh with Displacements at Soil Nodes

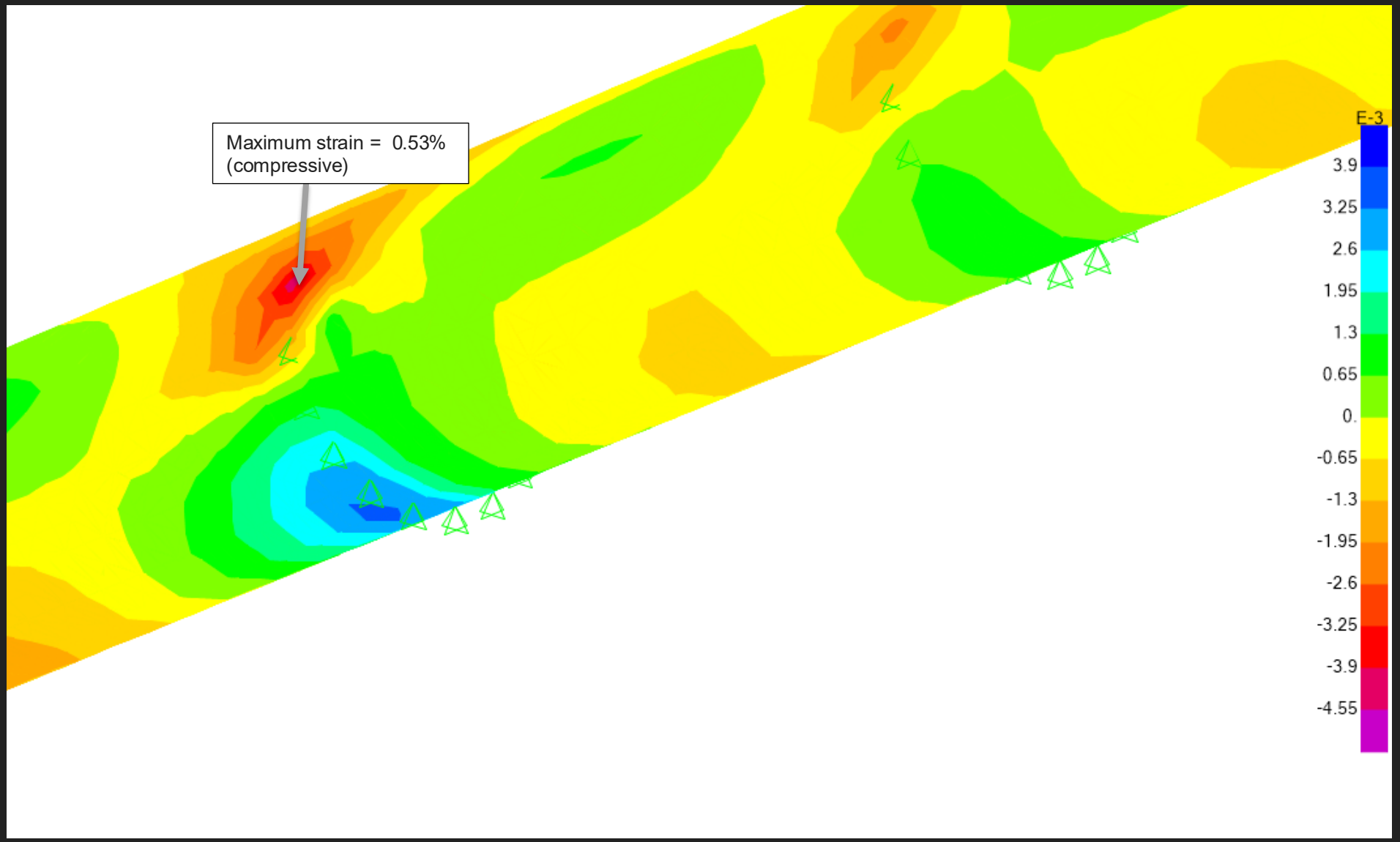

RESULTS

RESULTS



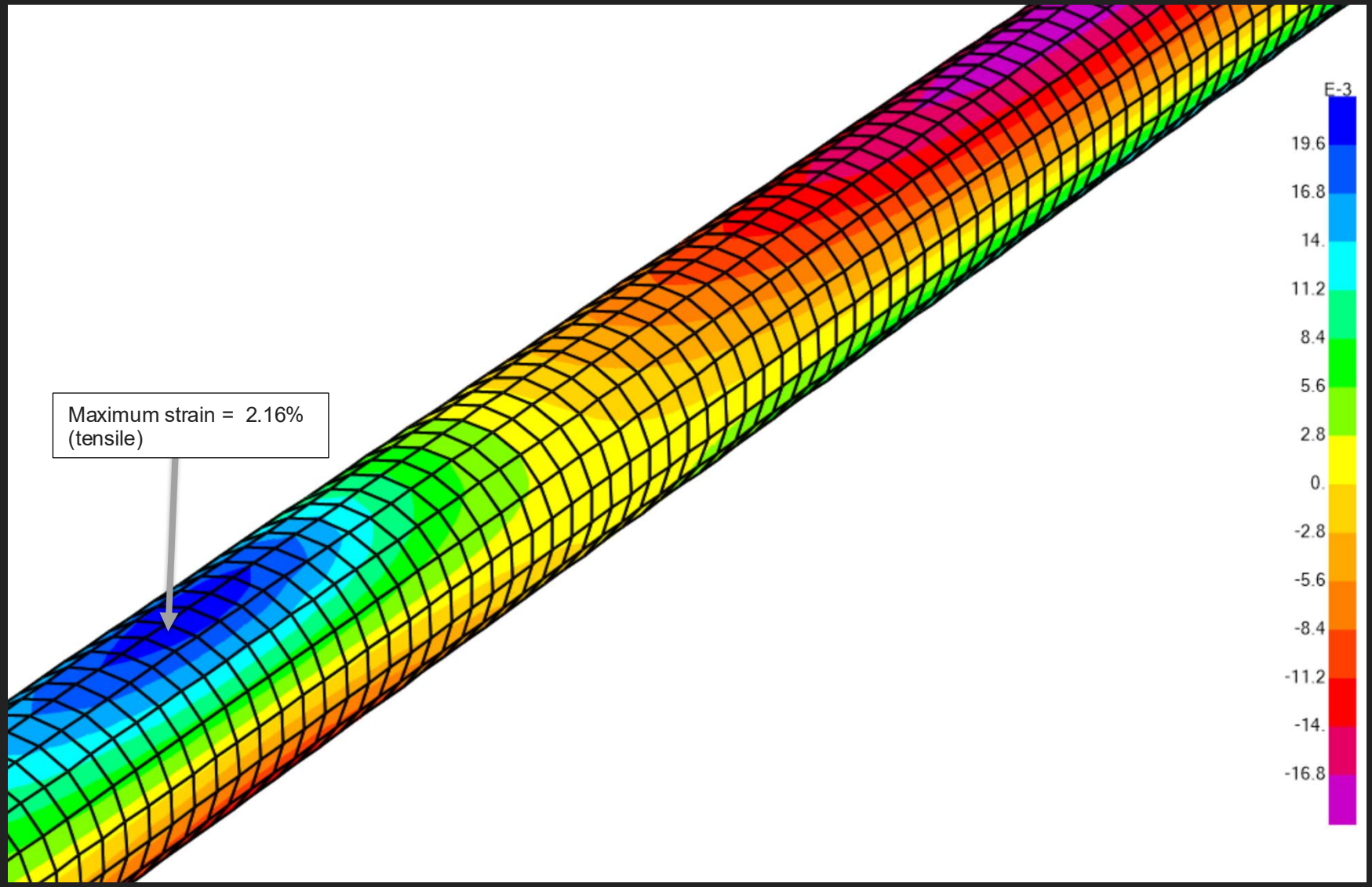
CRPL 1 & 3 Strain Maxima for Settlement Case 1 (values shown x 10^-3)

RESULTS



CRPL 1 & 3 Strain Maxima for Settlement Case 2 (values shown x 10^-3)

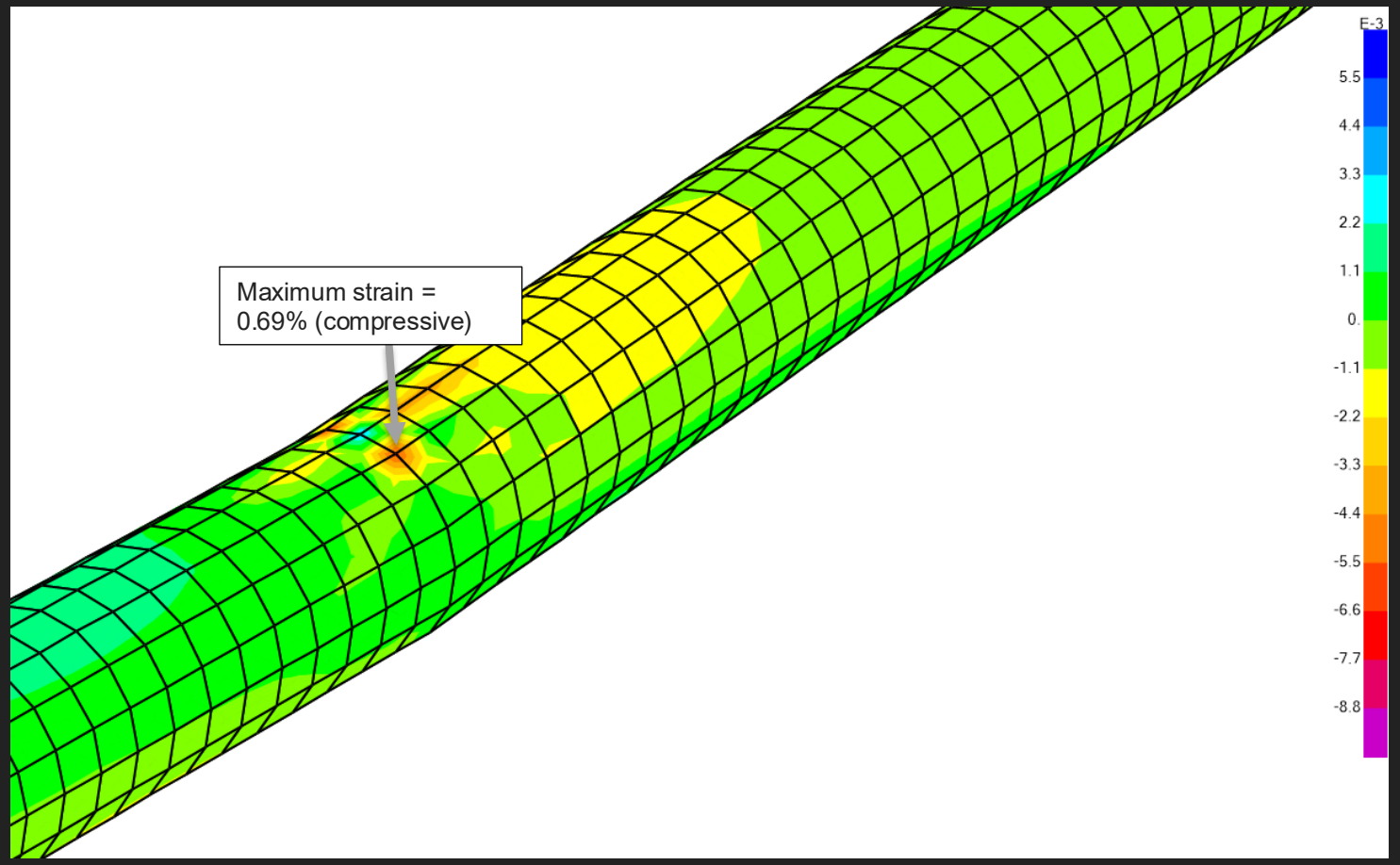
RESULTS



CRPL 1 & 3 Strain Maxima for Settlement Case 3 (values shown x 10^-3)

OBSERVATIONS

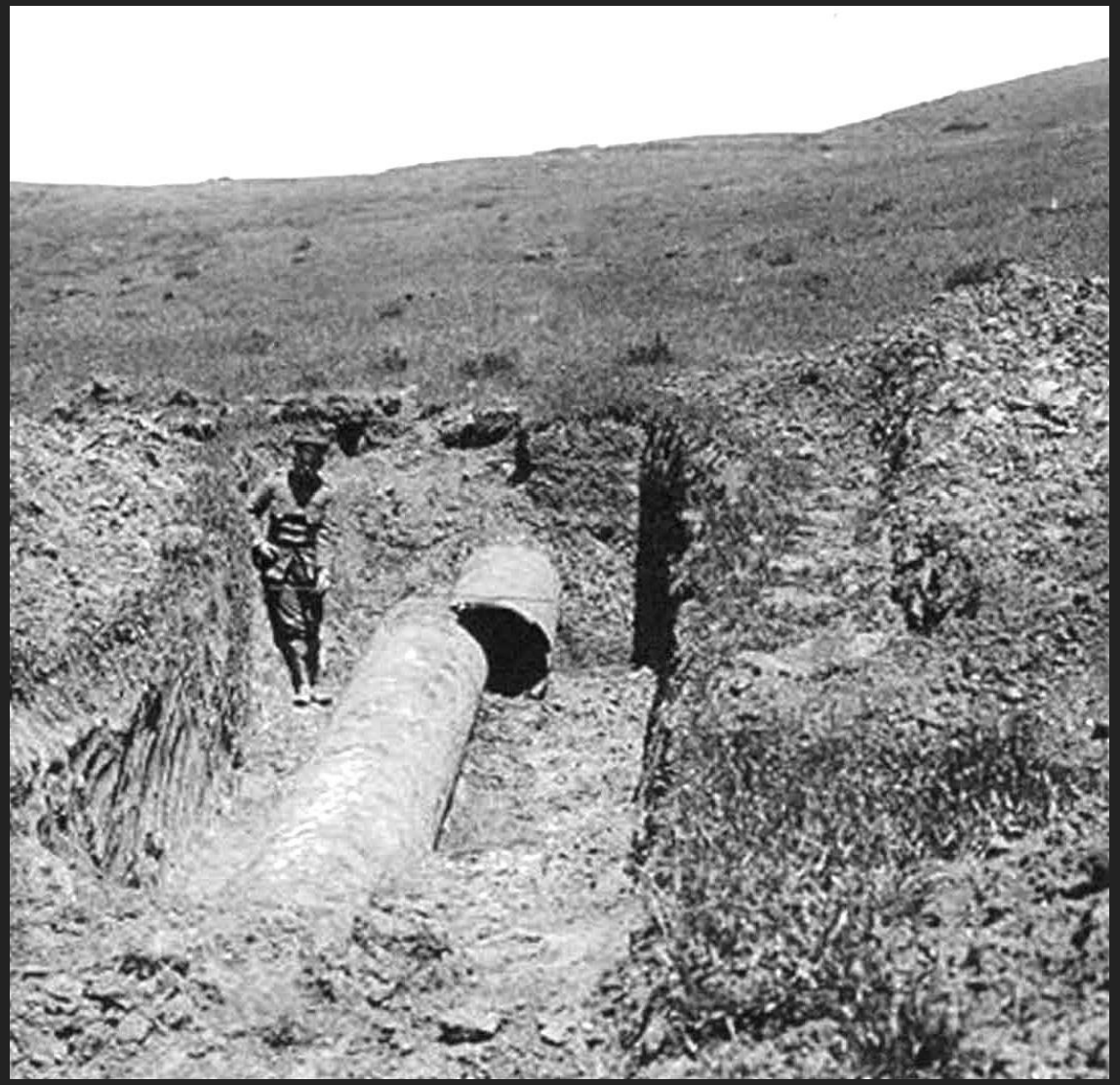
- All three pipelines were found to have locations where the rupture strain of the rivets was exceeded
- Strains were concentrated within the Black River Channel for all three pipes
- For CRPL 1 & 3, highest strains observed for modeling condition where voiding occurs
    - However: strains still exceeded rivet capacity for modeling conditions where piers and pipe remain in contact
    - Reason: forces concentrate at locations of highest stiffness
    - In other words, strains would decrease if the pipes were entirely soil-supported
- Models ONLY account for the vertical post-seismic position of the pipe
    - Models DO NOT account for the actual ground motion during a seismic event
    - Models DO NOT account for horizontal displacements



CRPL 2 Strain Maxima for Settlement Case 3 (values shown x 10^-3)

IMPLICATIONS

- Pacific Northwest is severely under-prepared for a large earthquake
- Even if we can design our treatment and filtration facilities to withstand seismic forces….
- ….there is no guarantee that our older pipelines can still transmit water to affected populations
- Ensuring the seismic resilience of our water transmission lines could be the difference between months and years of recovery.
- This analysis provides a framework for assessing our legacy systems with the modern analytical tools at our disposal



Seismic-Induced Pipeline Failure at Crystal Springs from 1906 San Francisco Earthquake (source: California Department of Conservation)


QUESTIONS?