Lifelines & Utilities: Natural Hazards Research

Joint Academia-Industry NHERI@UC San Diego Workshop
University of California, San Diego
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Lifeline Damage and Assessment for Natural Hazards Outline

- **Lifelines Overview**
- **2023 Turkey Earthquake**
  - **Interdependencies**
  - **Non-structural components**
  - **SSI**
  - **Fault offset - Tunnel**
- **Testing Facilities**
- **Research Progressions**

Lifelines & Utilities

- **Transportation**
  - **Bridges, Tunnels, Roads, airports**
- **Water**
  - **Drinking Water Transmission/Distribution**
  - **Water and Wastewater Treatment Facilities**
  - **Water Towers & Storage**
  - **Dams**
- **Energy**
  - **Electrical Transmission, Distribution, and Substations**
  - **Coal and Gas Powerplants**
  - **Wind/ Solar/ Hydro Dams**
  - **LPG/Industrial Gas Facilities/ Petrol Stations**
  - **Natural Gas Transmission/Distribution**

- **Hospitals**
- **Evacuation Centers**
- **Emergency Service (fire, search/rescue)**
- **Industrial Facilities**
- **University Campuses**

Interdependencies

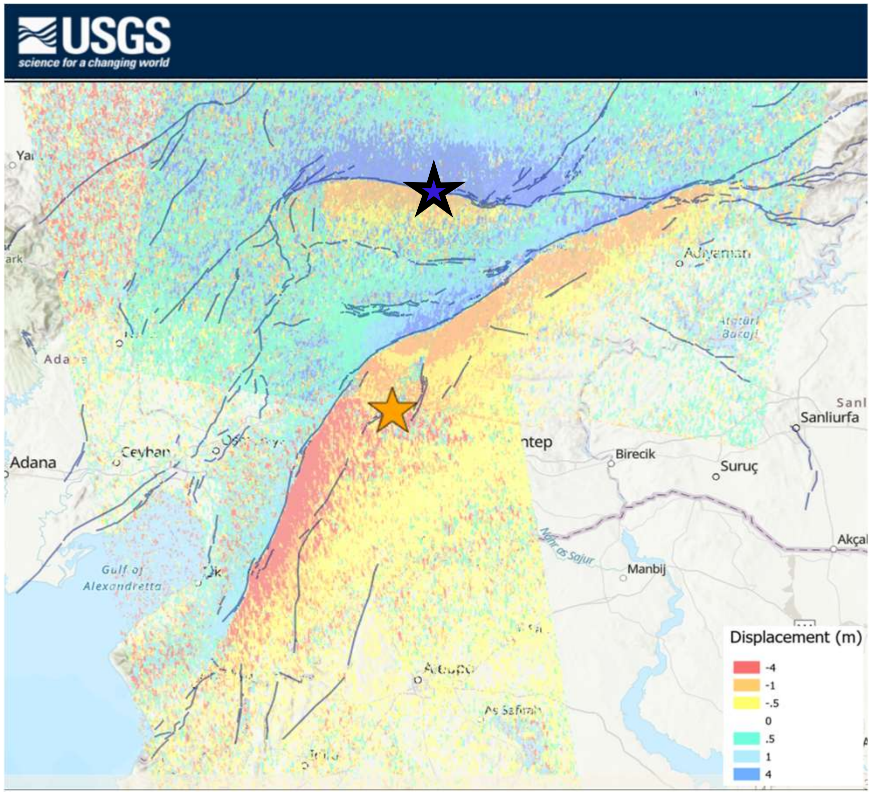
Soil-structure Interaction

Combined Hazards

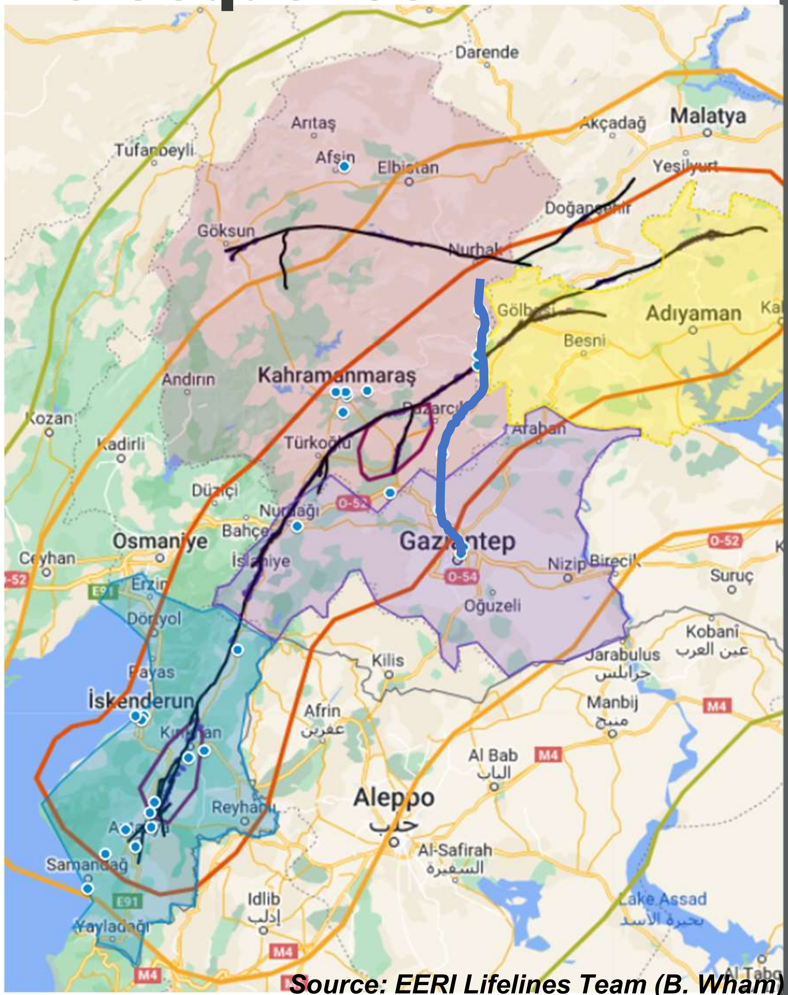
Data/monitoring

Community Impact

2023 Kahramanmaraş, Turkey Earthquake Sequence
Water & Wastewater



- Gaziantep Water and Sewerage Administration (GASKI)
  - 2.15m people
- 3 water sources



Source: EERI Lifelines Team (B. Wham)

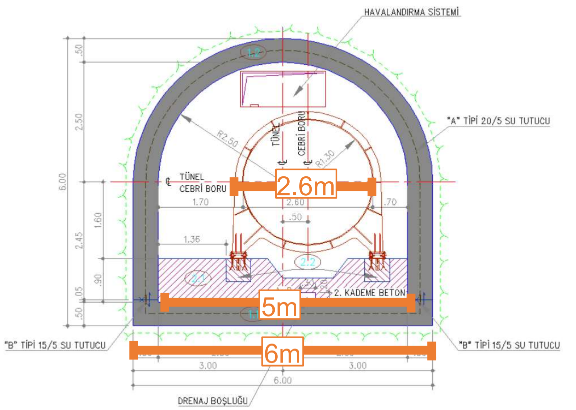
Gaski Water – Düzbağ Water Source (Turkey)

- Constructed starting 2016
- Supported by 21 km of power dist. Line (damaged)
- Water quality issues

- Transmission Pipeline (83 km)
  - 2.6m dia., 2.4mm thick steel (D/t=1080)
  - Air valve damage at 10 locations
  - Vault structure damage
  - Tunnel fault rupture
  - Fault rupture

Gaski Water – Düzbağ Water Source (Turkey)

Source: EERI Lifelines Team (B. Wham)



Source: EERI Lifelines Team (B. Wham)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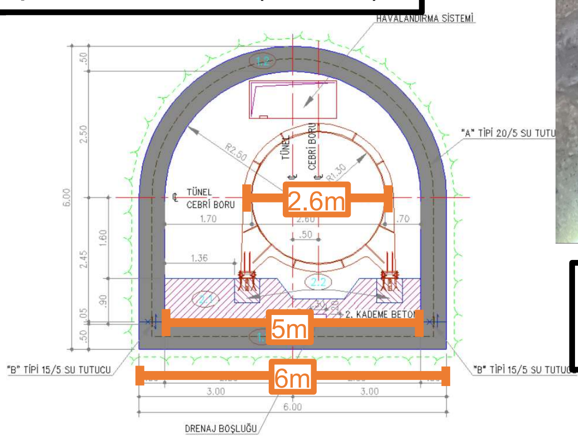
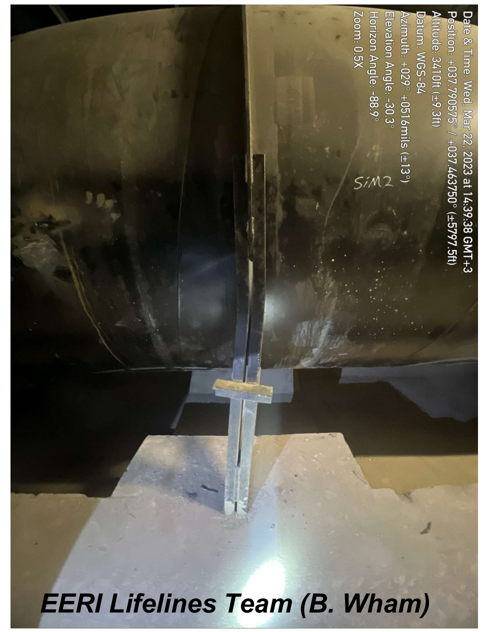
Gaski Water – Düzbağ Water Source (Turkey)

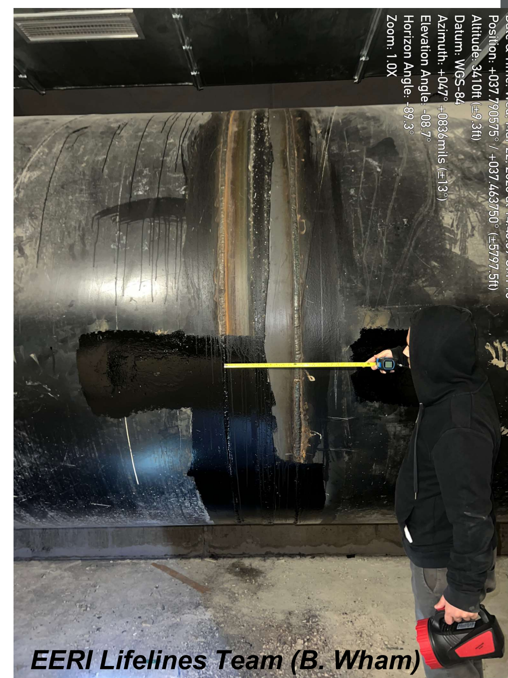
Expansion Joints (± 7 cm)



Residual offsets at pipeline supports



Fixed support damage



30 cm insert welded in at midpoint of tunnel

Gaski Water – Düzbağ Water Source (Turkey)

- ~4.5 m of fault offset
- 1000mm dia. natural gas transmission crossing (~80 deg intersection)

EERI Lifelines Team (B. Wham)

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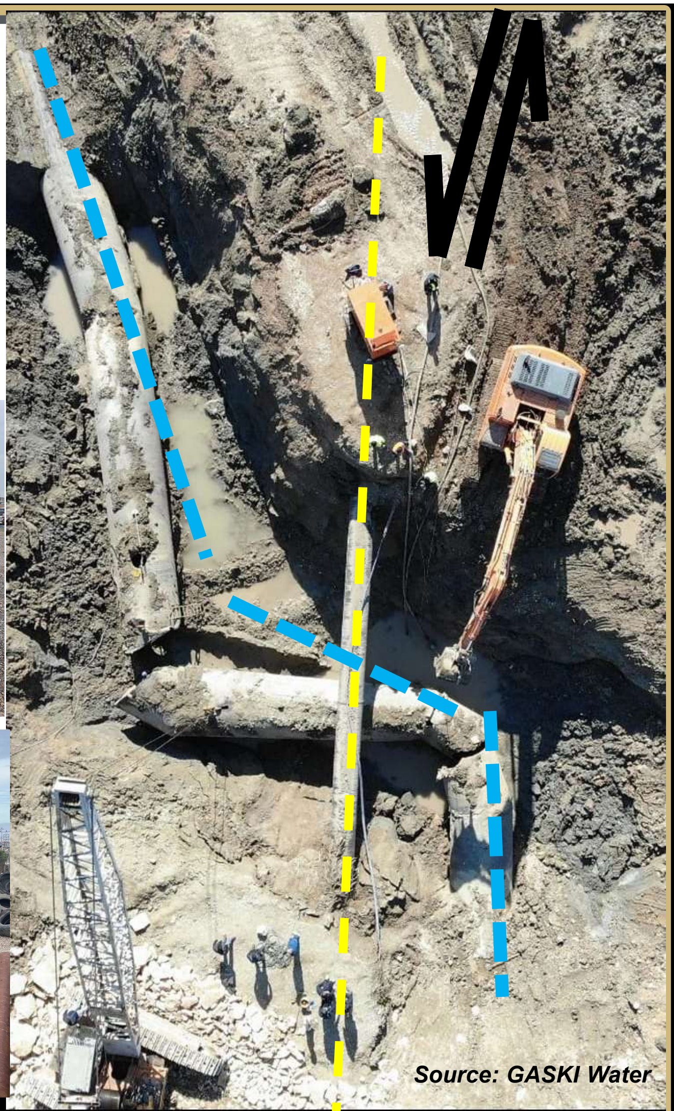
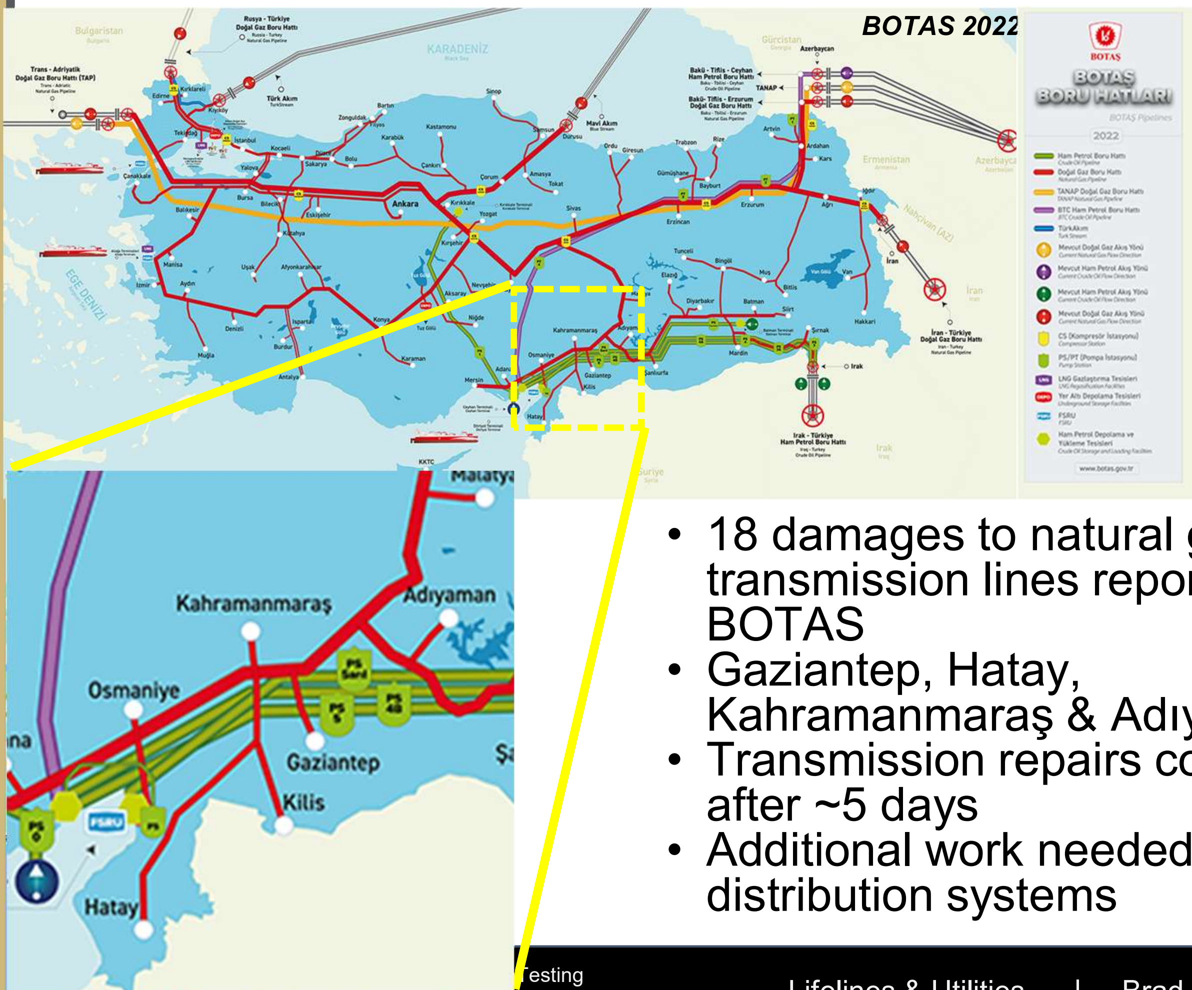


Source: GASKI Water

Energy Pipelines

Natural Gas



- 18 damages to natural gas transmission lines reported by BOTAS
- Gaziantep, Hatay, Kahramanmaraş & Adıyaman
- Transmission repairs completed after ~5 days
- Additional work needed in distribution systems

Source: various

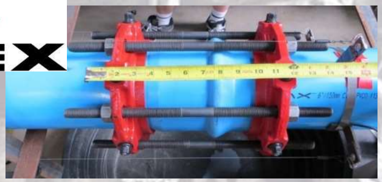
Source: Google Maps

Hazard-Resistant Pipelines

US PIPE

JFE

IPEX

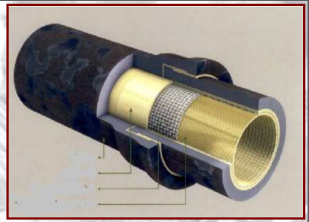


AMERICAN CAST IRON PIPE COMPANY

iPVC PPI SYSTEM

Insituform

starline



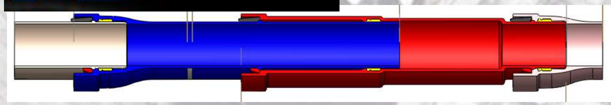
PPM www.progressivepipe.com

Northeast GAS ASSOCIATION NYSEARCH

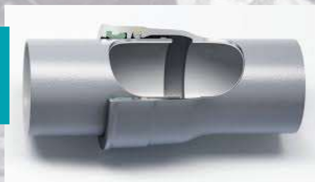
SANEXEN ENVIRONMENTAL SERVICES

ALTRA PROVEN SOLUTIONS

McWANE DUCTILE



Kubota



Recent/Current Testing at CU Boulder

AEGION Stronger. Safer. Infrastructure.

Underground Solutions

EBAA IRON Built Stronger. Lasts Longer. EBAA IRON SALES, INC.

RieberLok

+GF+ GEORG FISCHER PIPING SYSTEMS

S&B TECHNICAL PRODUCTS

JM Eagle DELIVERING GOOD WATER TO YOU

iPVC PPI SYSTEM

HYMAX

EAST BAY MUNICIPAL UTILITY DISTRICT

DENVER WATER

Reports available:
https://www.colorado.edu/center/ciest/ciest-reports
https://lifelines.cee.cornell.edu/

Seismic Design of Water Pipelines: Connection Force Capacity Overview

Outline | References

Demand

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Analytical Model

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Soil-Structure Interaction

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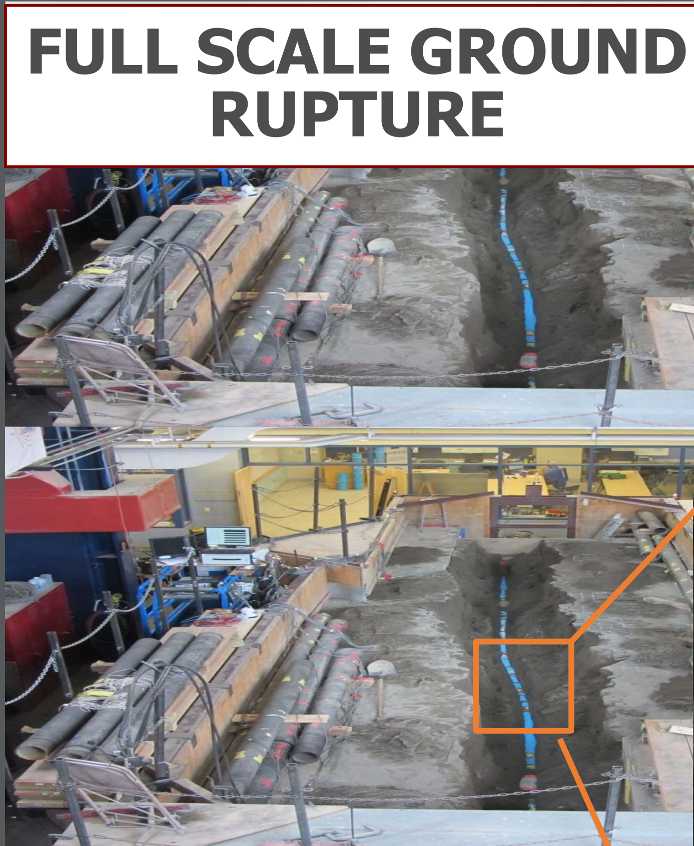
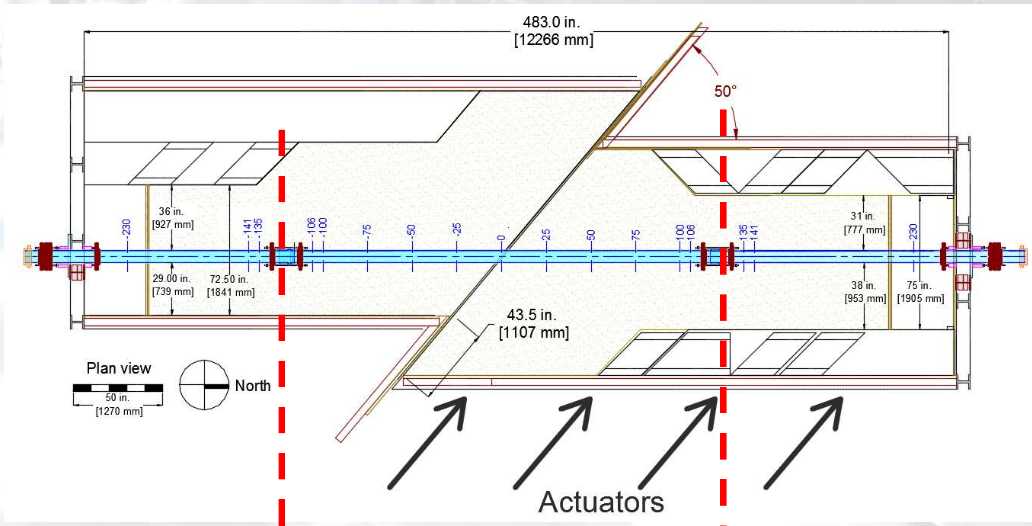
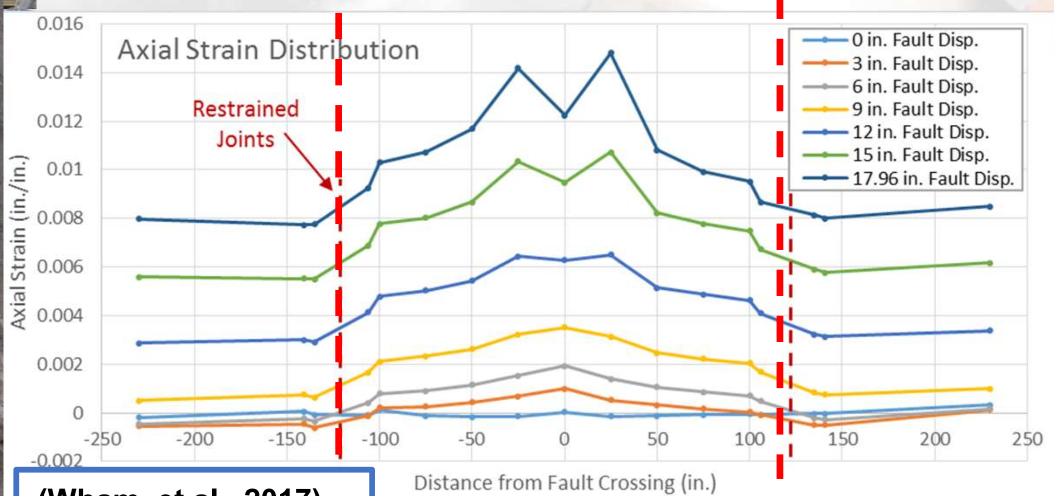
Application

Berty*, N., Wham, B.P., Ihnotic, C.R., Ramos*, J.L., Rose*, H.R. (2022) "Seismic Performance Classification of Hazard Resilient iPVC Pipeline Systems". *Proc., ASCE/UESI Pipelines*, Indianapolis, IN. (*Accepted*).

FULL SCALE GROUND RUPTURE

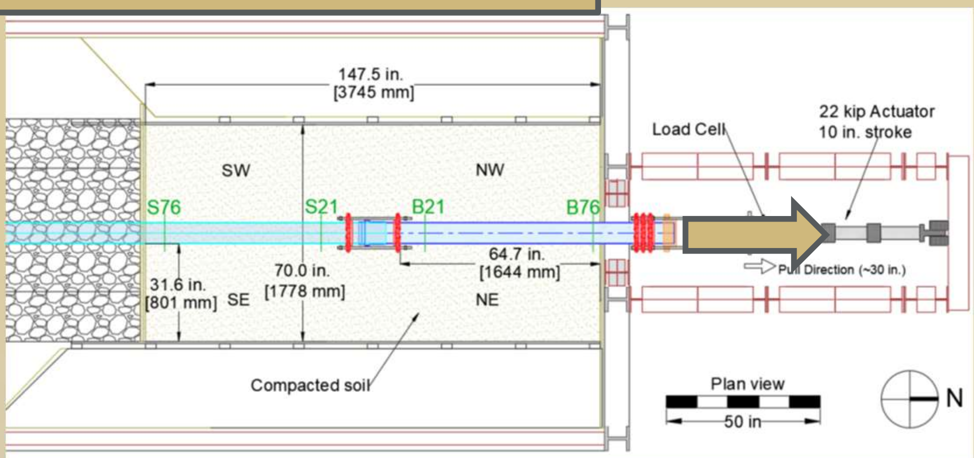




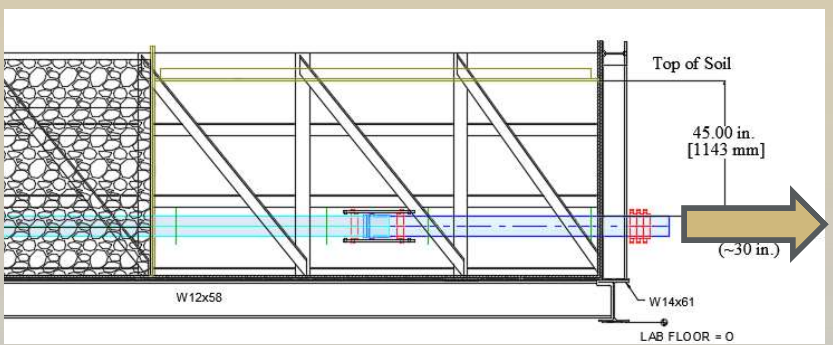


(Wham, et al., 2017)

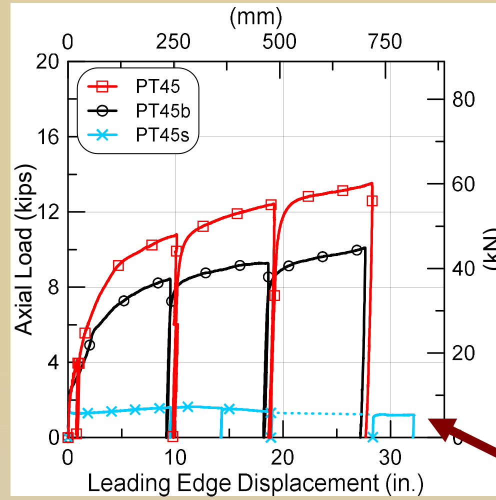
Axial Pull-through Tests



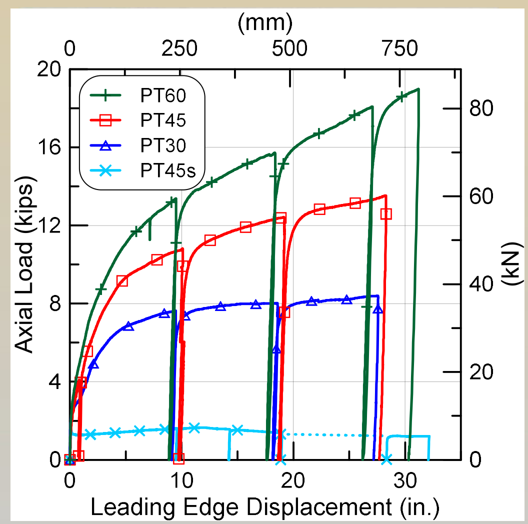
Planview



Profile View

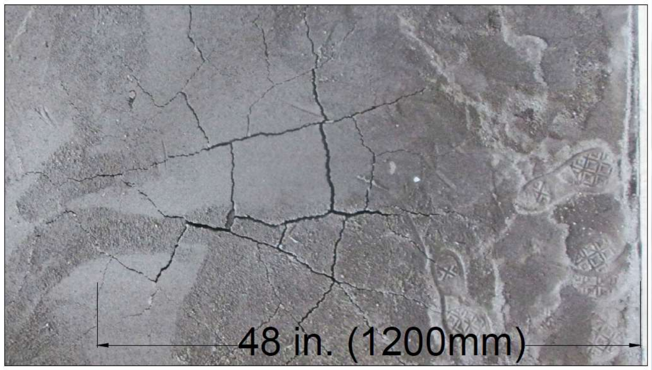


Straight pipe barrel

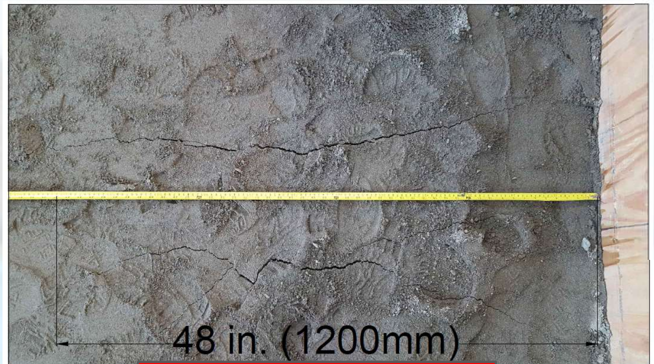


(Wham, et al., 2018)

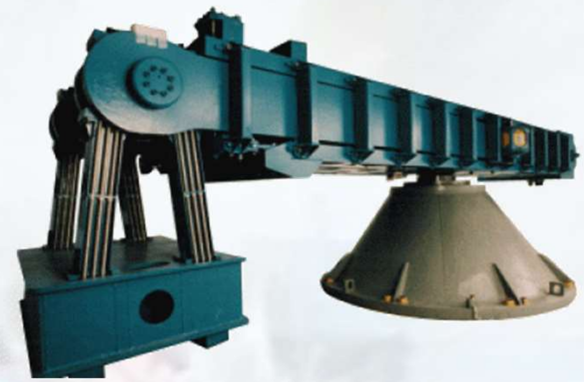
Axial Pull-through Tests

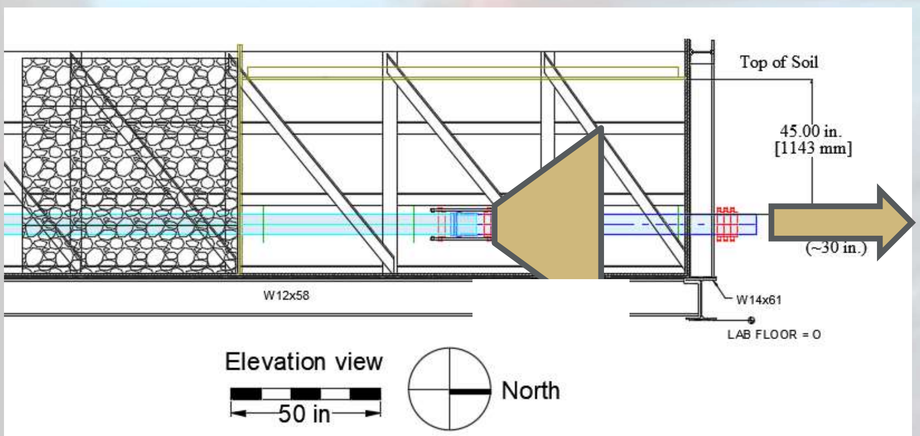


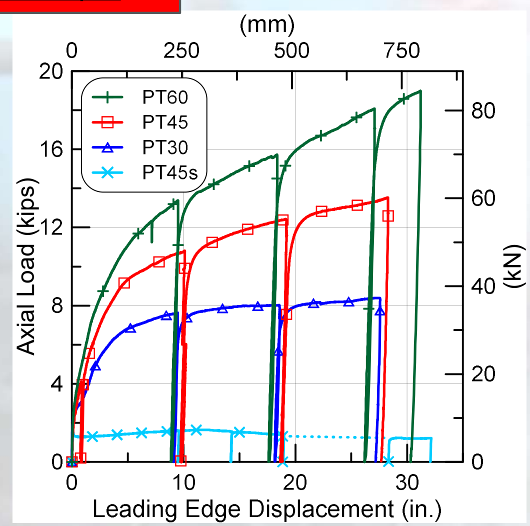
30 in Burial depth



45 in Burial depth







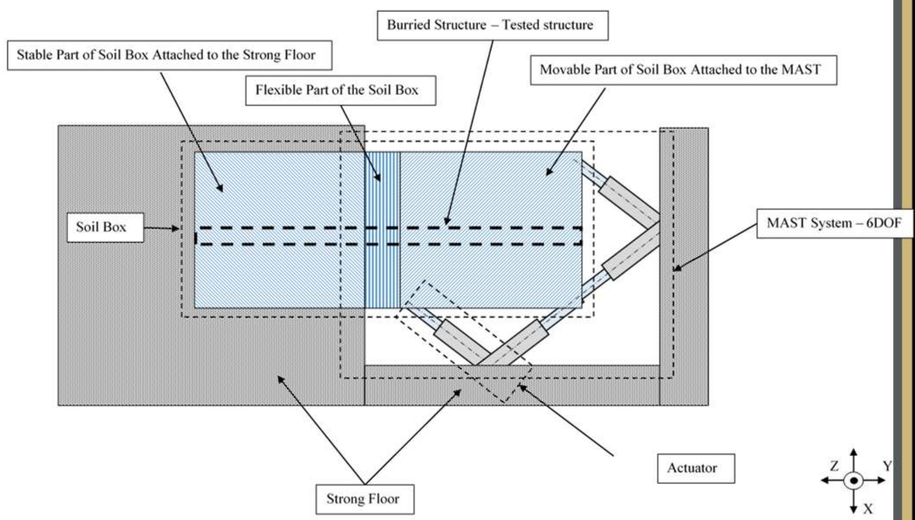
(Wham, et al., 2019)

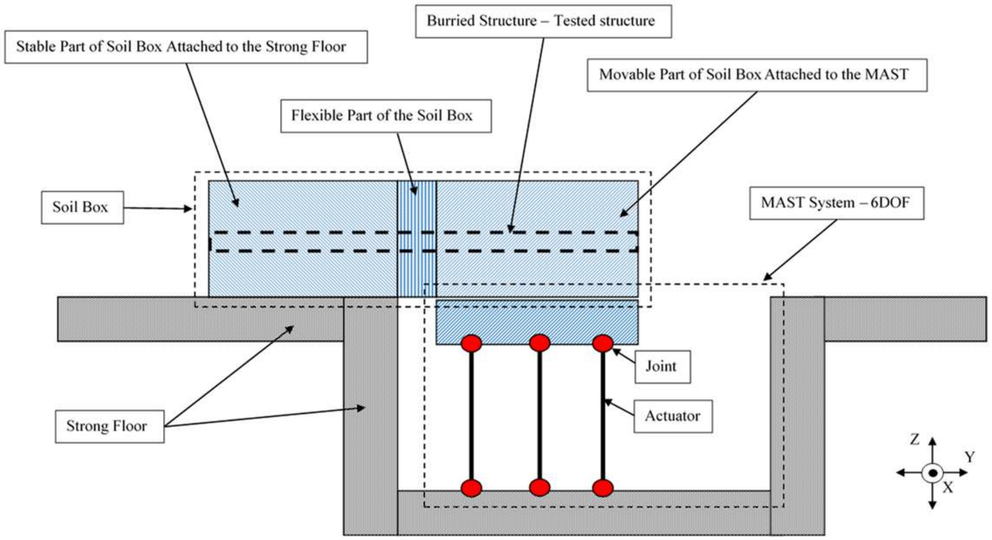
(Rose et al., 2023)

Large-scale Ground Deformation Simulator

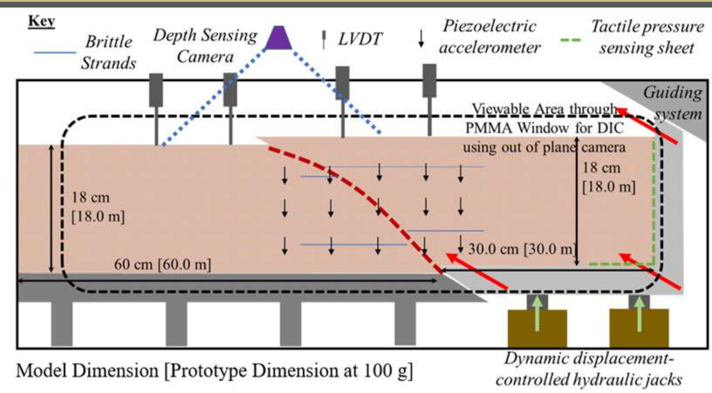
-this is the general big picture idea for a fault rupture simulation capability large enough to test ¼ scale transportation tunnels (5 ft model of 20 ft dia. prototype)

- approx. 4-5 times the size of Cornell's facility and internationally unique capability





Centrifuge Offset



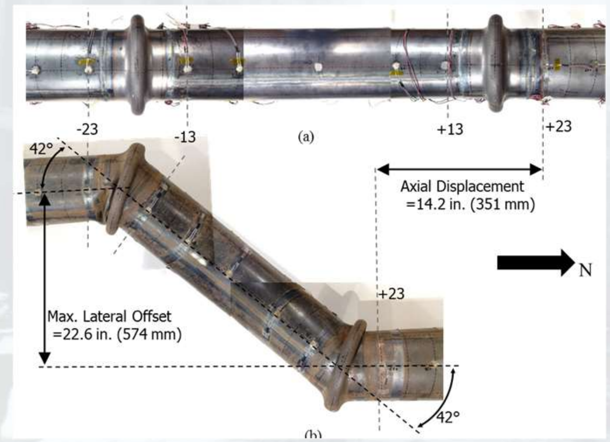
Research Opportunities

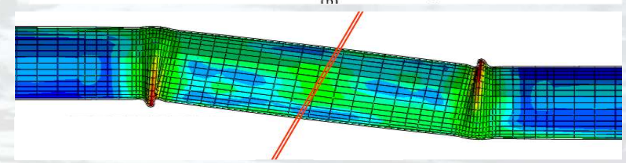
Testing and analysis of pipeline rehabilitation technologies

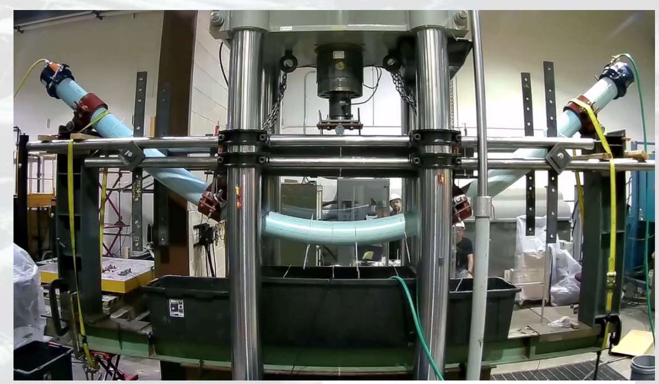
- need for innovative repair techniques for aging pipeline systems is illustrated by DOE/ARPA-E $38m Rapid Encapsulated of Pipelines Avoiding Intensive Replacement (REPAIR) project for the natural gas industry.
- developing a suite of physical tests and numerical models which is assessing structural performance of new products over a 50-year design life, with hazard resilience as a next step.
- The procedures and methods are fueling research advancements that will provide benefits across the utility sectors and serve as a reoccurring research opportunity as systems move through the regulatory process (e.g., PHMSA grants)

Hazard-resilient & Adaptive Lifeline Systems: Design and Assessment

- ASCE MOP on Seismic Design of Water and Wastewater Pipelines: has identified several needed research directions to improve seismic design procedures.
    - need for quantifying the performance of new and existing systems to various levels of ground movement
    - Design tools for Seismic Regions – SSI, geometric features, thrust restraint, service connections, etc.
    - Testing standard for seismic qualification: new ASCE standard committee to develop a testing standard for pipelines in seismic regions. Once accepted, the standard will be incorporated into municipality bid documents
- Experimental evaluation of hazard-resilient pipelines: quantify and validate new hazard-resistant lifeline technologies for use in hazard-prone regions.
    - this research opportunity, in addition to others, lends itself particularly well to hybrid testing

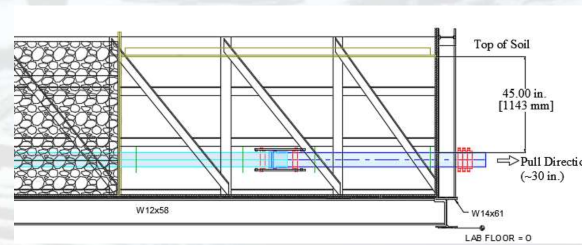






Hazard-resilient & Adaptive Lifeline Systems: Soil-structure interaction

- Hazard-resistant pipeline soil-structure interaction: hazard-resilient pipelines require larger mechanical components along the pipe to accommodate ground deformation.
  - Incorporating couplings/valves/blowoffs/etc in the ground during relative movement between pipe and soil, and significantly increase the demand on the connections and structure
  - experimental assessment to provide inputs to develop simplified analytical estimates for immediate design needs, as well as the basis for 3D continuum modeling approaches to investigate vertical/horizontal bearing capacity and progressive shear plane development



- Statistical assessment of pipeline response and earthquake-induced ground movement magnitude:
  - statistical characterization of expected permanent ground movements associated with seismically-induced landslides and lateral spreading; as well as human-induced deformations
  - Monitoring and data collection before and after events

Thank You!

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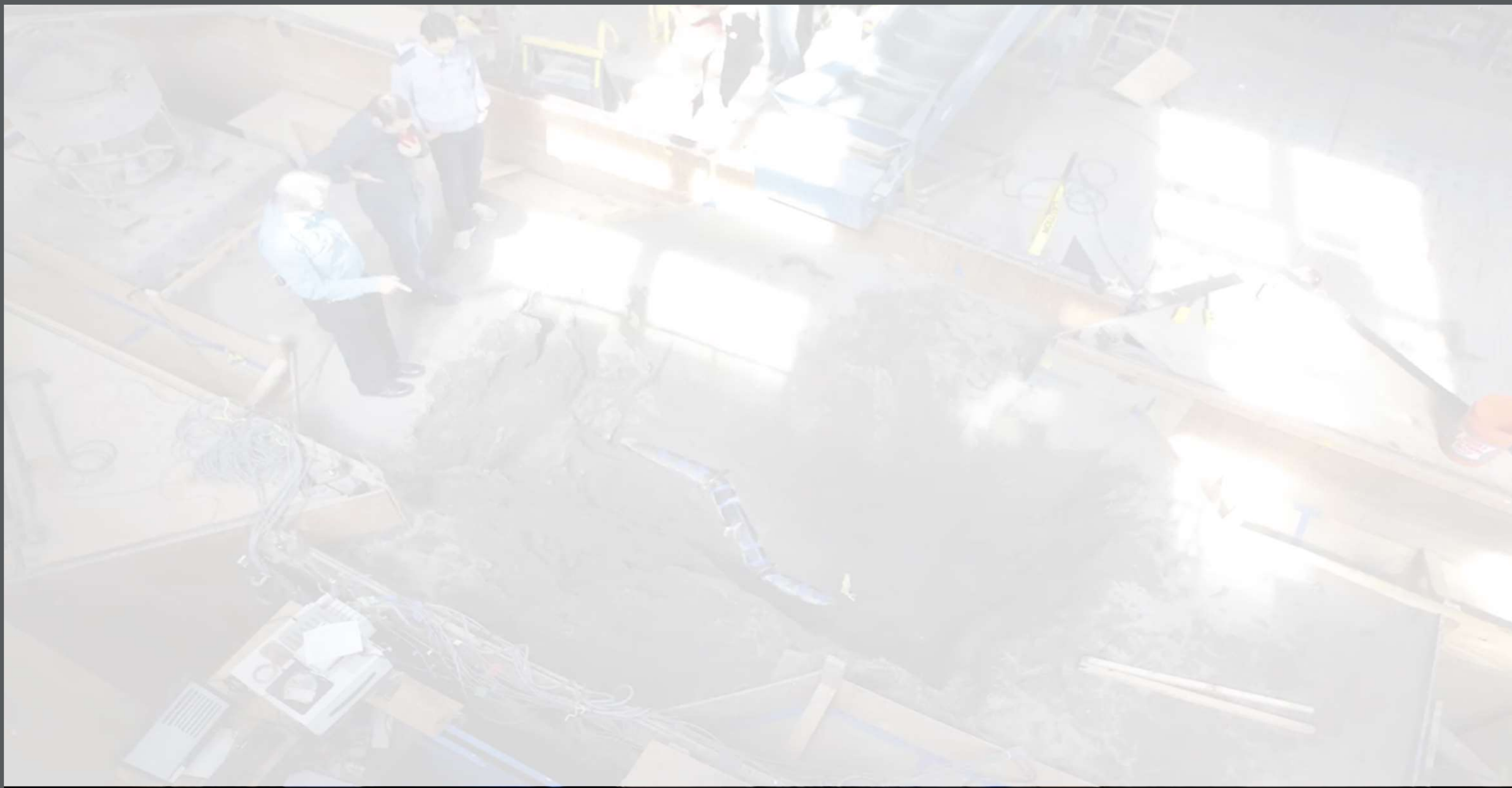

Thank You!

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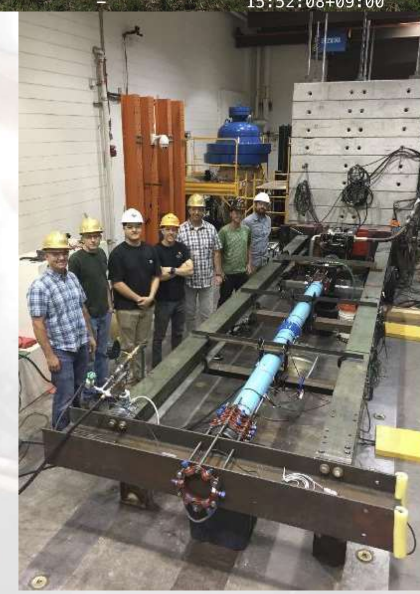
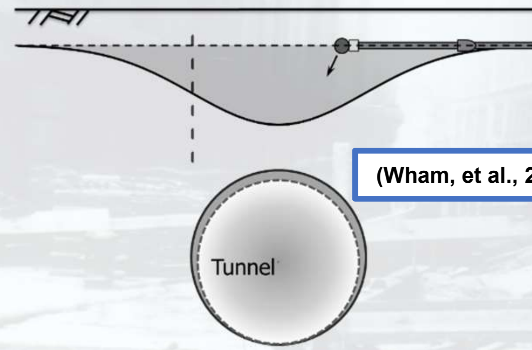


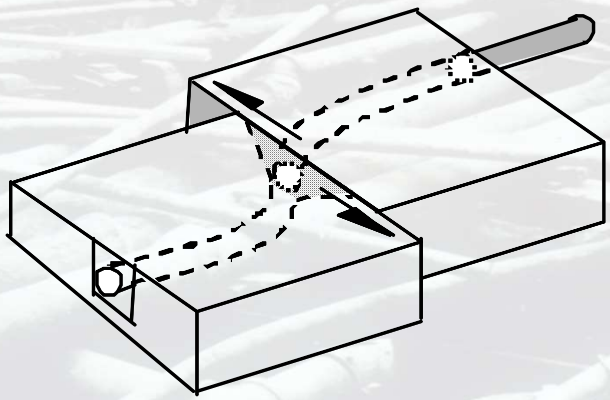
Ground Movement

Sources

- Urban Construction
  - Tunneling
  - Deep excavations
  - Subsidence from dewatering and mining activities
- Flooding/ Extreme Weather
  - Freeze/thaw
  - Scour and undermining
  - Landslides/ground failure
- Expansive soils
- Earthquake
  - Fault rupture
  - Soil liquefaction
  - Lateral spreading
  - Landslides

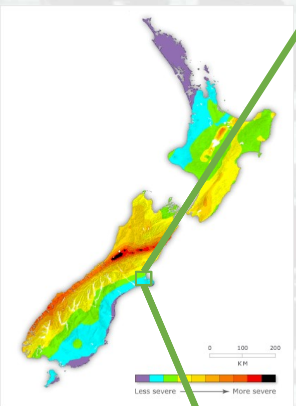


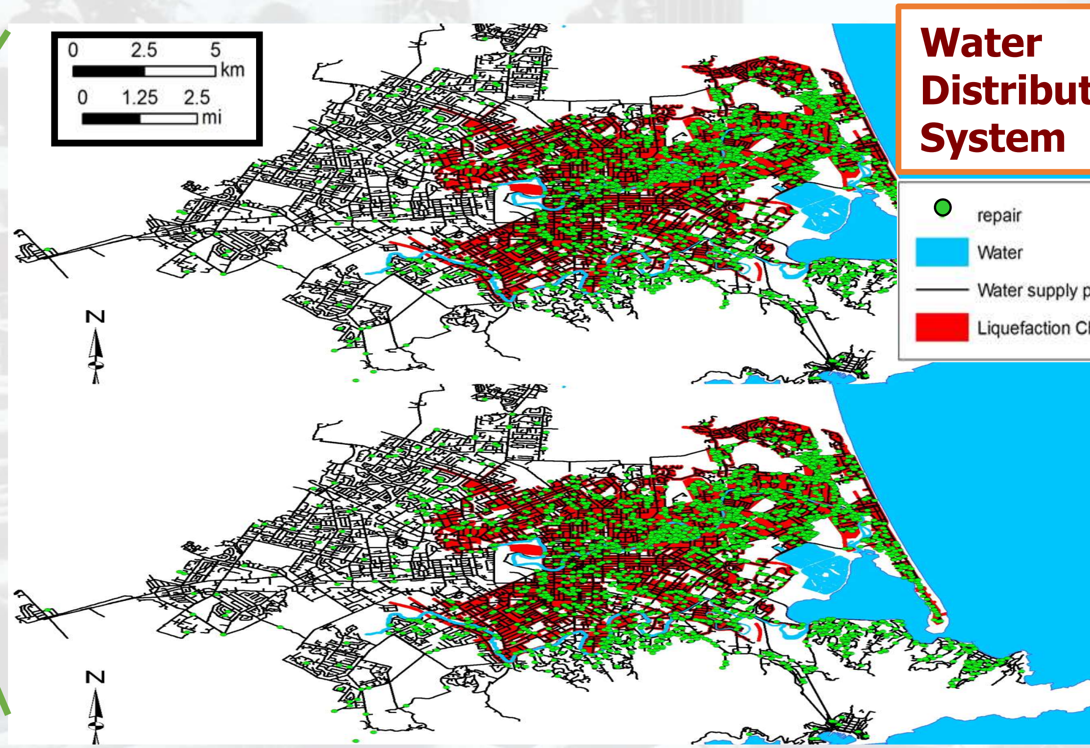
(Wham, et al., 2017)



Seismic Response of Pipeline Systems: Canterbury Earthquake Sequence

Four major seismic events over a year
- Mw = 7.1 (Sep. 2010)
- Mw = 6.2 (Feb. 2011)
- Mw = 6.0 (June 2011)
- Mw = 5.9 (Dec. 2011)





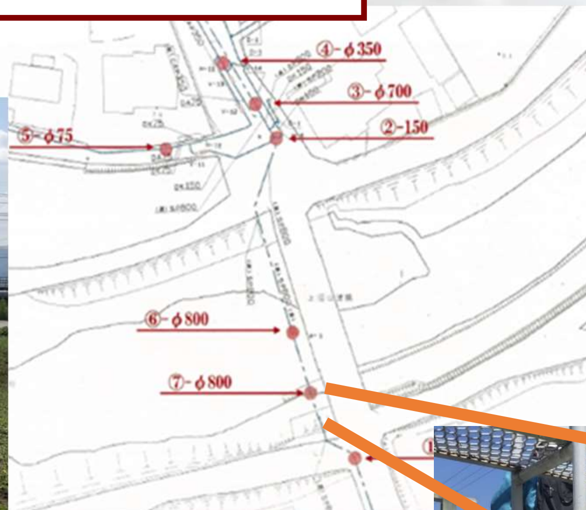
Water Distribution System

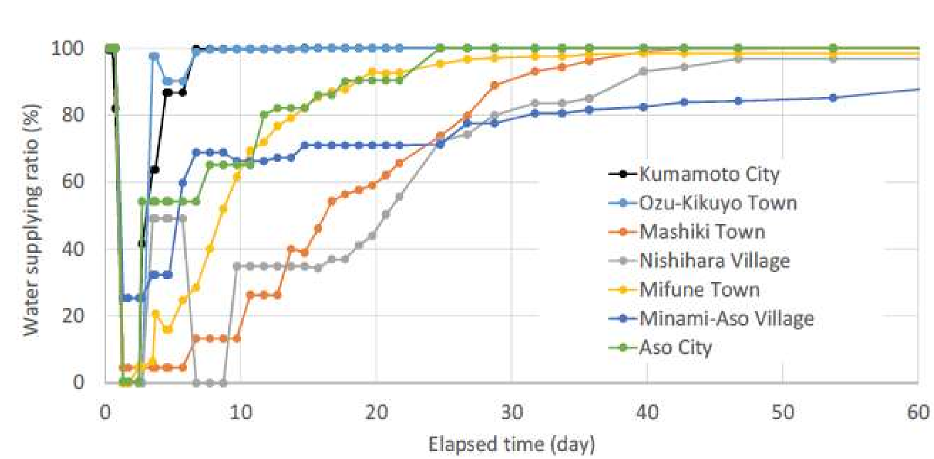
CANTERBURY EARTHQUAKE SEQUENCE

Horizontal Ground Strain: LiDAR Measurements

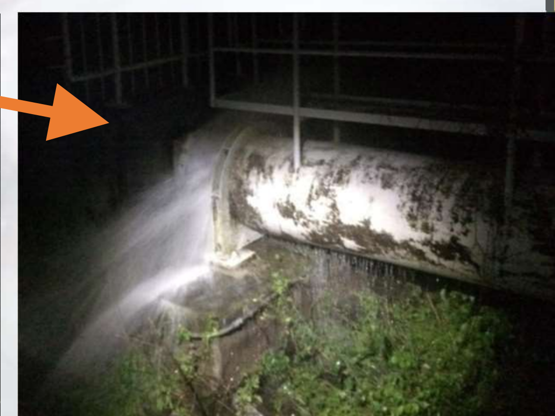
(Jeon et al., 2014)

Kumamoto Earthquakes (April, 2016)

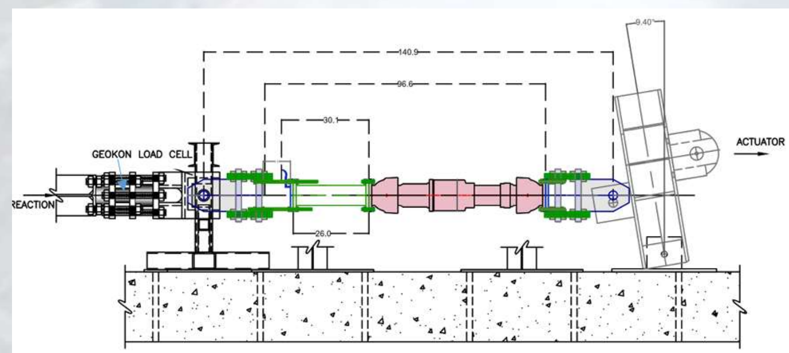




(NOJIMA & MARUYAMA, 2016)

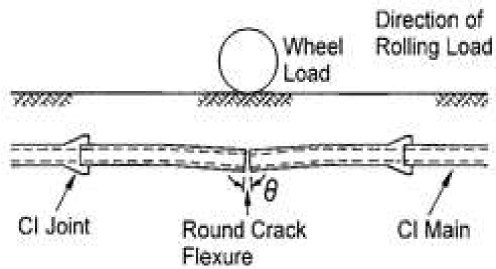
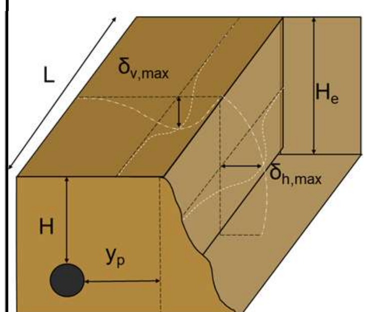


Flextend Evaluation

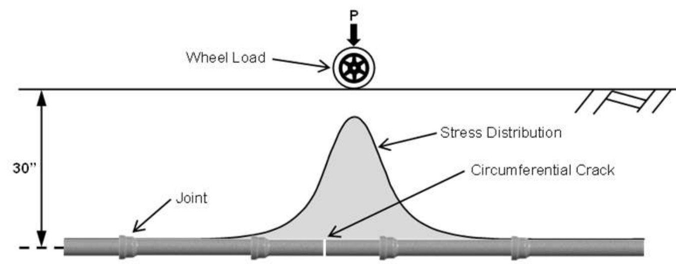


DOE/ARPA-E REPAIR

<u>External Loading Tests</u>: Lateral Deformation

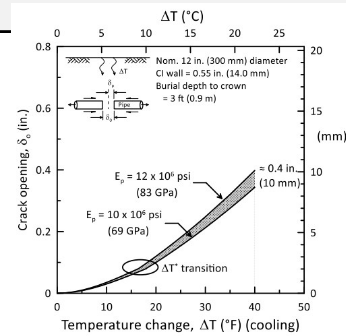
Task	Hardware	Sub-Task	
T4. External load testing (all external loads to be applied to each specimen in series)	T4.1. Four-point bending frames *[POs 1, 2, 3]*	T4.1.1. Vibration/traffic loads (*PO1*) [500,000 cycles] - *For compliant pipe linings spanning weak joints, the imposed vertical displacement was about 0.08 in.*	 Stewart et al., 2015
		T4.1.2. Deflection (lateral deformation) (*PO2*) [Large defl. + 100,000 cy.] - *For compliant pipe linings spanning weak joints, the imposed vertical displacement ~0.20 in*	 Klingaman et al., 2022

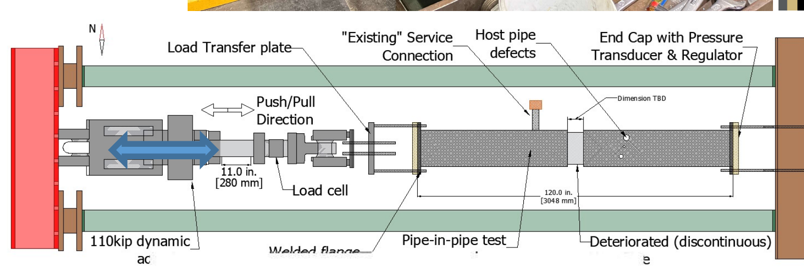
*FM3: cross-sectional ovalization to be monitored/assessed during lateral load application



DOE/ARPA-E REPAIR

External Loading Tests: Axial Deformation

Task	Hardware	Sub-Task	
T4. External load testing (all external loads to be applied to each specimen in series)	T4.2. Axial load frames [*PO4,8*]	T4.2.1. Axial/thermal deformation (*PO4*) [~1 hr per cycle, 50 cycles] - For compliant pipe linings spanning weak joints, the crack opening displacement ~ 0.4 in	 Stewart et al., 2019
		T4.2.2. Bonding/de-bonding at coating/pipe interface (*PO8*) Termination point capacity.	Dixon et al., 2023



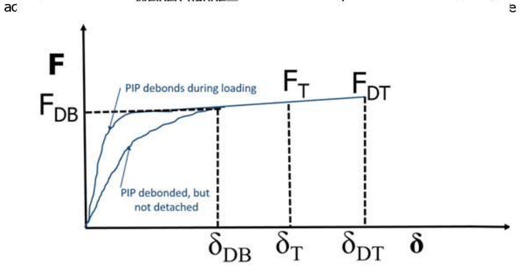


Figure 1. Force vs Displacement for a Relatively Low Modulus PIP

Developing Design/Testing Efforts

ASCE Task Committee: Seismic Design of Water/Wastewater Pipelines

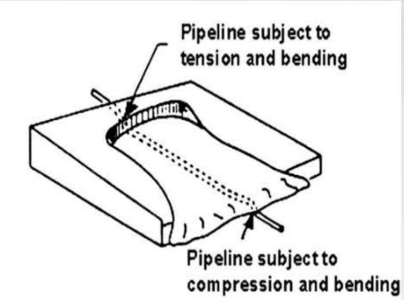
- Collaborative Effort Between:
  - Pipelines Division (PLD) of UESI
  - Infrastructure Resilience Division (IRD) of CTA
- Contributions:
  - Develop MOP (current)
  - Develop White Paper (current)
  - Guidelines on Seismic Testing (underway)
  - **National Standard on Seismic Design (Future)**

MOP Outline

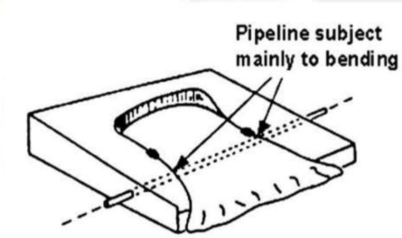
I. General
II. Policy Goals & Measures
III. Seismic Hazards
IV. Seismic Design Guidelines
V. Additional Considerations
VI. Analysis Methods

Testing Standard Outline (STEPS)

I. General Basis
II. Material Characterization
III. Test design
  i. Axial Tension
  ii. Axial Compression
  iii. Transverse
IV. Interpretation & Reporting



Parallel Crossing



Perpendicular Crossing

ASCE MOP: Demand vs. Capacity

ISO 16134: Earthquake- and subsidence-resistant design of ductile iron pipe (Japanese Standard)

Types of joints			K-joint		A-joint		Flange joint†	
Specimen serial number			1	2	1	2	1	2
Items	Seismic classification	Range						
Expansion capacity δ(mm)	S-1	$\delta \geq 1\%L$	√	√				
	S-2	$0.5\%L \leq \delta < 1\%L$						
	S-3	$\delta < 0.5\%L$			√	√	√	
Contraction capacity δ(mm)	S-1	$\delta \geq 1\%L$						
	S-2	$0.5\%L \leq \delta < 1\%L$						
	S-3	$\delta < 0.5\%L$	√	√	√	√		
Slip-out resistance F(kN)	A	$F \geq 3d$						
	B	$1.5d \leq F < 3d$						
	C	$0.75d \leq F < 1.5d$						
	D	$F < 0.75d$	√	√	√	√	√*	√*
Rotation deflection capacity θ(deg)	M-1	$\theta \geq 15°$						
	M-2	$7.5° \leq \theta < 15°$	√	√				
	M-3	$\theta < 7.5°$			√	√	√	√

L: nominal pipe length (mm);
d: nominal pipe diameter (mm);
†: compression strength was too high to be tested to failure;
*: tensile strength at which water pressure was lost.

ISO, 2020

Demand

Davis, et al., 2019

Parameter (+ and -)	Class	Seismic Strain Demand	
Axial Strain (α)	α_A	0.01% up to 0.1%	
	α_B	0.1% up to 0.5%	
	α_C	0.5% up to 1%	
	α_D	1% or greater	
Radius of Curvature (R)/ Deflection Angle (ϕ)	ρ_A	$R_A > 344$m (1130 ft)	$\phi_A/L_g < 0.167$ deg./m (0.051 deg./ft)
	ρ_B	115 m (376 ft) $< R_B \leq 344$m (1130 ft)	$0.167 \leq \phi_B/L_g < 0.5$ deg./m (0.152 deg./ft)
	ρ_C	46 m (150 ft) $< R_C \leq 115$ m (376 ft)	$0.5 \leq \phi_C/L_g < 1.25$ deg./m (0.381 deg./ft)
	ρ_D	$R_D \leq 46$ m (150 ft)	$\phi_D/L_g \geq 1.25$ deg./m (0.381 deg./ft)

Capacity

Performance Class	ISO 16134 (kN)	ISO 16134 (US units) (kips)	ISO DIP F_{CFC} for D = 6 in. (kips)
Φ_A	less than 0.75D	less than 4.3D	< 25.7
Φ_B	0.75D to 1.5D	4.3D to 8.6D	25.7
Φ_C	1.5D to 3D	8.6D to 17.1D	51.4
Φ_D	greater than 3D	greater than 17.1D	102.8

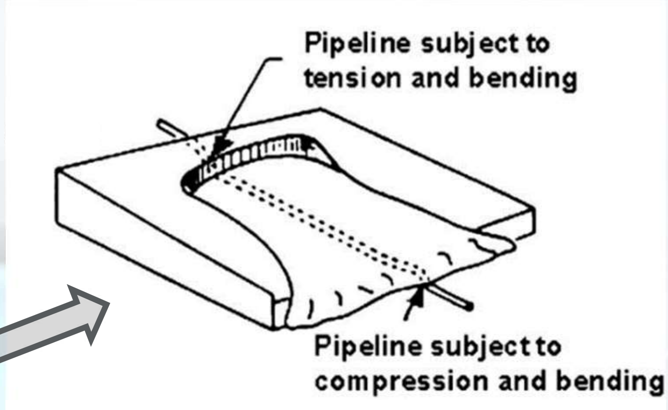
Seismic Design: Ground Deformation Demands

Parameter (+ and -)	Class	Seismic Strain Demand	
Axial Strain (α)	α_A	0.01% up to 0.1%	
	α_B	0.1% up to 0.5%	
	α_C	0.5% up to 1%	
	α_D	1% or greater	
Radius of Curvature (R)/ Deflection Angle (ϕ)	ρ_A	$R_A > 344$m (1130 ft)	$\phi_A/L_g < 0.167$ deg./m (0.051 deg./ft)
	ρ_B	115 m (376 ft) $< R_B \leq 344$m (1130 ft)	$0.167 \leq \phi_B/L_g < 0.5$ deg./m (0.152 deg./ft)
	ρ_C	46 m (150 ft) $< R_C \leq 115$ m (376 ft)	$0.5 \leq \phi_C/L_g < 1.25$ deg./m (0.381 deg./ft)
	ρ_D	$R_D \leq 46$ m (150 ft)	$\phi_D/L_g \geq 1.25$ deg./m (0.381 deg./ft)

Davis et al. 2019

Continuous Pipe (radius of curvature)

Segmented Pipe (deflection angle)



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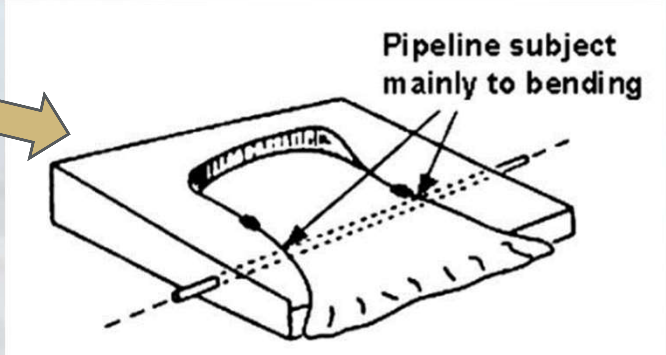

Perpendicular Crossing

Outline | References

Connection Force Capacity Overview

Demand

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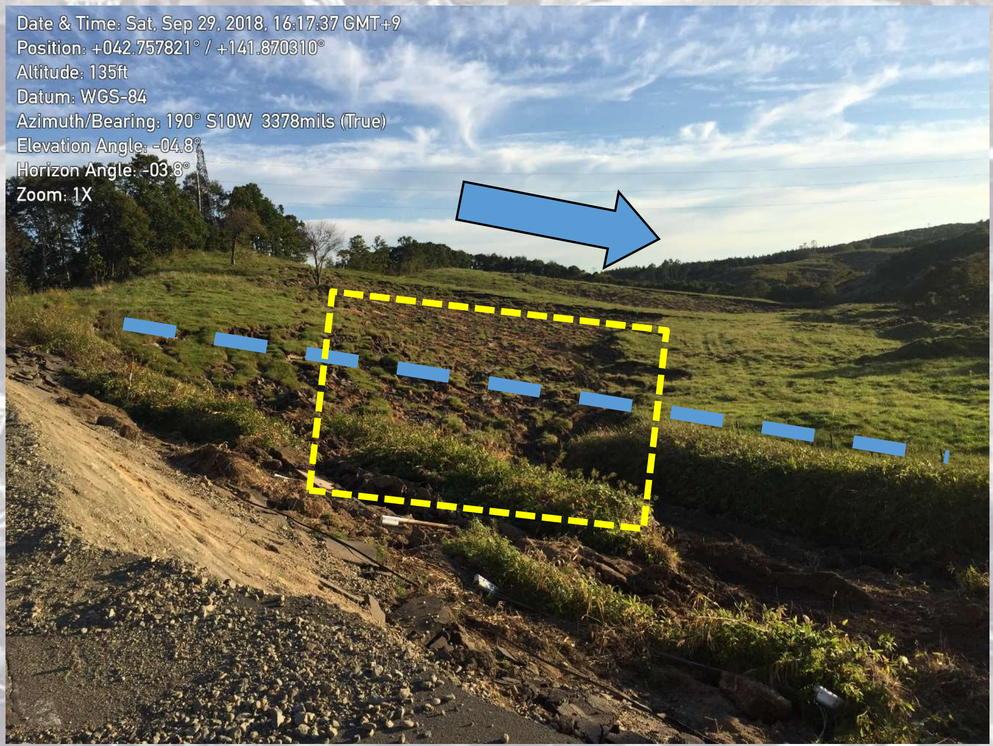
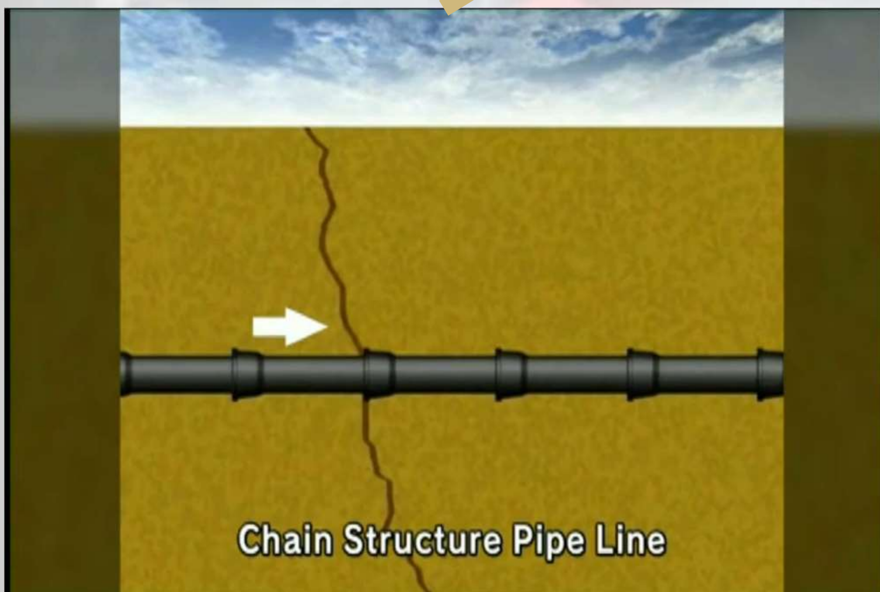
Berty*, N., Wham, B.P., Ihnotic, C.R., Ramos*, J.L., Rose*, H.R. (2022) "Seismic Performance Classification of Hazard Resilient iPVC Pipeline Systems". *Proc., ASCE/UESI Pipelines*, Indianapolis, IN. (*Accepted*).

2018 Hokkaido Earthquake and Typhoon GEER Reconnaissance

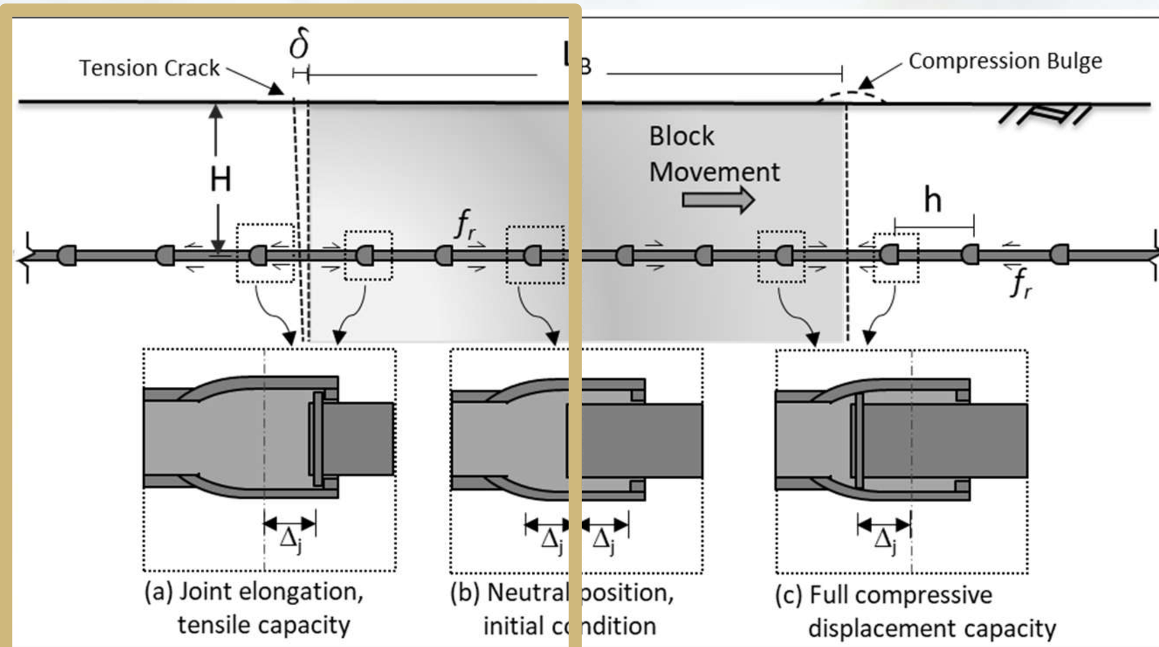


Kayen et al., 2019

Analytical Model:
Longitudinal Ground Movement



Kubota Corp.



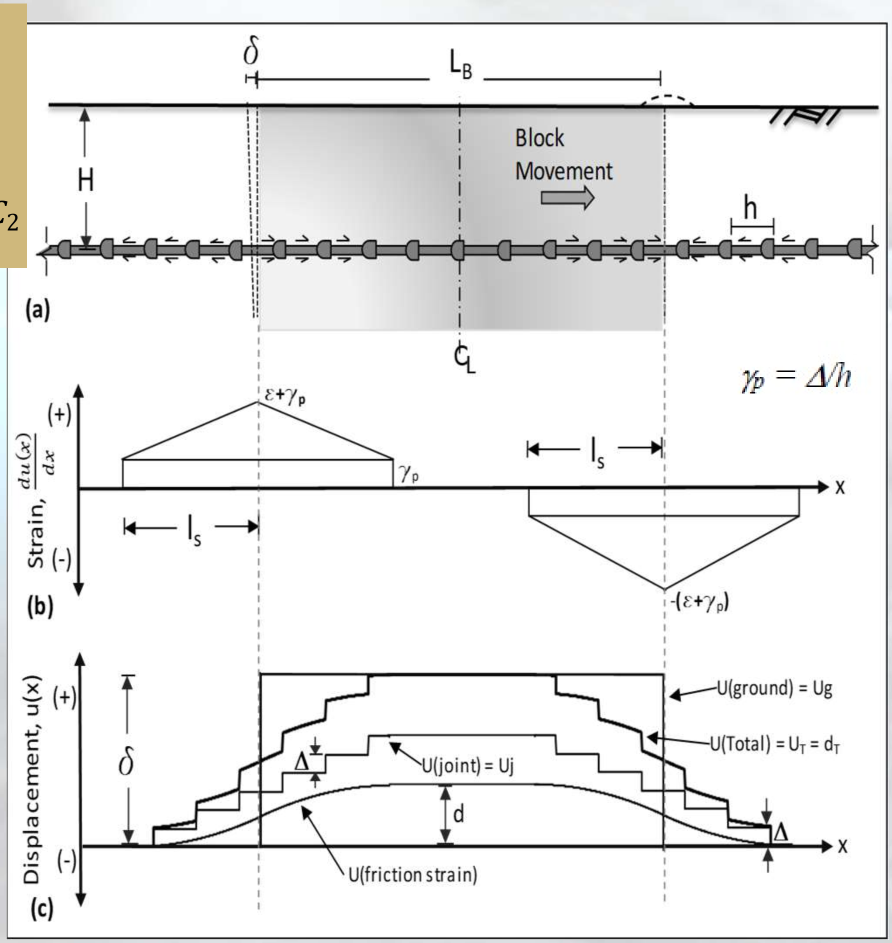
Wham & Davis, 2019

Analytical Model: Longitudinal Ground Movement

$$EA\frac{d^2U_p}{dx^2} = -f_r$$

$$EA\frac{dU_p}{dx} = -f_r x + C_1$$

$$EAU_p = -\frac{1}{2}f_r x^2 + C_1 x + C_2$$



Note: hybrid-segmented solution simplifiess to continuous pipe solution when $\gamma_P = 0$

$l_s = \left|-\gamma_p + \sqrt{\gamma_p^2 + \frac{f_r\delta}{EA}}\right| \frac{EA}{f_r}$ (Eq. 47)

$l_s < L_b/2$?

- Y (Condition I): $\varepsilon = \frac{f_r l_s}{EA}$ (Eq. 36) or $\varepsilon_{max} = -\gamma_p + \sqrt{\gamma_p^2 + \frac{f_r\delta}{EA}}$ (Eq. 48) → $d_T = \delta$ → $d = \frac{f_r l_s^2}{EA}$ (Eq. 37) or $d = \delta - 2\gamma_p l_s$ (Eq. 49)
- N* (Condition II): $l_s = L_b/2$ → $\varepsilon = \frac{f_r l_s}{EA} = \frac{f_r L_b}{2EA}$ (Eq. 55) → $d = \frac{f_r l_s^2}{EA} = \frac{f_r L_b^2}{4EA}$ (Eq. 37) → $d_T = \frac{f_r L_b^2}{4EA} + L_b\gamma_p$ (Eq. 52)

*Requires $\delta \geq \frac{f_r L_b^2}{4EA} + L_b\gamma_p$ (Eq. 51)

$$F_{max} = f_r l_s = \left[-\gamma_p + \sqrt{\gamma_p^2 + \frac{f_r\delta}{EA}}\right] EA$$

Wham & Davis, 2019

Influence by and consistent with O'Rourke & Nordberg, 1992 and O'Rourke & Lui, 2012

Connection Force Capacity Overview

Outline | References

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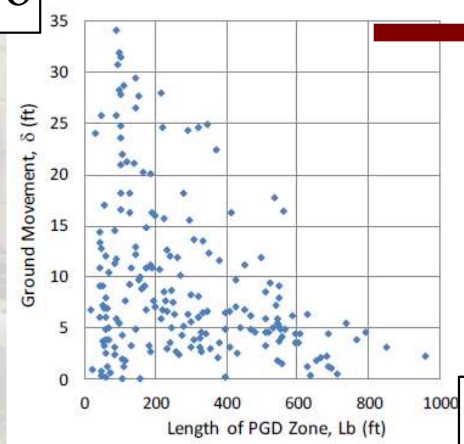
Axial Connection Force Capacity (CFC)

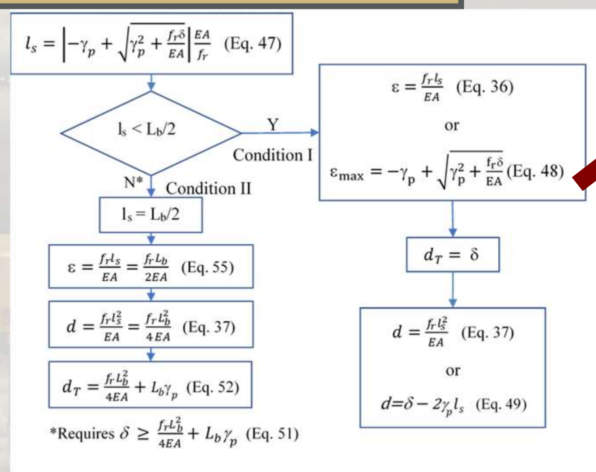
- Equip with:
  - An analytical model (Wham & Davis, 2019)
  - representative frictional resistance (Wham et al., 2019)
  - Statistical representation of ground movement patterns (Bartlett & Youd, 1992)
  - Properties/characteristics of a pipe system known to perform well in past Eqs (Davis, et al, 2019)
- We can assess expected performance of known system – determine expected Survivor Rate

Bartlett and Youd (1992) data:
197 total data points

δ



L_B



$$F_{max} = f_r l_s = \left[-\gamma_p + \sqrt{\gamma_p^2 + \frac{f_r\delta}{EA}}\right]EA$$

Axial Connection Force Capacity Required for Buried Pipelines Subjected to Seismic Permanent Ground Displacement

Brad P. Wham, Ph.D., A.M.ASCE[1], Craig A. Davis, Ph.D., P.E., G.E., M.ASCE[2] & Sri Rajah, Ph.D., P.E., G.E., S.E., P.Eng., F.ASCE[3]

# failures	# survivors	Survior rate
77	120	**60.9%**

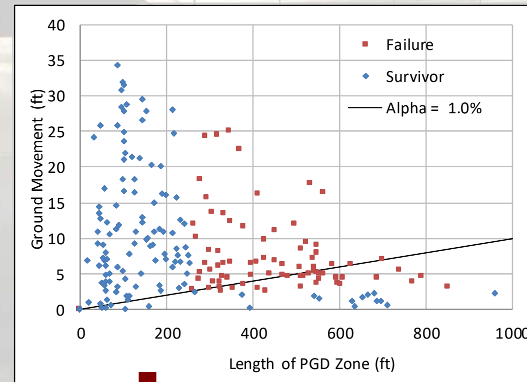
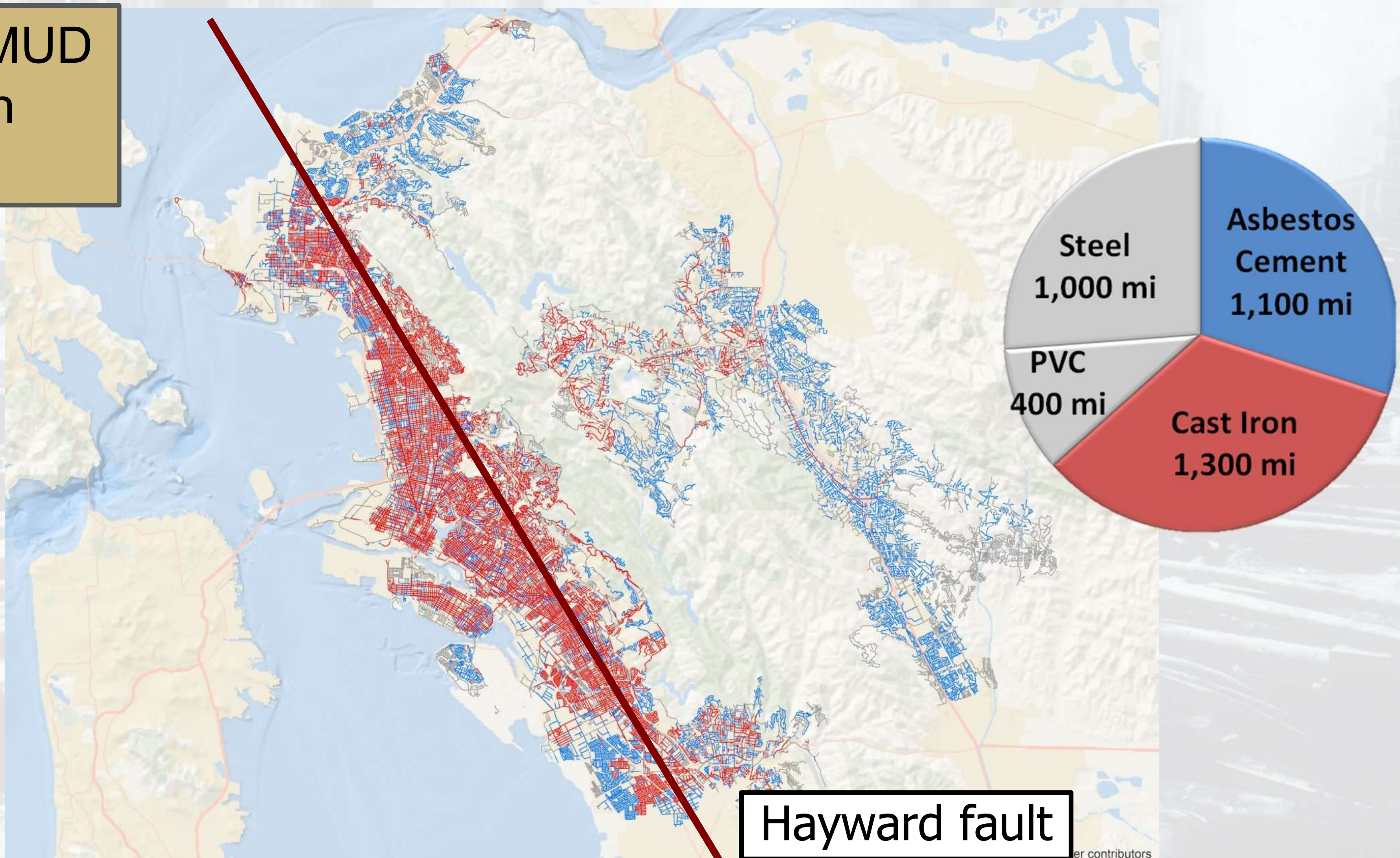


Table 3. Example K_1 values for individual pipe systems

Pipe System	CFC factor, K_1
ISO 16134 ERDIP (γ_p = 1%)	1.0
PVCO with 1559 restrained slip joints (γ_p = 1%)	0.71
Other pipe systems …	TBD

East Bay MUD Distribution System



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Application

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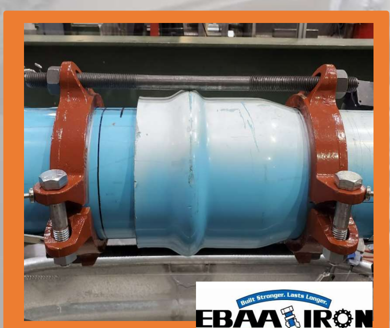
Example Testing Overview

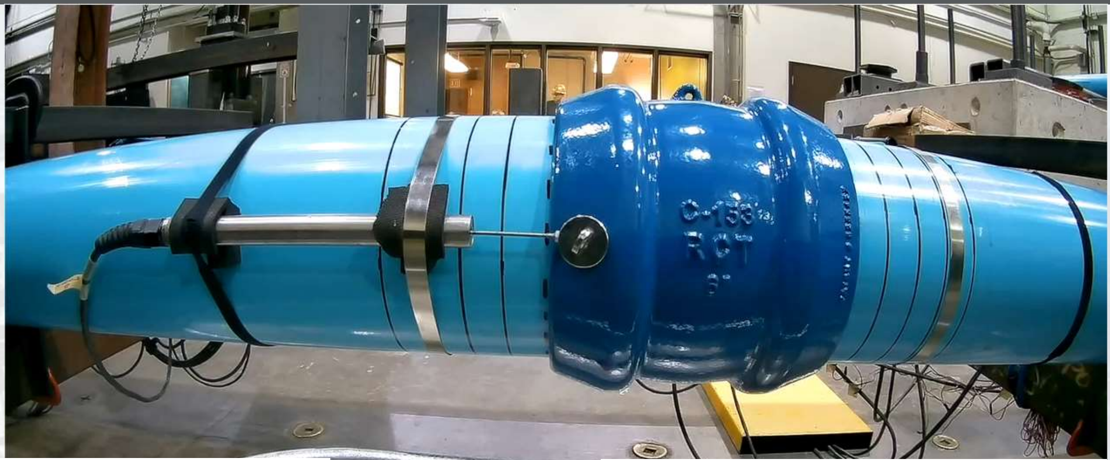
- Twenty Large Scale Tests
- AWWA C900 iPVC Pipe
- 6 in. (150 mm) Nominal Diameter Pipe
- Pressure Class 305 psi – DR14
- 5 – Coupling Systems

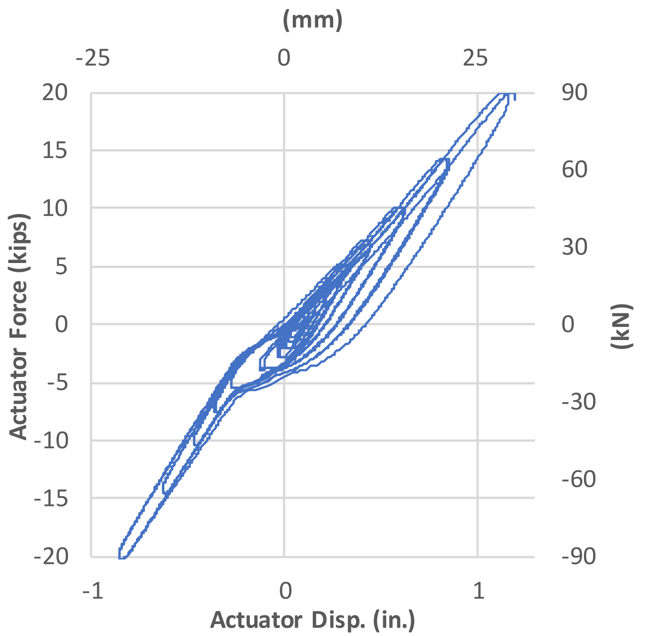
Test # (CIEST)	Test Type	Pipe-Connection	Pipe-Material	Average Pressure Psi	(kPa)
PT02	Axial-Tension	RCT	iPVC-DR14	59	(407)
PT27	Axial-Tension	TurnerLok	iPVC-DR14	61	(421)
PT30	Axial-Tension	EBAA C1900	iPVC-DR14	63	(434)
PT33	Axial-Tension	Lokx	iPVC-DR14	64	(441)
PT38	Axial-Tension	Hymax Grip	iPVC-DR14	64	(441)
PC37	Axial-Compression	RCT	iPVC-DR14	64	(441)
PC28	Axial-Compression	TurnerLok	iPVC-DR14	65	(448)
PC31	Axial-Compression	EBAA C1900	iPVC-DR14	67	(462)
PC35	Axial-Compression	Lokx	iPVC-DR14	64	(441)
PS12	Axial-Cyclic	RCT	iPVC-DR14	63	(434)
PS29	Axial-Cyclic	TurnerLok	iPVC-DR14	65	(448)
PS32	Axial-Cyclic	EBAA C1900	iPVC-DR14	66	(455)
PS36	Axial-Cyclic	Lokx	iPVC-DR14	65	(448)
PS39	Axial-Cyclic	Hymax Grip	iPVC-DR14	65	(448)
PB02	Bending	RCT	iPVC-DR14	53	(365)
PB11	Bending	TurnerLok	iPVC-DR14	65	(448)
PB12	Bending	EBAA C1900	iPVC-DR14	67	(462)
PB13	Bending	Continuous	iPVC-DR14	65	(448)
PB14	Bending	Lokx	iPVC-DR14	64	(441)
PB15	Bending	Hymax Grip	iPVC-DR14	63	(434)

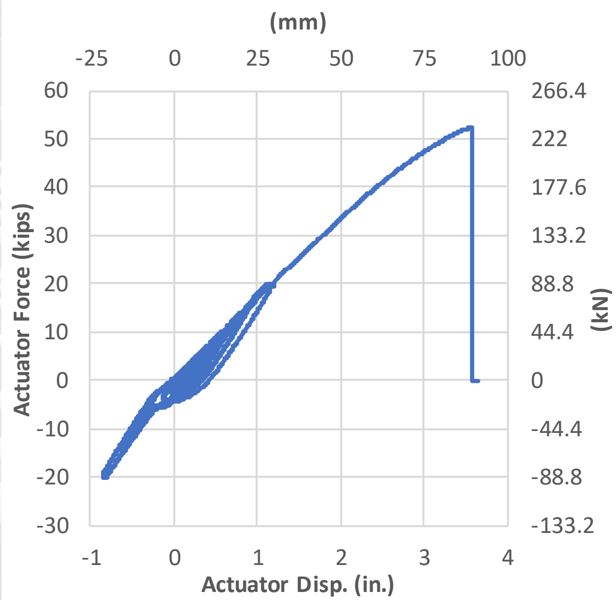


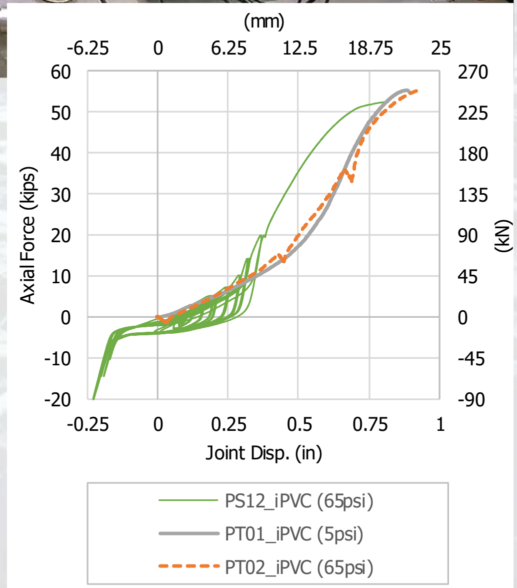
Axial Cyclic Test

Protocol adapted from FEMA 461 for structural and non-structural building components



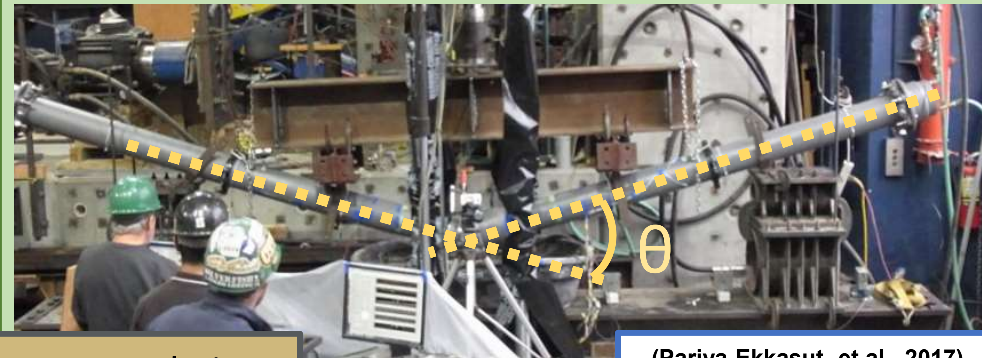






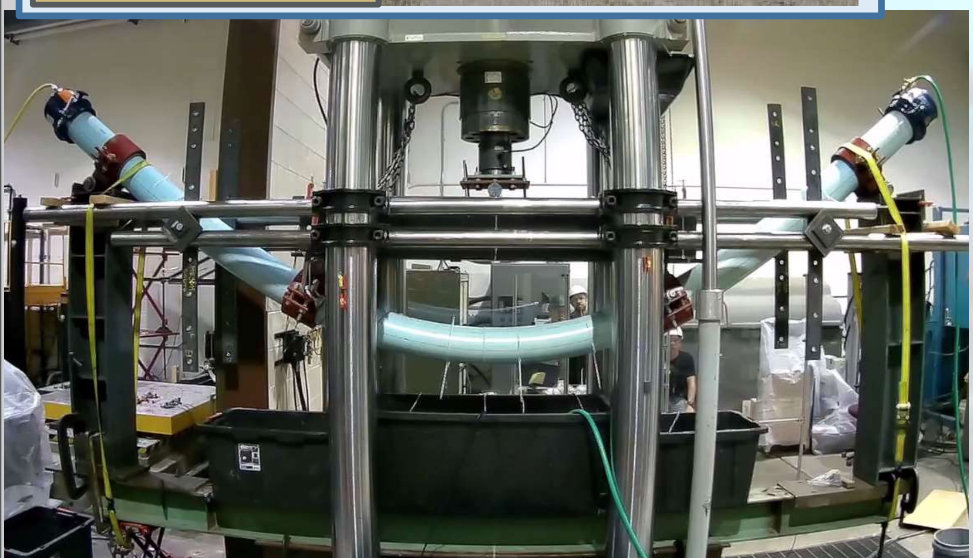
Hazard Resistant Pipeline Systems: Lateral Response

Continuous Pipe



Segmented Pipe

(Pariya-Ekkasut, et al., 2017)

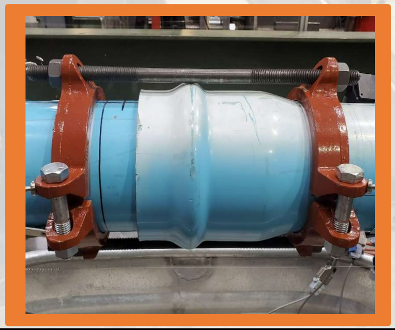


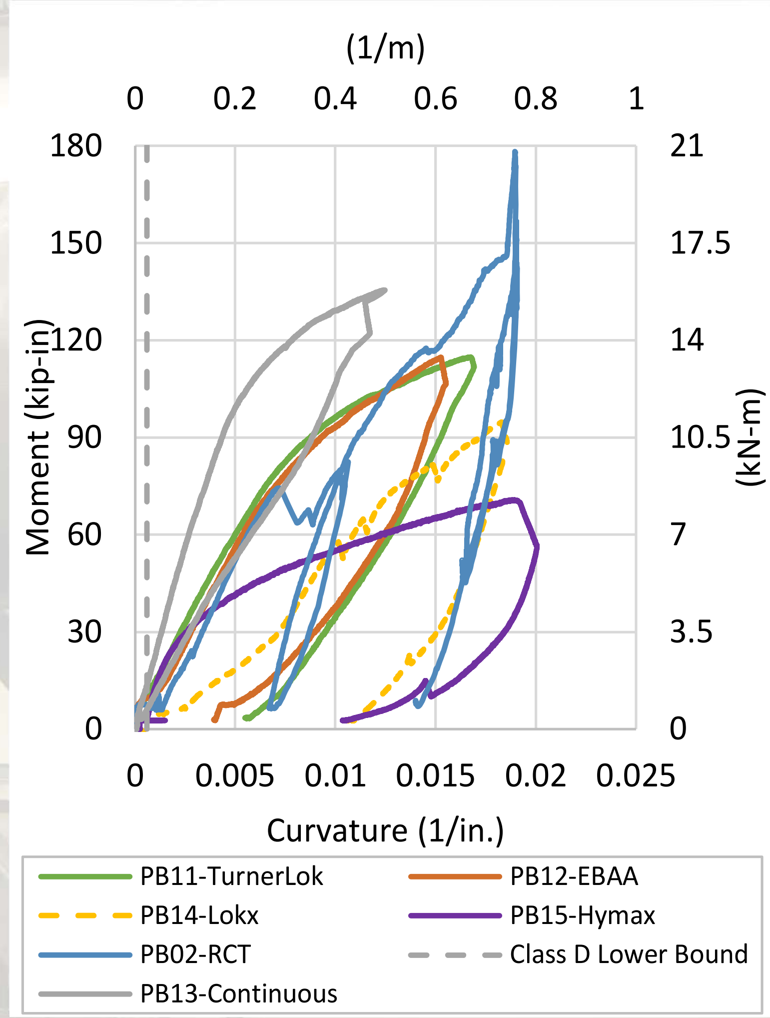
(Wham, et al., 2017)

Combined Response

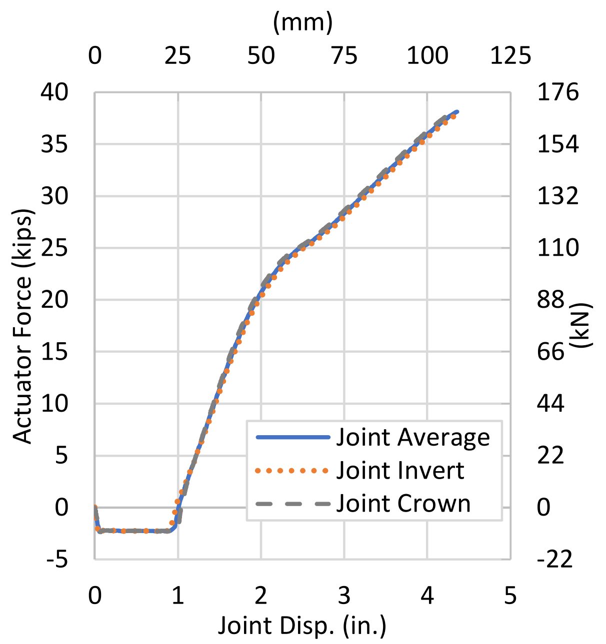
Four Point Bending Test Summary and Comparison

Test # (CIEST)	Pipe-Connection	Max. Moment kip-in	Max. Moment (kN-m)	Min. Radius of Curvature in	Min. Radius of Curvature (m)	Max. Curvature in^{-1}	Max. Curvature (m^{-1})
PB11	TurnerLok	115	(13.0)	59.1	(1.50)	0.0169	(.665)
PB11 at Leak	TurnerLok	100	(11.3)	62.7	(1.59)	0.0159	(.626)
PB12	EBAA C1900	115	(13.0)	64.5	(1.64)	0.0155	(.610)
PB14	Lokx	94.8	(10.7)	53.9	(1.37)	0.0186	(.732)
PB14 at Leak	Lokx	57.5	(6.50)	98.5	(2.50)	0.0102	(.402)
PB15	Hymax	70.7	(7.99)	49.9	(1.27)	0.0201	(.791)
PB02	RCT	178	(20.1)	52.0	(1.32)	0.0192	(.756)
PB02 at Leak	RCT	75.3	(8.51)	95.4	(2.42)	0.0105	(.413)





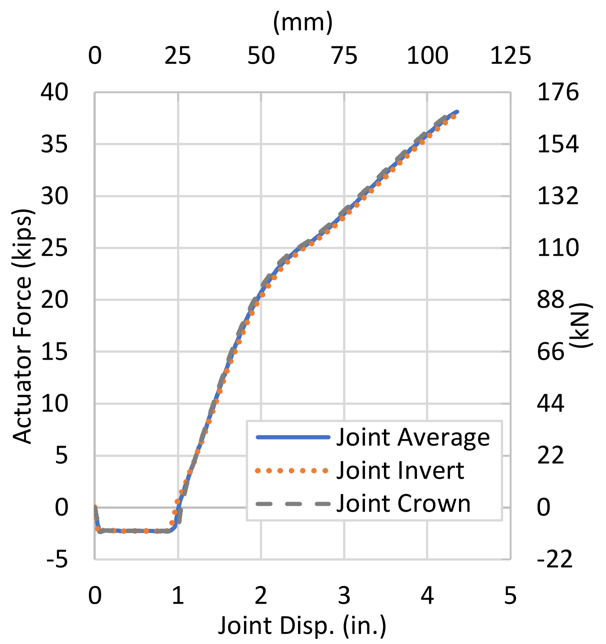
Axial Tension Test:
6 in. dia. iPVC pipe w/
C1900 Restraint Harness

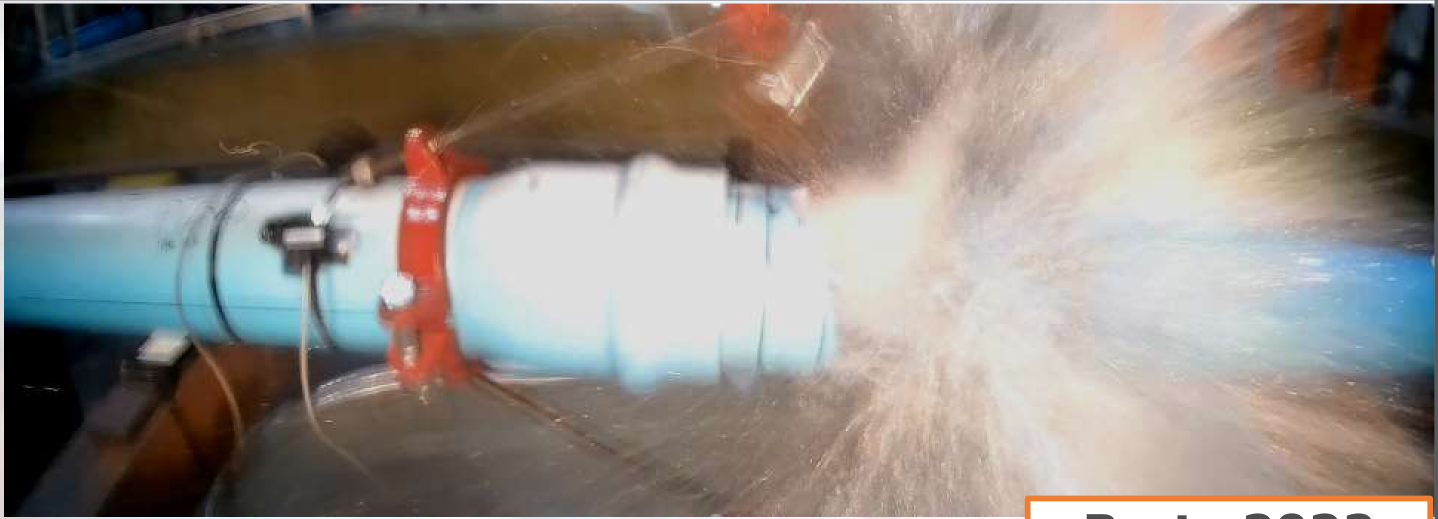


Berty 2022

CIEST YouTube: https://www.youtube.com/channel/UCZjhbAjGa3dmEn0__4ex2vg/videos

Axial Tension Test:
6 in. dia. iPVC pipe w/
C1900 Restraint Harness



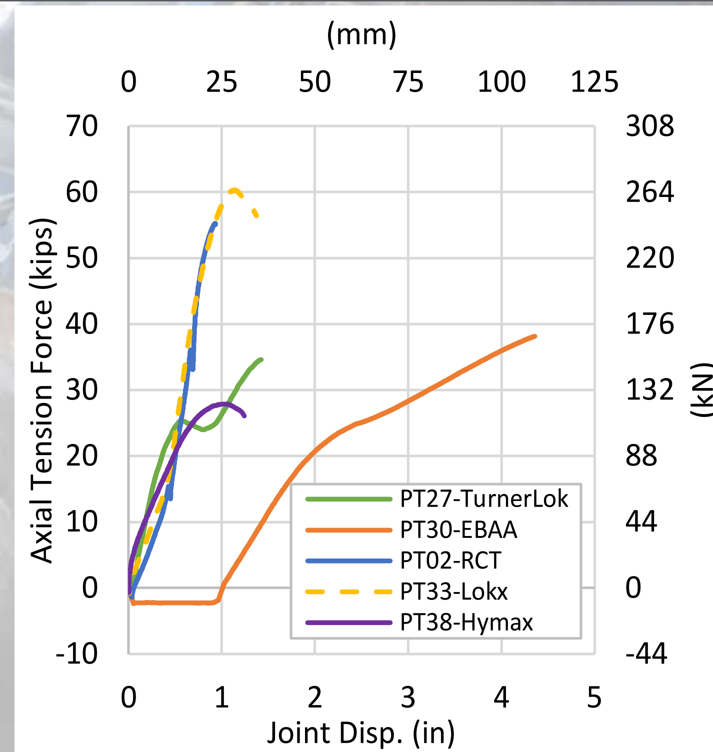


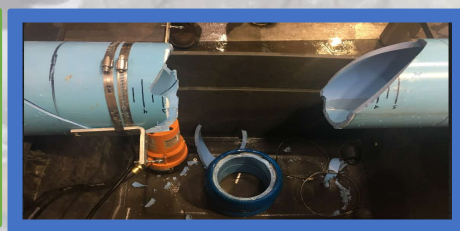
Berty 2022

CIEST YouTube: https://www.youtube.com/channel/UCZjhbAjGa3dmEn0__4ex2vg/videos

Tension Test Summary and Comparison

Test # (CIEST)	Pipe-Connection	Max. Axial Force		Max Axial Strain		Max Act. Disp.		Joint Disp.	
		Kips	(kN)	in/in	%	in	(mm)	in	(mm)
PT02	RCT	55.3	(246)	-	-	4.10	(104)	0.93	(24)
PT27	TurnerLok	34.6	(154)	0.0078	0.78	2.96	(75)	1.42	(36)
PT30	EBAA C1900	38.1	(169)	0.0086	0.86	6.07	(154)	4.36	(111)
PT33	Lokx	60.3	(268)	0.0169	1.69	4.28	(109)	1.37	(35)
PT38	Hymax Grip	27.9	(124)	0.0063	0.63	2.47	(63)	1.24	(31)
PT38 at Leak	Hymax Grip	27.9	(124)	0.0063	0.63	2.34	(59)	1.06	(27)





Strain Demand Results

Parameter (+ and -)	Class	Seismic Strain Demand	
Axial Strain (α)	α_A	0.01% up to 0.1%	
	α_B	0.1% up to 0.5%	
	α_C	0.5% up to 1%	
	α_D	1% or greater	
Radius of Curvature (R)/ Deflection Angle (ϕ)	ρ_A	$R_A > 344$m (1130 ft)	$\phi_A/L_g < 0.167$ deg./m (0.051 deg./ft)
	ρ_B	115 m (376 ft) $< R_B \leq 344$m (1130 ft)	$0.167 \leq \phi_B/L_g < 0.5$ deg./m (0.152 deg./ft)
	ρ_C	46 m (150 ft) $< R_C \leq 115$ m (376 ft)	$0.5 \leq \phi_C/L_g < 1.25$ deg./m (0.381 deg./ft)
	ρ_D	$R_D \leq 46$ m (150 ft)	$\phi_D/L_g \geq 1.25$ deg./m (0.381 deg./ft)

Axial Strain Demand (System Strain)

Test # (CIEST)	Pipe-Connection	Applied Force Direction	System Stain in./in.	System Stain %	Strain Demand Class*	Percent Exceeding Class D %
PT02	RCT	Tension	0.0196	1.96	D	95.8
PC37	RCT	Compression	0.0139	1.39	D	38.7
PT27	TurnerLok	Tension	0.0131	1.31	D	30.9
PC28	TurnerLok	Compression	0.0407	4.07	D	307
PT30	EBAA C1900	Tension	0.0259	2.59	D	159
PC31	EBAA C1900	Compression	0.0345	3.45	D	245
PT33	Lokx	Tension	0.0205	2.05	D	105
PC35 (Leak)	Lokx	Compression	0.0110	1.10	D	10.5
PT38 (Leak)	Hymax Grip	Tension	0.0104	1.04	D	3.62
PS39 (Comp.)	Hymax Grip	Compression	0.0112	1.12	D	11.7

Bending Strain Demand (RoC)

Test # (CIEST)	Pipe - Connection	Min Radius of Curvature in	Min Radius of Curvature (m)	Max Curvature in^{-1}	Max Curvature (m^{-1})	Strain Demand Class	Percent Exceeding Class D %
PB11 (Leak)	TurnerLok	62.7	(1.59)	0.0159	(0.626)	D	2762
PB12	EBAA C1900	64.5	(1.64)	0.0155	(0.610)	D	2690
PB13	Continuous	80.2	(2.04)	0.0125	(0.491)	D	2150
PB14 (Leak)	Lokx	98.5	(2.50)	0.0102	(0.402)	D	1736
PB15	Hymax Grip	49.9	(1.27)	0.0201	(0.791)	D	3518
PB02 (Leak)	RCT	95.4	(2.42)	0.0105	(0.413)	D	1790

ASCE MOP: Demand vs. Capacity

ISO 16134: Earthquake- and subsidence-resistant design of ductile iron pipe (Japanese Standard)

Types of joints			K-joint		A-joint		Flange joint†	
Specimen serial number			1	2	1	2	1	2
Items	Seismic classification	Range						
Expansion capacity δ(mm)	S-1	δ≥1%L	√	√				
	S-2	0.5%L≤δ<1%L						
	S-3	δ<0.5%L			√	√	√	
Contraction capacity δ(mm)	S-1	δ≥1%L						
	S-2	0.5%L≤δ<1%L						
	S-3	δ<0.5%L	√	√	√	√		
Slip-out resistance F(kN)	A	F≥3d						
	B	1.5d≤F<3d						
	C	0.75d≤F<1.5d						
	D	F<0.75d	√	√	√	√	√*	√*
Rotation deflection capacity θ(deg)	M-1	θ≥15°						
	M-2	7.5°≤θ<15°	√	√				
	M-3	θ<7.5°			√	√	√	√

L: nominal pipe length (mm);
d: nominal pipe diameter (mm);
†: compression strength was too high to be tested to failure;
*: tensile strength at which water pressure was lost.

ISO, 2020

Demand

Davis, et al., 2019

Parameter (+ and -)	Class	Seismic Strain Demand	
Axial Strain (α)	α_A	0.01% up to 0.1%	
	α_B	0.1% up to 0.5%	
	α_C	0.5% up to 1%	
	α_D	1% or greater	
Radius of Curvature (R)/ Deflection Angle (ϕ)	ρ_A	R_A > 344m (1130 ft)	ϕ_A/L_g < 0.167 deg./m (0.051 deg./ft)
	ρ_B	115 m (376 ft) < R_B ≤ 344m (1130 ft)	0.167 ≤ ϕ_B/L_g < 0.5 deg./m (0.152 deg./ft)
	ρ_C	46 m (150 ft) < R_C ≤ 115 m (376 ft)	0.5 ≤ ϕ_C/L_g < 1.25 deg./m (0.381 deg./ft)
	ρ_D	R_D ≤ 46 m (150 ft)	ϕ_D/L_g ≥ 1.25 deg./m (0.381 deg./ft)

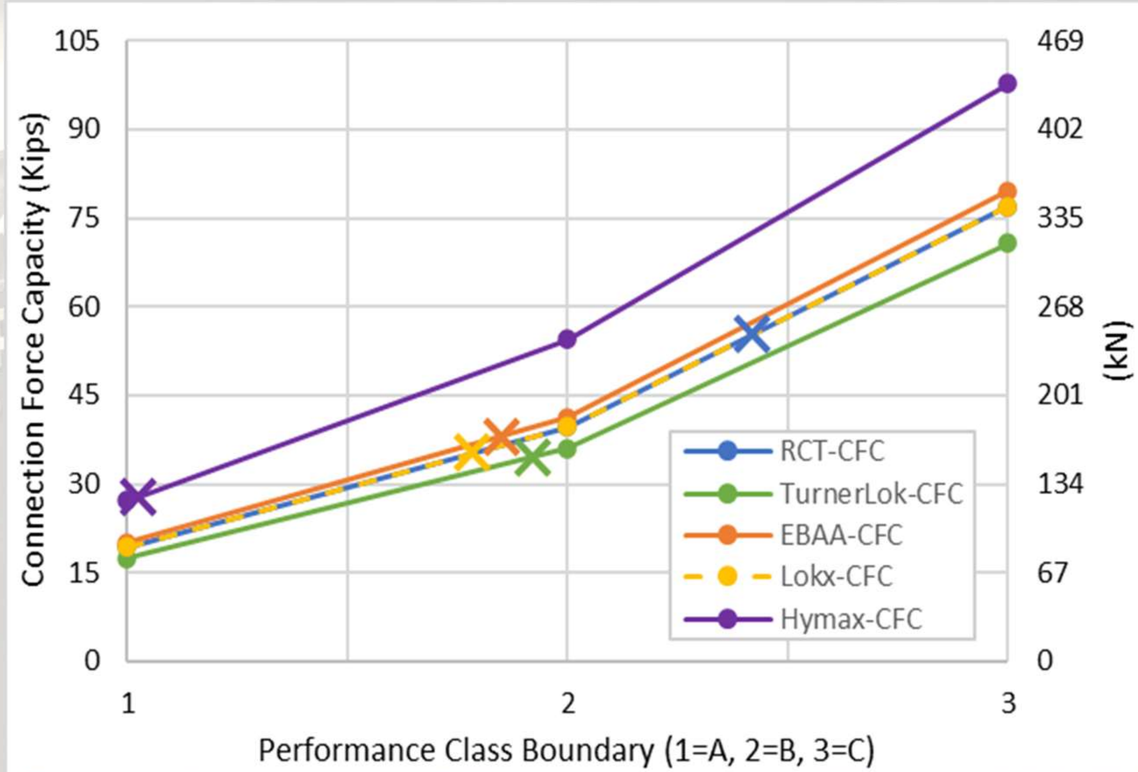
Capacity

Performance Class	ISO 16134 (kN)	ISO 16134 (US units) (kips)	ISO DIP F_{CFC} for D = 6 in. (kips)
Φ_A	less than 0.75D	less than 4.3D	< 25.7
Φ_B	0.75D to 1.5D	4.3D to 8.6D	25.7
Φ_C	1.5D to 3D	8.6D to 17.1D	51.4
Φ_D	greater than 3D	greater than 17.1D	102.8

Connection Force Capacity Results

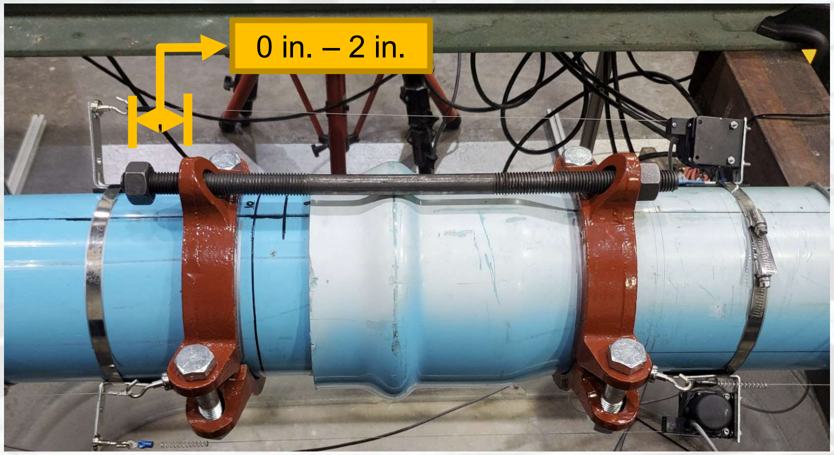
Pipe-Connection	Axial Capacity Kips	(kN)	Connection Force Capacity Class
RCT Coupling	55.3	(246)	C
TurnerLok Gasket	34.6	(154)	B
EBAA C1900 Restraint	38.1	(169)	B-C
Lokx Coupling	-35.3	(-157)	B
Hymax Coupling	27.9	(124)	B

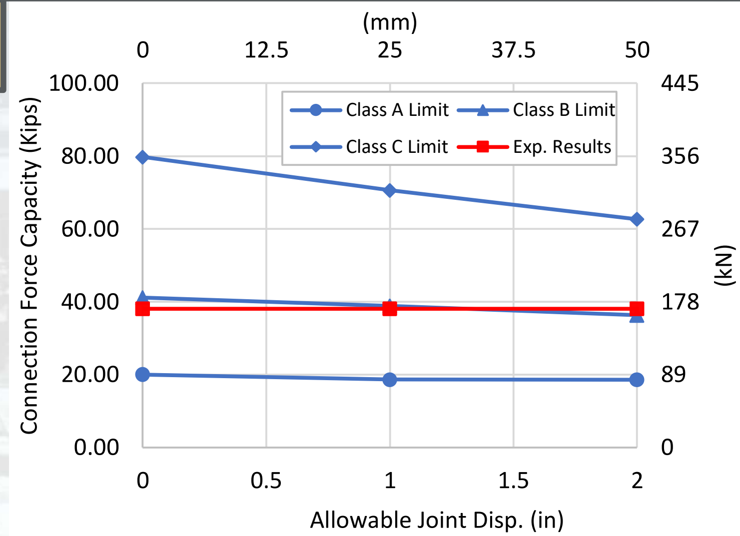
System Parameter	Units		RCT (iPVC)		TurnerLok (iPVC)		EBAA C1900 (iPVC)		Lokx (iPVC)		Hymax Grip (iPVC)	
Outer Diameter, D_o	in.	(mm)	6.9	(175)	6.9	(175)	6.9	(175)	6.9	(175)	6.9	(175)
Thickness, t	in.	(mm)	0.49	(12)	0.49	(12)	0.49	(12)	0.49	(12)	0.49	(12)
Connection Diameter, D_b	in.	(mm)	8.73	(222)	8.0	(203)	9	(229)	8.75	(222)	11.3	(287)
Lay Length, L_p	ft.	(m)	20	(6.1)	20	(6.1)	20	(6.1)	20	(6.1)	20	(6.1)
Allowable Joint Displacement, Δj	in.	(mm)	0	(0)	0	(0)	0-2	(0-49)	0	(0)	0	(0)
Young's Modulus, E	ksi	(GPa)	450	(3.1)	450	(3.10)	450	(3.10)	450	(3.10)	450	(3.10)
Allowable Joint Strain, γ_p	%		0	(0)	0	(0)	0 - 0.83	(0 - 0.83)	0	(0)	0	(0)
d_i/Φ	-		0.7	(0.7)	0.7	(0.7)	0.7	(0.7)	0.7	(0.7)	0.7	(0.7)



Connection Force Capacity Overview

EBAA Allowable Joint Displacement





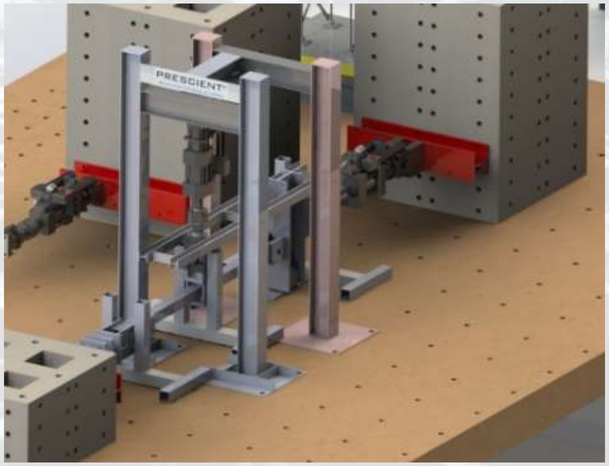
Performance Class	CFC Equation	EBAA C1900 Restraint - 0 in.		EBAA C1900 Restraint - 1 in.		EBAA C1900 Restraint - 2 in.	
		K Values	Min. CFC (kips)	K Values	Min. CFC (kips)	K Values	Min. CFC (kips)
Φ_A	Less than $4.3DK_A$	-	0	-	0	-	0
Φ_B	$4.3DK_A$ to $8.6DK_B$	$K_A = 0.78$	20.1	$K_A = 0.73$	18.8	$K_A = 0.72$	18.7
Φ_C	$8.6DK_B$ to $17.1DK_C$	$K_B = 0.80$	41.3	$K_B = 0.82$	42.1	$K_B = 0.71$	36.4
Φ_D	Greater than DK_C	$K_C = 0.78$	79.6	$K_C = 0.74$	75.7	$K_C = 0.61$	62.6

Unrestrained Bell and Spigot

- 5.8 in. (147 mm) Allowable Joint Displacement
- 200 lbs. (0.89 kN) Axial Capacity
- Min. Class B Threshold = 12.9 kips
- Class A (lowest class)

Looking Forward & Research Opportunities

- **Evaluation and qualification of new/existing infrastructure systems**
  - **Develop seismic testing standard for product adoption (HR system)**
  - **Combined (bi-axial) and cyclic loading without soil – hybrid testing applications**
- **Centrifuge modeling for parametric studies**
  - **Axial response of enlarged components (paired with FEM)**
  - **Transverse response of segmented systems**



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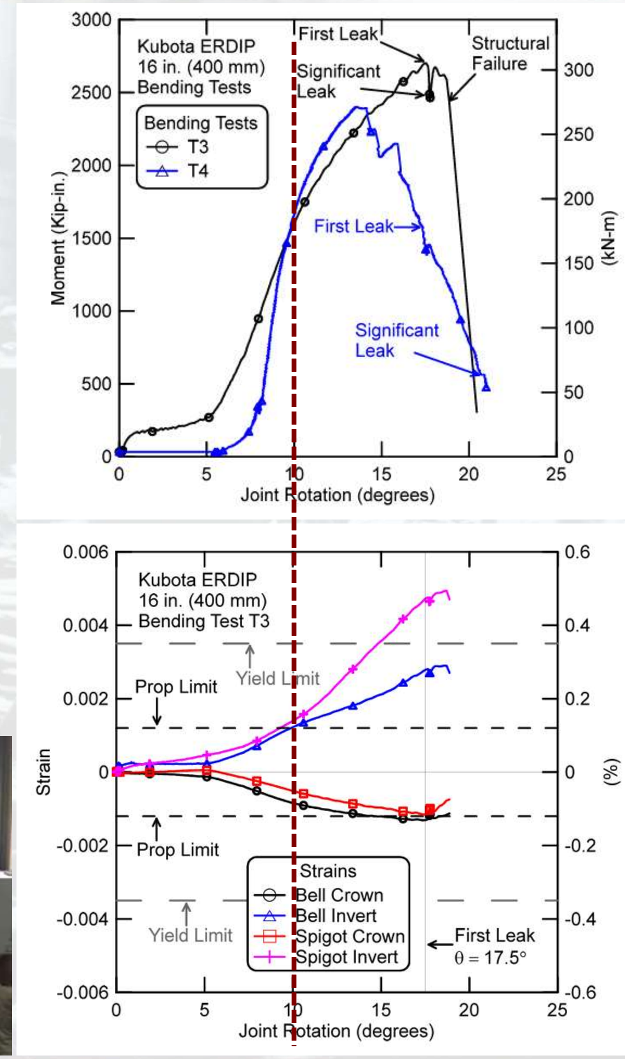
  - **Transverse loading considering M-R resistance a joints**



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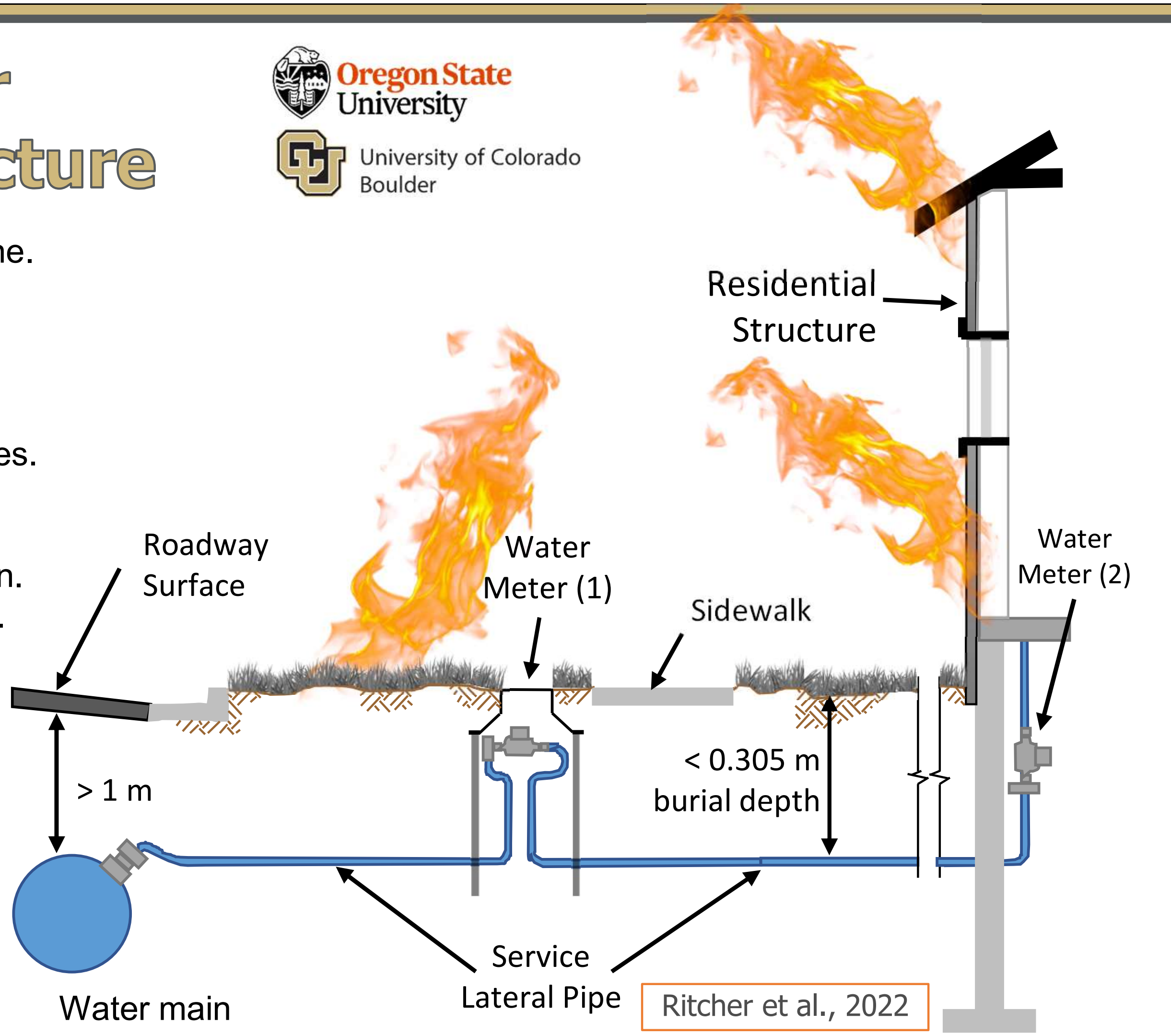
  - **Transverse response of segmented systems**
- **Analytical approaches to characterize performance and provide generalized comparison of systems (propose improvements!)**
  - **FEM validation of methods**
  - **Transverse loading considering M-R resistance a joints**
- **Seismic design of water and wastewater pipelines (ASCE Manual of Practice, AWWA, etc.)**
  - **CFC Design Charts for Prescriptive Design Method**
  - **Transverse Response (considering pipe stiffness and joint deflection capacity)**
- **Life cycle (mechanical aging) testing of infrastructure (rehabilitation)**
- **Smart infrastructure sensors/instrumentation for use in buried environments**
- **Wildfire effects on Infrastructure**

Fire Impacts on Water Distribution Infrastructure

Oregon State University
University of Colorado Boulder

- Burning homes **release chemicals**, like benzene. They also act as a fuel source, heating **service lines beneath the ground**.
- Increased water usage during a fire creates decompression and backflow in waterlines.
- Vacuum draws these chemicals into the pipelines. Service lines are heated/damaged.
- Contaminants may absorb into pipe or thermoplastics release VOCs due to combustion.
- Damaged service lines will need to be replaced.
- Interdependences across Lifeline systems



Thank You!

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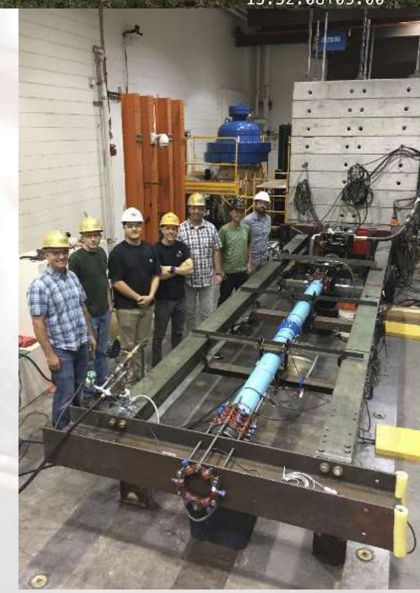

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