Critical Evaluation of Strain Limits on the In-ground Hinge of Steel Pipe Piles for Piers and Wharves

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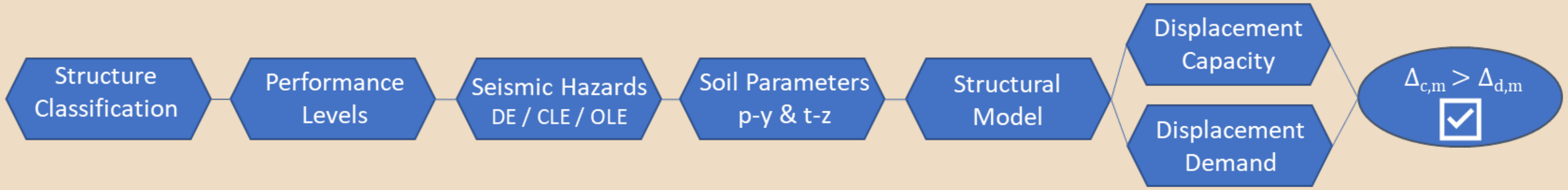
ASCE/COPRI 61 Prescribed Limits

State of the Practice

Performance-based design method to meet ASCE/COPRI 61 Standard Requirements



Piers and wharves are designed to develop top of pile hinges and in-ground hinges

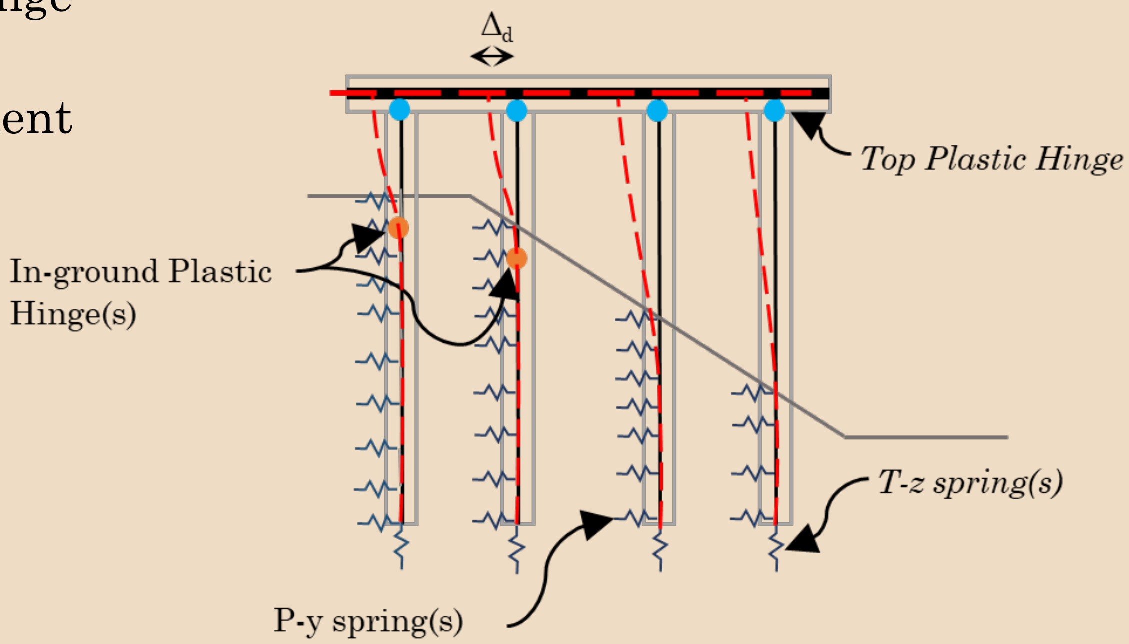
Current code(s) use prescribed strain limits in the plastic hinge region to determine displacement capacity.

The in-ground hinge in the current ASCE 61-14 lacks sufficient research to support the strain limits prescribed.

ASCE/COPRI 61-14 performance-level strain limits for steel pipe piles.

Performance level	Hinge location	
	In-ground	Deep in-ground (>10D)
Minimal damage (MD)	0.01	0.01
Controlled and repairable damage (CD)	0.025[a]	0.035
Life safety (LS)	0.035[a]	0.05

[a] Where concrete infill is provided, the in-ground plastic hinge strain limits are allowed to be increased to 0.035 and 0.05 for the CD and LS performance levels, respectively.



ASCE/COPRI 61 Strain Limits Concerns

Strain Determination

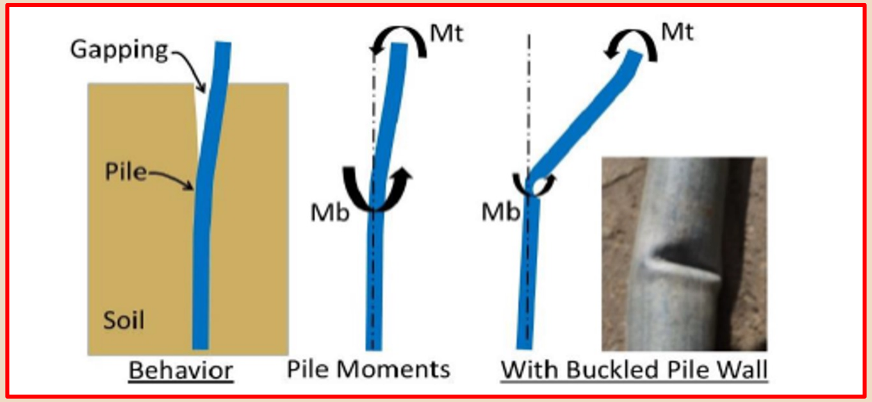
Per ASCE/COPRI 61, critical strain, ε_{LS}, is determined considering plane sections hypothesis and assuming a uniform strain field along the plastic hinge length.

Unlike concrete, steel pipe wall buckles and thus invalidates the plane-sections hypothesis.

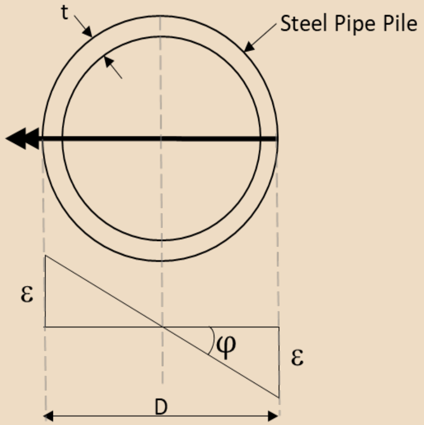
Code defines a single strain limit for both compression and tension, ignoring the effect of cyclic loading and loading history.

Axial load is not currently factored into the code prescribed strain limits.

Harn et al (2019)

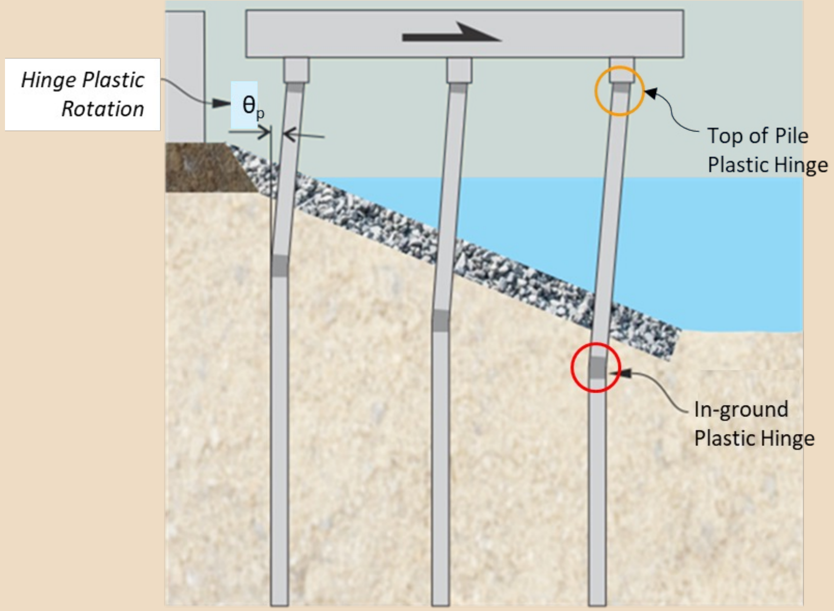


Plane Sections Remain Plane



Plastic Rotation

$$\theta_p = L_p\varphi_p$$
$$= L_p(\varphi_m - \varphi_y)$$



Literature Review

Concerns Identified

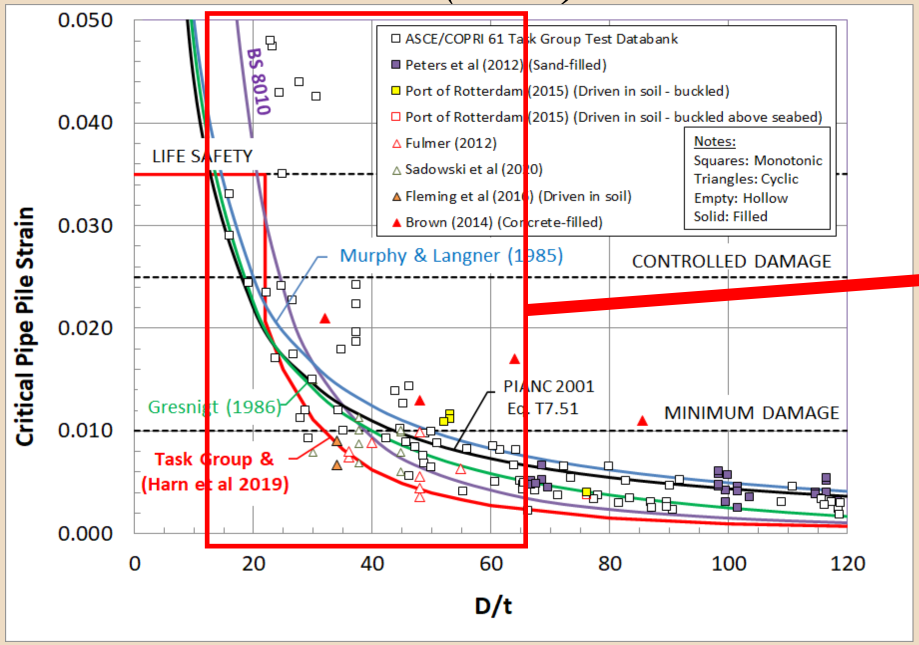
Limited research to-date proposes critical strains be defined as a function of D/t

Experimental research is not directly comparable; varied test parameters, ε_{cr} measurement procedure(s) and initiation of buckling definitions

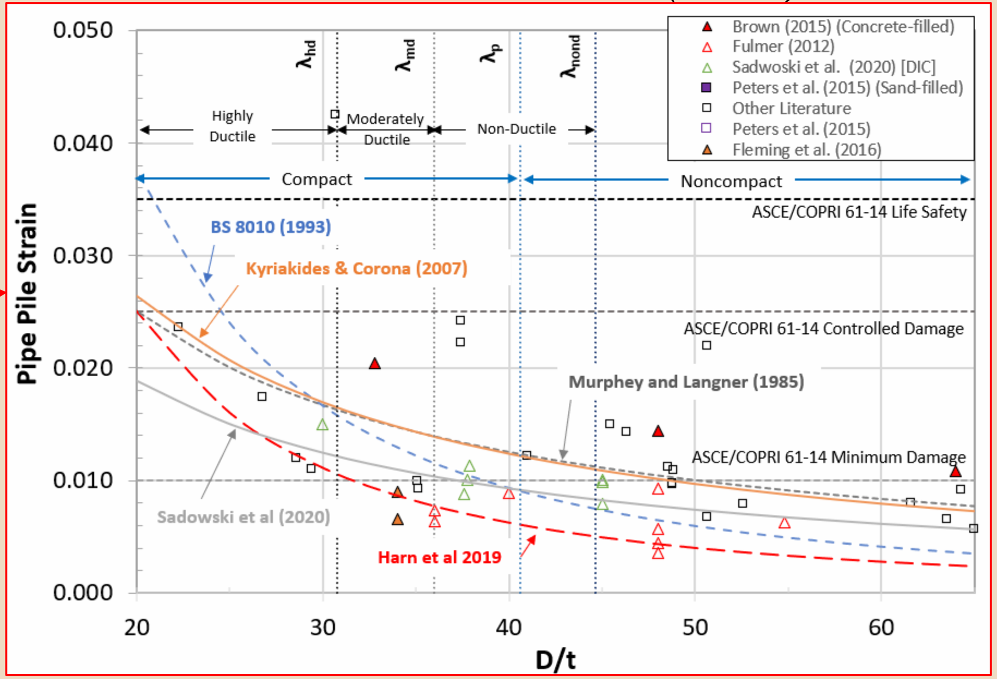
Cyclic testing results in the literature suggest that the strain limits are not achievable

Residual axial load in the pile is not evaluated

Harn et al (2019)



Recreated Harn et al (2019)



Research Goals and Objectives

Component Level Performance

Performance of piles from minimal damage to failure under realistic conditions

- What is the residual flexural capacity?
- What is the effect of the axial (gravity) load on lateral load capacity?

Examination of Critical Strains

Critical strains are defined to occur prior to the onset of buckling. How reliable are the critical strains at predicting the residual strength of the pile? Does this define absolute failure of the component?

Define if strain is the best metric to use? Should rotation be used as a metric to define life safety?

Steel Material Properties

Should limits on steel material properties be incorporated?

System Level Performance

How detrimental is axial shortening in the buckled region of the steel pipe-pile to the system performance?

Given that the system is designed with redundancy, what is the potential for redistribution of load?

Research Plan

Detailed Nonlinear FEM Simulations & Validations

Single pile (component level)

Multi-pile (system level)

Large-Scale Testing

Steel piles embedded in soil

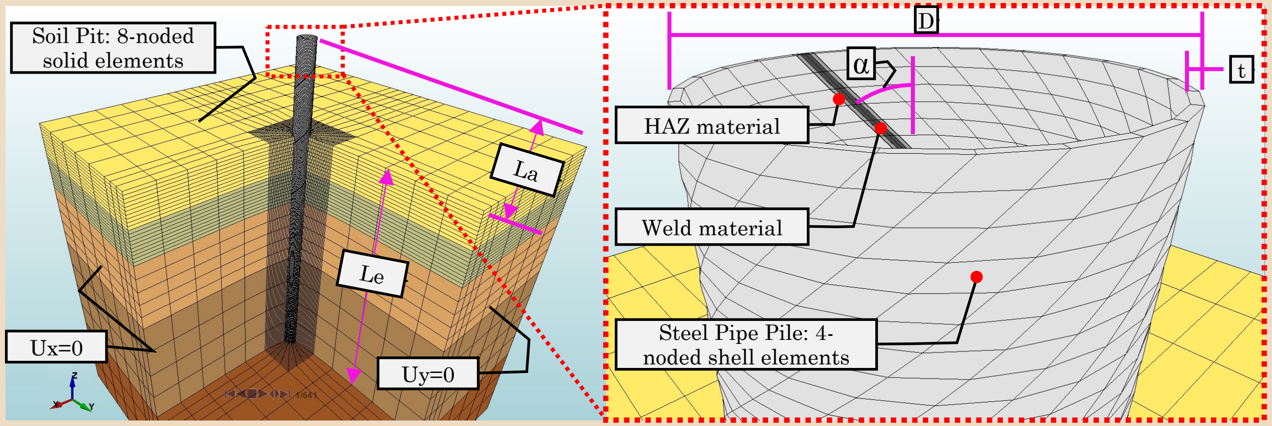
Recommendations

Appropriate strain limits

Other metrics that provide safe and economical designs

FEM: Details and Parametric Study Table

Soil-Pile Model



Model Development (LS-Dyna)

Soil (8-noded solid elements):

- Drucker-Prager constitutive model

Pile/Pipe (4-noded shell elements):

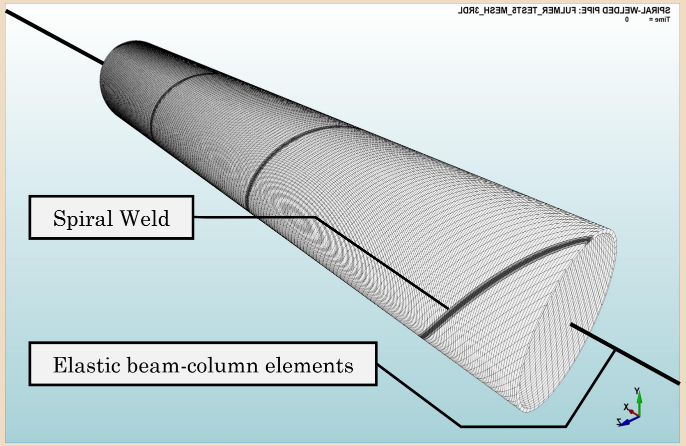
- Chaboche constitutive model
- Weld material and geometry modeled

Nonlinear contact between pipe and soil

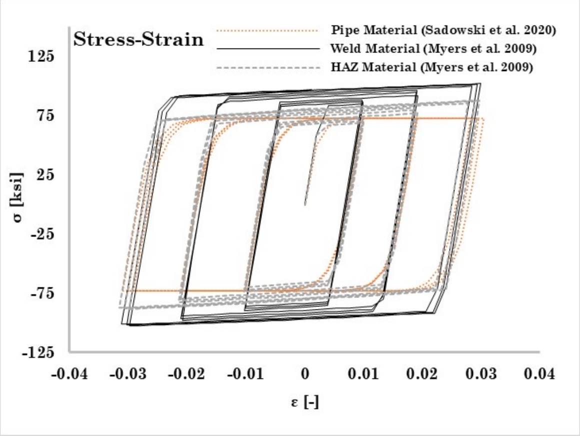
Calibrations conducted:

- Steel material model parameters

In-air Testing Model



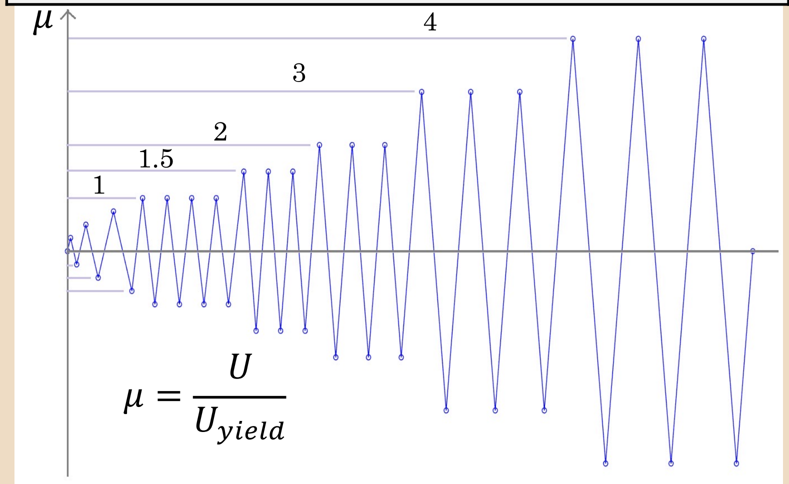
Steel Material Modeling



Parametric Study Table	
Variable	Range
☆ D/t	24-64
L_e/L_a	0.5-7.5
★ α [degrees]	0-60
Load History	[1] Far Field [2] Near Field [3] Bidirectional
☆ P/P_y	0-0.13
☆ Steel F_y/F_u	[1] High [2] Low
☆ Soil Profile	[1] Rip-Rap [2] Sloped [3] Sand-clay combinations

FEM: Parametric Study Introduction

Lateral Loading Protocol	Critical Strain, ε_{cr}	S_{ph}, D_{ph}, and Chord Rotation



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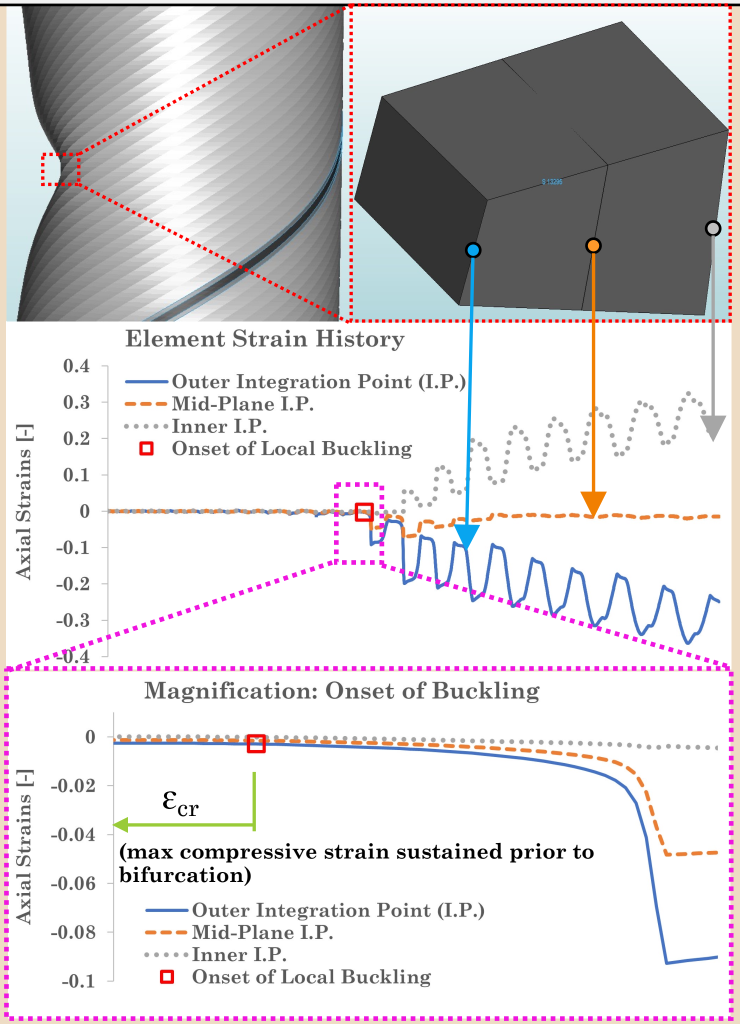
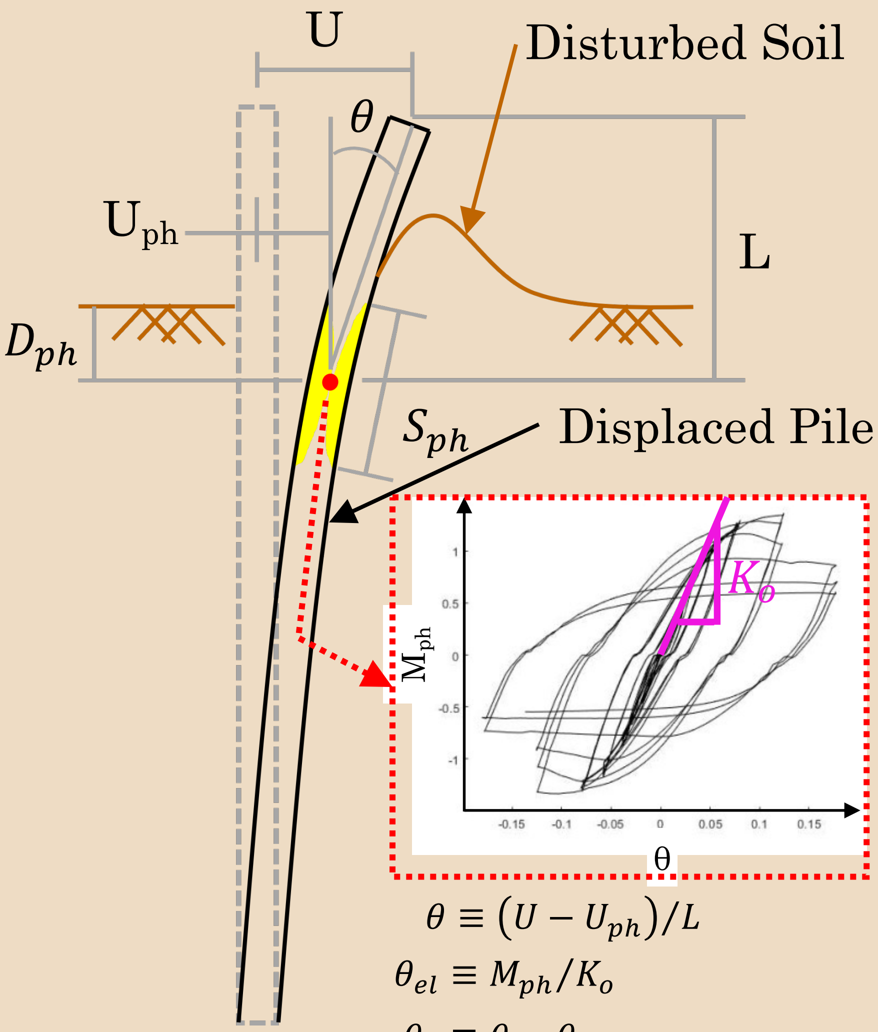




$\theta \equiv (U - U_{ph})/L$

$\theta_{el} \equiv M_{ph}/K_o$

$\theta_p \equiv \theta - \theta_{el}$

FEM: Fulmer et al. 2012 Validation

Test 5 Description

D=24”, t=0.5” (D/t=48)

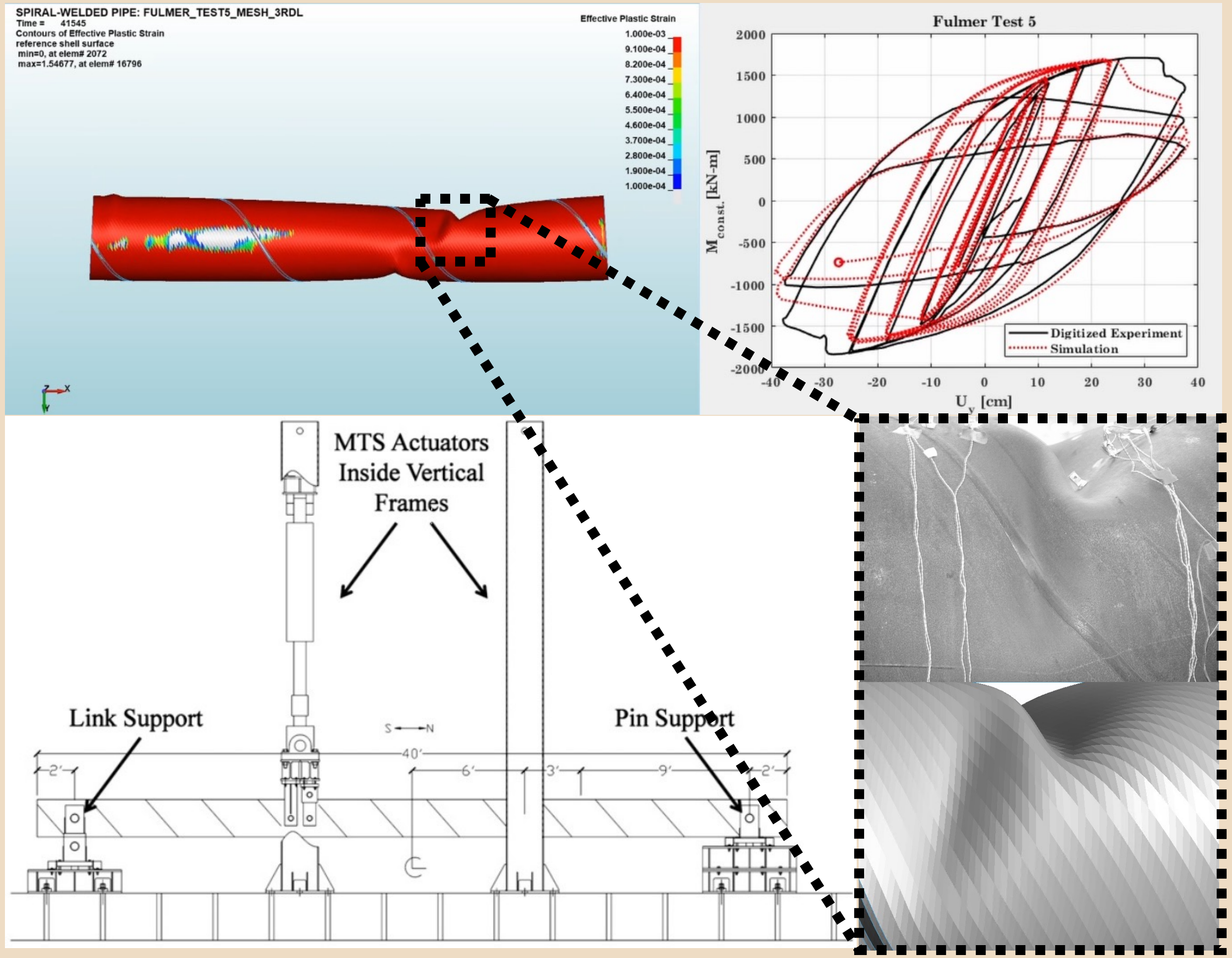
α=57.5°

ASTM A252 Gr. 3

- Reported F_y=59ksi

36’ span between supports

12’ span between actuators



FEM: Fleming et al. 2016 Validation

TPU Experiment Description

HSS12.75x0.375 (D/t=34)

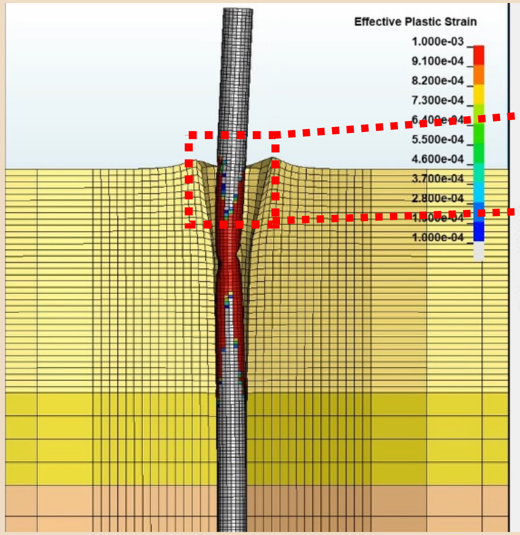
Single seam weld

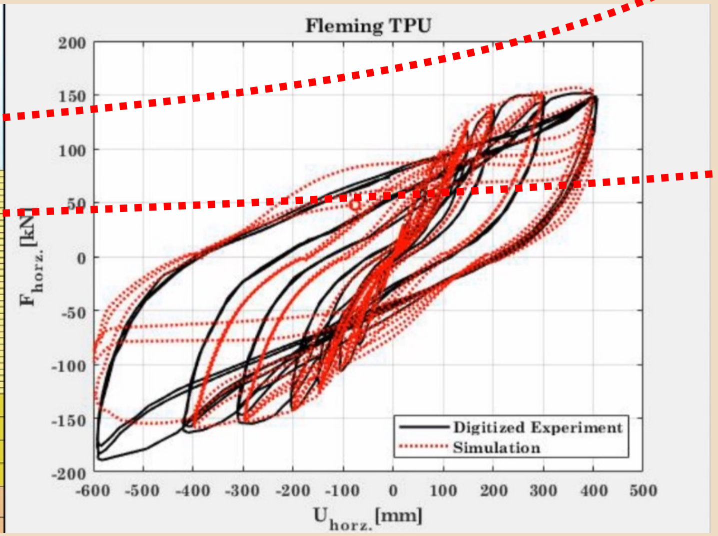
ASTM A106B Gr. 3

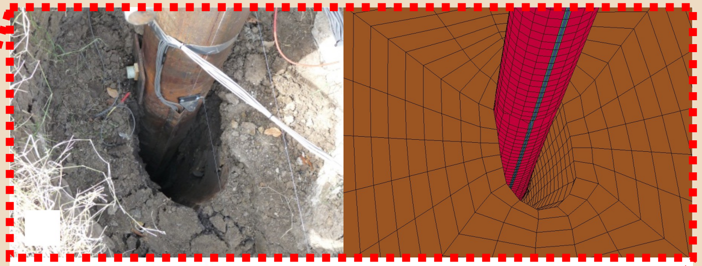
- Reported averages: F_y=54ksi & E=30.9ksi

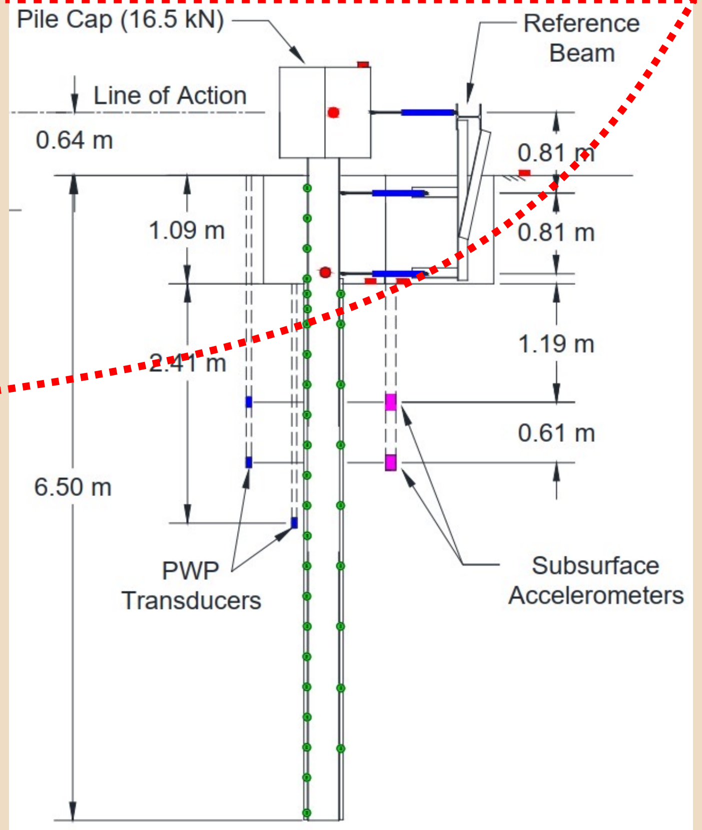
Above ground length, L_a=5'-8"

Embedded length, L_e=17'-9"









Results: Critical Strain

Critical Strains

Simulated ε_{cr} are similar to what was observed in experiments from literature:

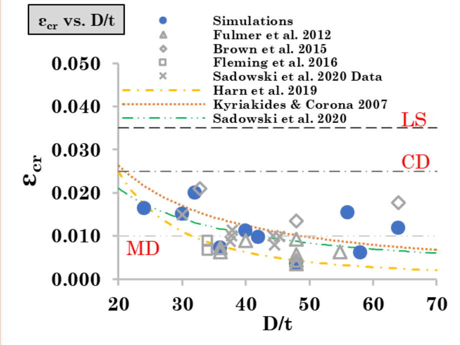
- Scattered predictions

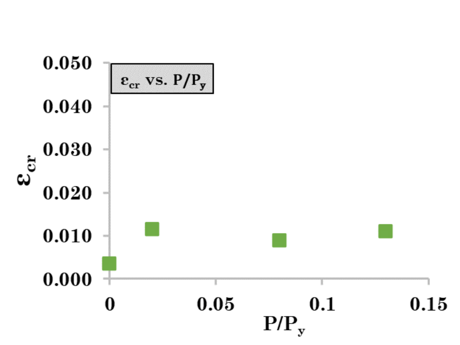
ε_{cr} insensitive to axial load ratio

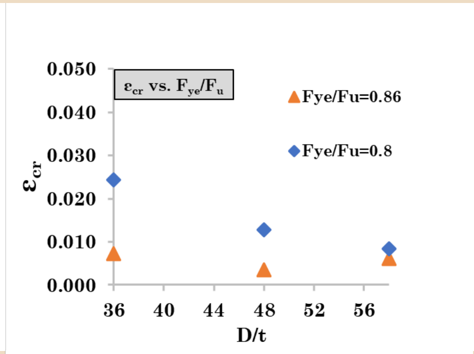
Effects of steel material properties need to be considered

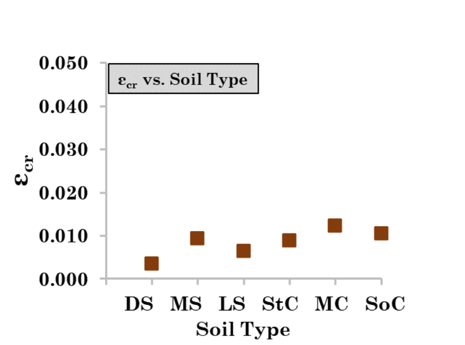
- Realistic and expected steel properties should be accounted for in lieu of nominal properties

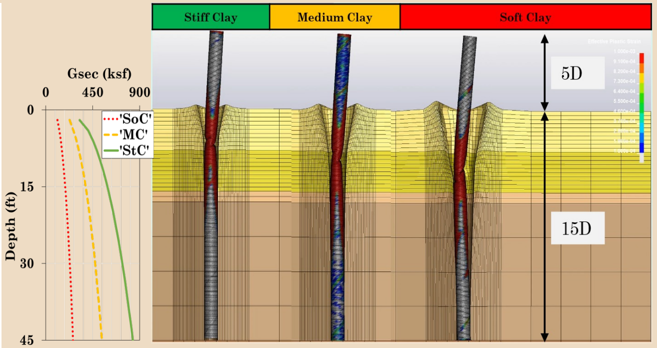
Stiffer soil generally results in larger ε_{cr} and upwards migration of plastic hinge.

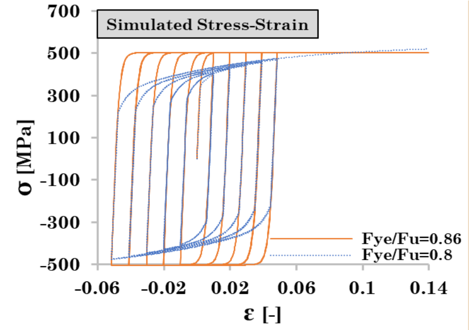












Soil Type Abbreviations	
DS:	Dense Sand
MS:	Medium Sand
LS:	Loose Sand
StC:	Stiff Clay
MC:	Medium Clay
SoC:	Soft Clay

Results: Plastic Rotation Capacity

Plastic Rotation Capacity

Pile's strain-based capacity is exhausted well before the pile has reached its peak lateral strength

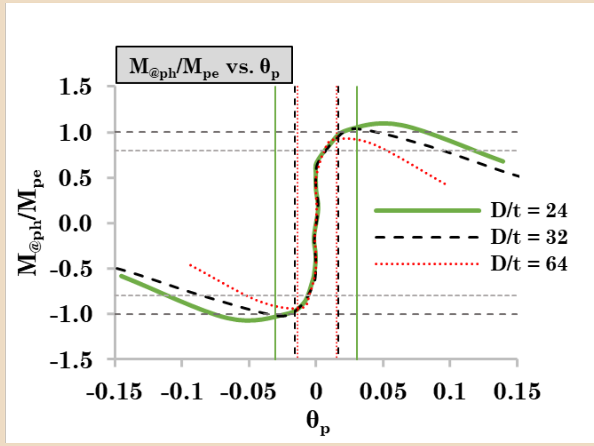
Pile's post-peak behavior cannot be exploited

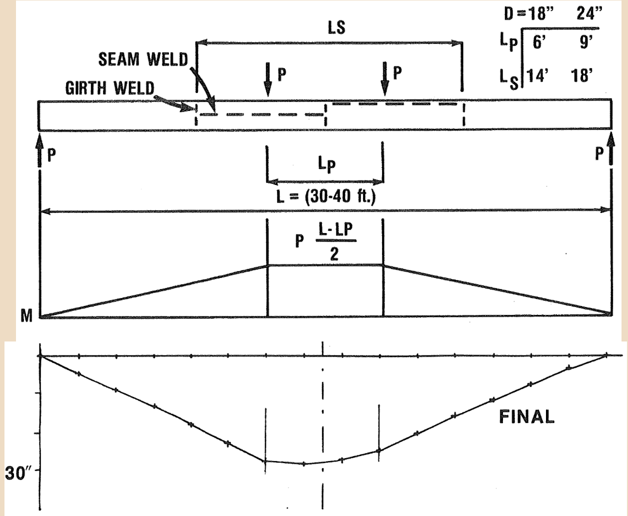
Sherman 1983 examined pipe bending capacity through rotations:

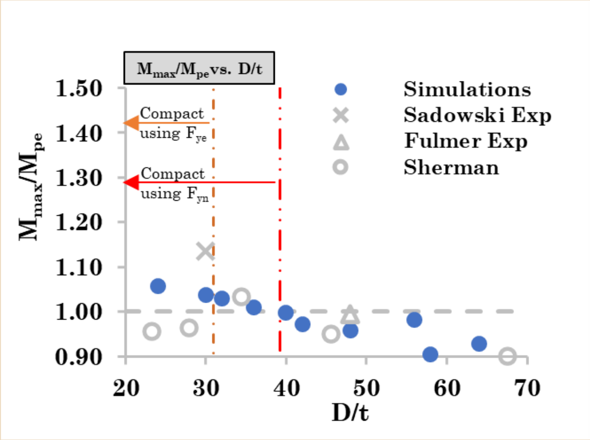
- M_{pe} not attainable for larger D/t → rotation capacity observed at peak response
- Simulated plastic rotations from soil-pile model are comparable to experimentally observed.

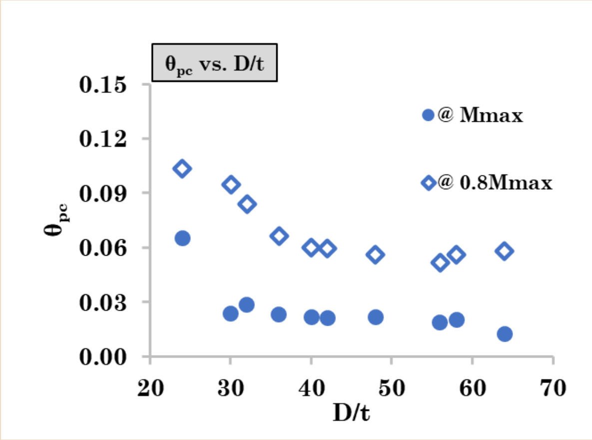
Increased rotation capacity by targeting 80% post-peak strength:

- Like established for design of other steel components (e.g. beam or column plastic hinges in moment frames).







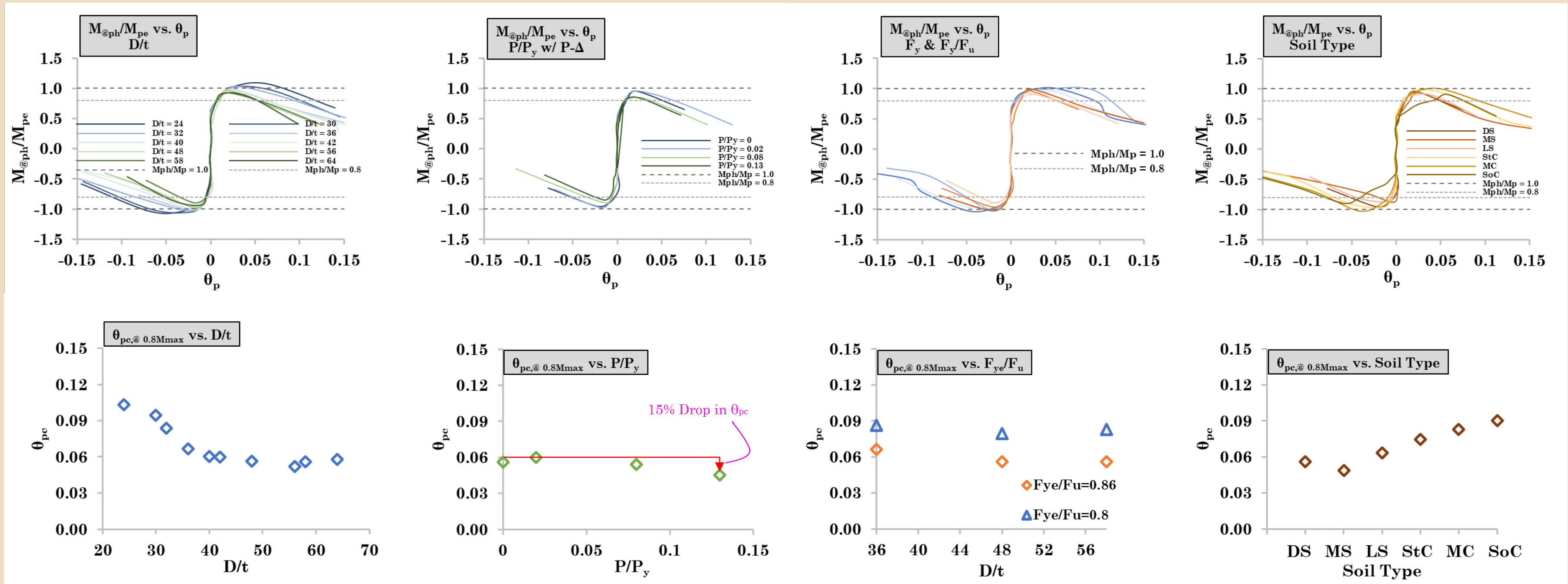


Results: Plastic Rotation Capacity

Plastic Rotations @ 0.8M_{max}

Illustrate clear and intuitive trends when defined by post-peak strength targets:

- Higher D/t and P/Py ratios exhibit diminished rotational capacity
- Low yield with high hardening steel properties show increased rotational capacity (delayed local buckling)
- Softer soils allow for larger relative displacements between load application and plastic hinge (resulting in larger chord rotations)



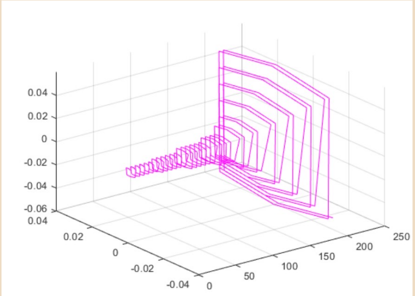
Future Work

Large-Scale Experimental Testing

Steel Pipe Testing Parameters

Test No.	D (in)	t (in)	D/t	P (kips)	P/P_y	End Conditions
1		0.25	43	25	5%	Open
2	10.75	0.25	43	80	19%	Open
3		0.5	22	63	8%	Open
4	12.75	0.375	34	63	8%	Open

FE Modeling



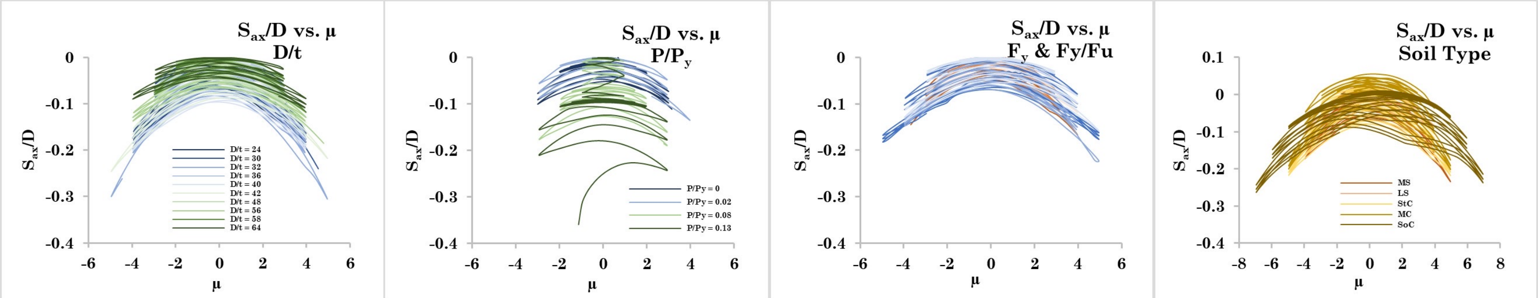
Validation with experimental testing

- Detailed material characterization

Effects of Bi-Directional Loading

Preliminary results show significant axial shortening (cause for concern!)

- System level implications? (e.g. axial load redistribution)



Inform/calibrate system level analyses

- Application of FEMA P695 framework to quantify probability of collapse and pile redundancy under different earthquake levels

Provide recommendations for future ASCE/COPRI 61

Thank You!