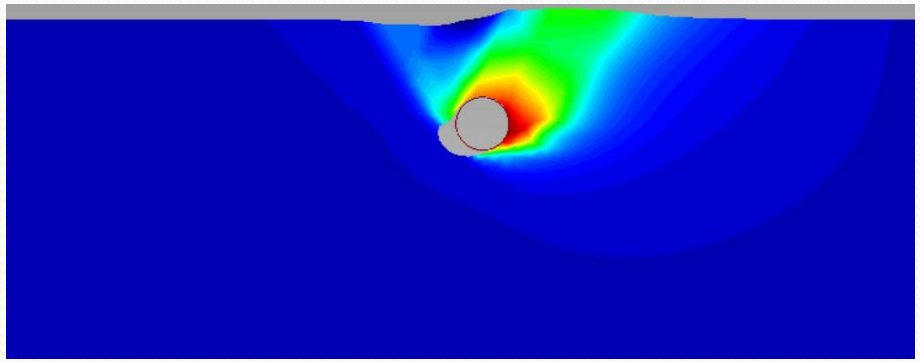
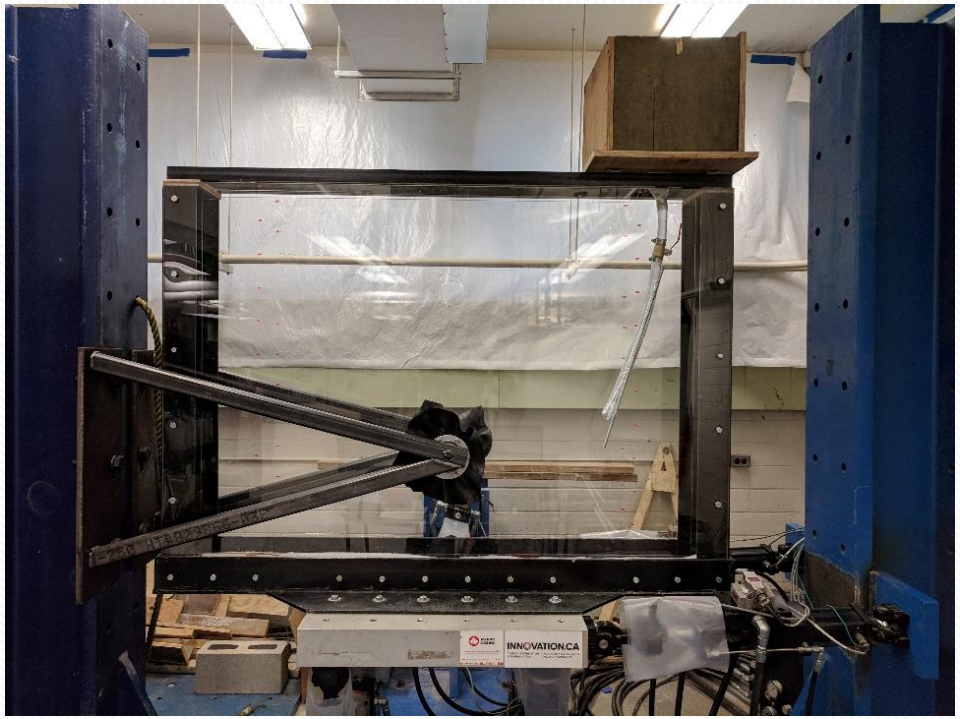
Soil-Pipe Interaction Under Lateral Loading

K. Tryfonos, PhD student, University of Patras

O. Kwon, Associate Professor, University of Toronto

S. Bousias, Professor, University of Patras





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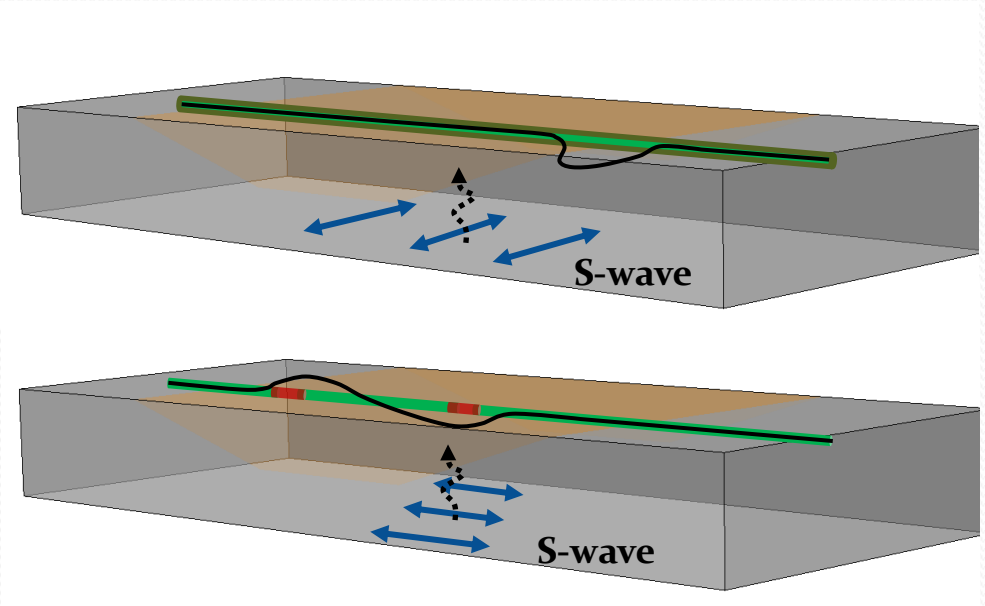
ExchangeRisk HORIZON 2020
http://www.exchange-risk.eu/

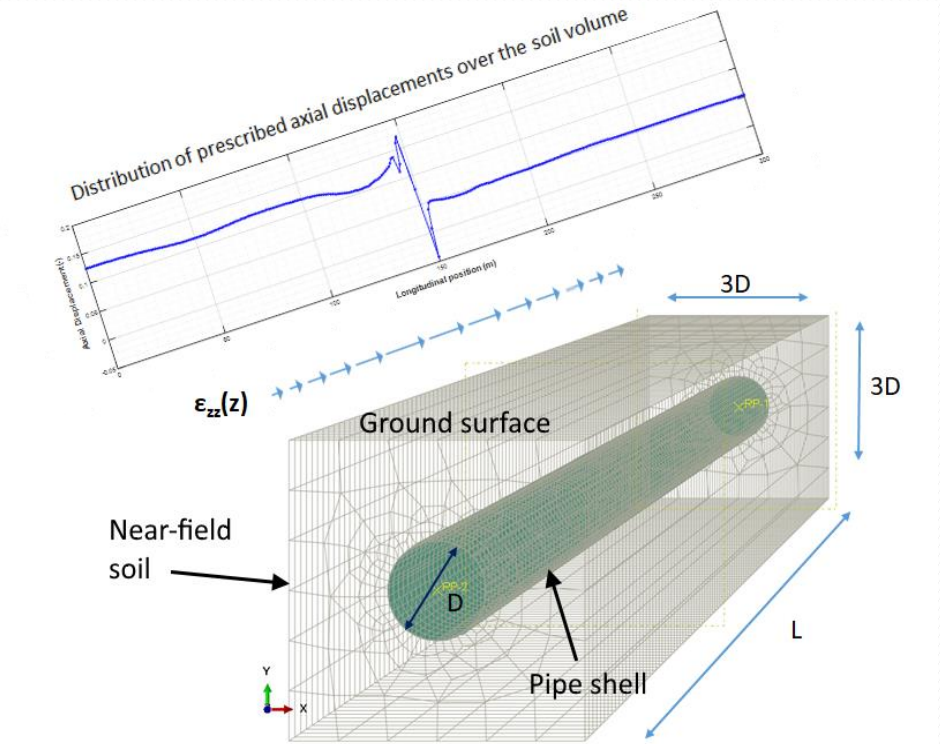
Outline

- Background
- Numerical Study
- Experimental Program
  - Soil Characterization
  - Monotonic and Cyclic Multi-axial Tests

Background

- Soil-pipe Interaction Analysis – Detailed Numerical Model

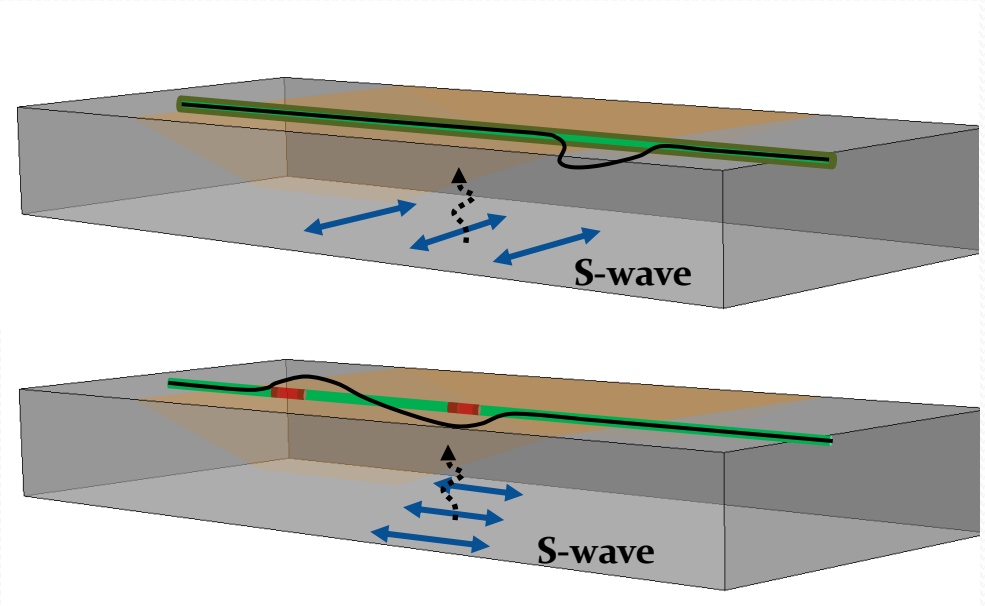


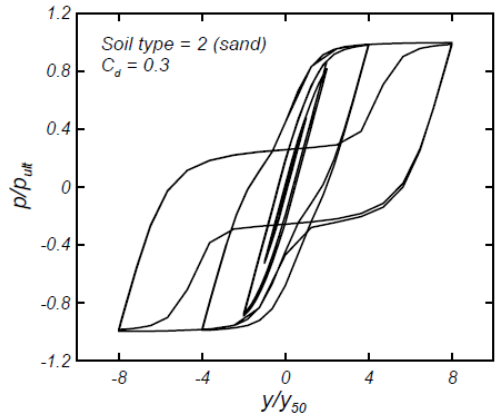


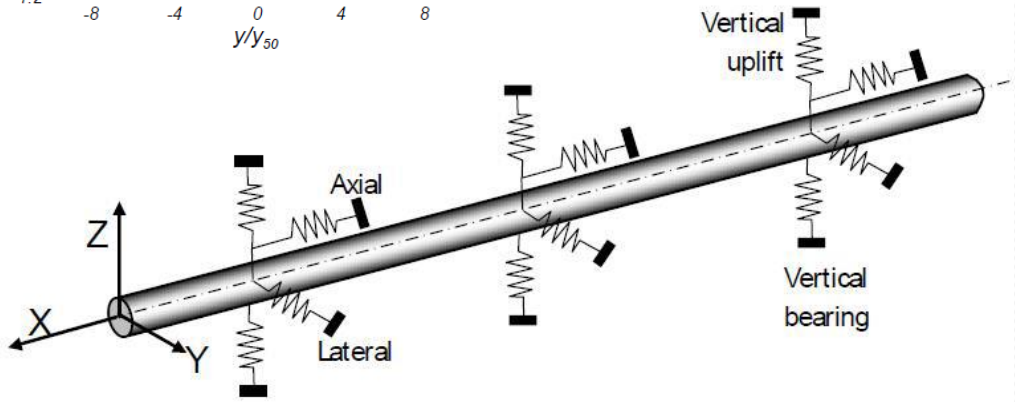
N. Psyrras et al. (2018)

Background

- Soil-pipe Interaction Analysis – Practical Numerical Model







Background

- Lumped Spring Model Representing Soil-Pipe Interaction
  - Monotonic force-deformation relationship
    - Audibert and Nyman 1977:
      - Tested pipes of diameter 25 to 114 mm
    - Trautmann and O' Rourke 1985:
      - Tested pipes of diameter 102 and 324 mm

$$P = \frac{y}{\frac{0.145\Delta_p}{P_u} + \frac{0.855y}{P_u}}$$

$$P = \frac{y}{\frac{0.17\Delta_p}{P_u} + \frac{0.83y}{P_u}}$$

Developed hyperbolic equations to describe force-displacement relationships

P_u: Maximum force which can be transferred pipeline per unit length

Δ_p: The displacement that corresponds into full development of P_u

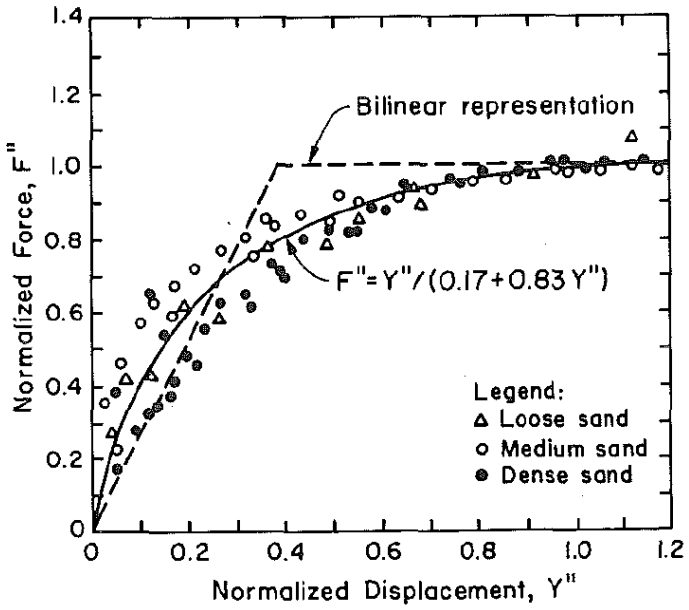
$P_u = \gamma' D H N_{qh}$

γ': Soil effective unit weight (equal to total unit weight for dry soil)

D: Pipeline outside diameter

H: Pipeline centerline burial depth

N_{qh}: Soil bearing capacity factor of lateral resistance for cohesionless soils.



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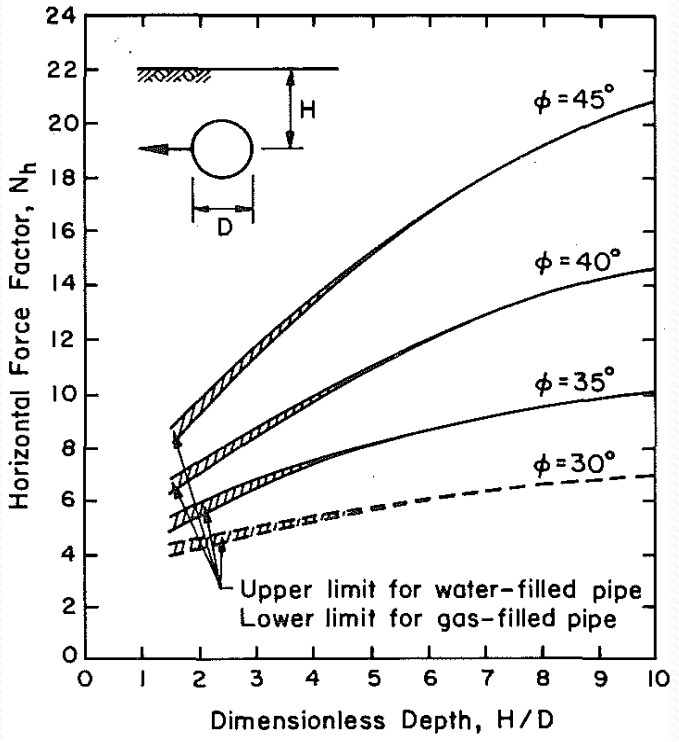
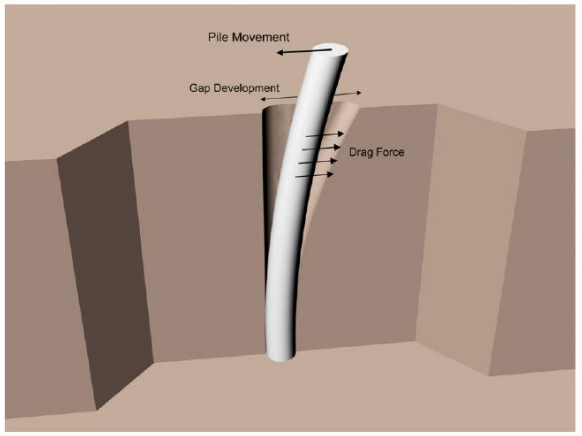
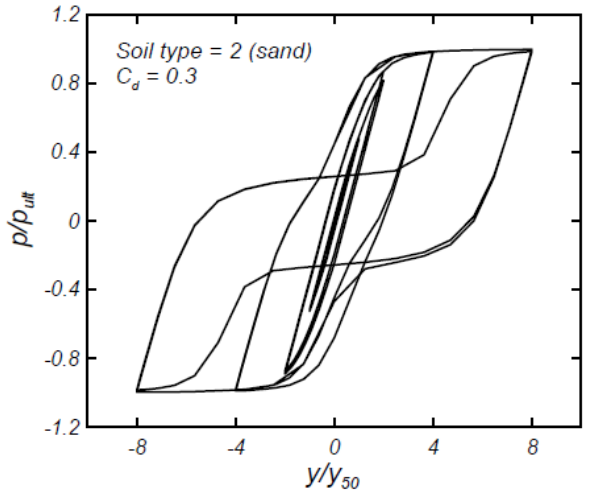
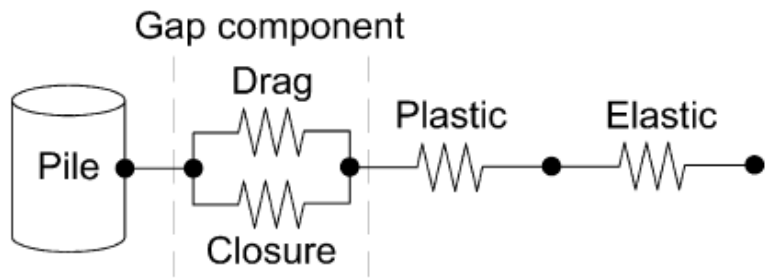


Background

- Lumped Spring Model Representing Soil-Pipe Interaction
  - Cyclic force-deformation relationship
    - No previous research for pipes under cyclic loading
    - Equations for cyclic behaviour of Piles developed by *Boulanger 2003*
    - Total displacement: $y = y^e + y^p + y^g$
    - Gap component: $P = P^d + P^c$







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    - Total displacement: $y = y^e + y^p + y^g$
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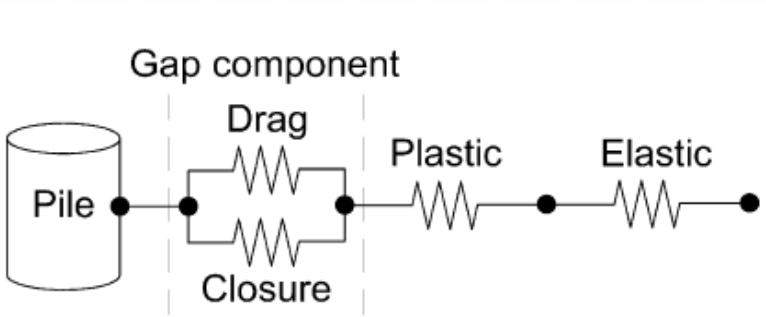
Elastic $$P = C_e \frac{P_u}{y_{50}} y^e$$

Plastic $$P = P_u - (P_u - p_0)\left[\frac{c\, y_{50}}{c\, y_{50} + \left|y^p - y_0^p\right|}\right]^n$$

Drag $$P^d = C_d P_u - (C_d P_u - p_0^d)\left[\frac{y_{50}}{y_{50} + 2\left|y^g - y_0^g\right|}\right]$$

Closure $$P^c = 1.8\, P_u \left[\frac{y_{50}}{y_{50} + 50(y_0^+ - y^g)} - \frac{y_{50}}{y_{50} - 50(y_0^- - y^g)}\right]$$



Outline

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- Numerical Study
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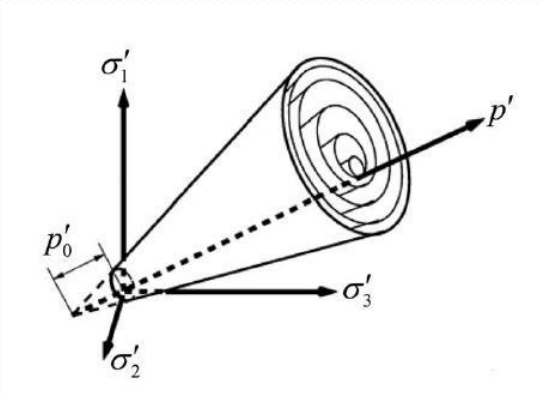
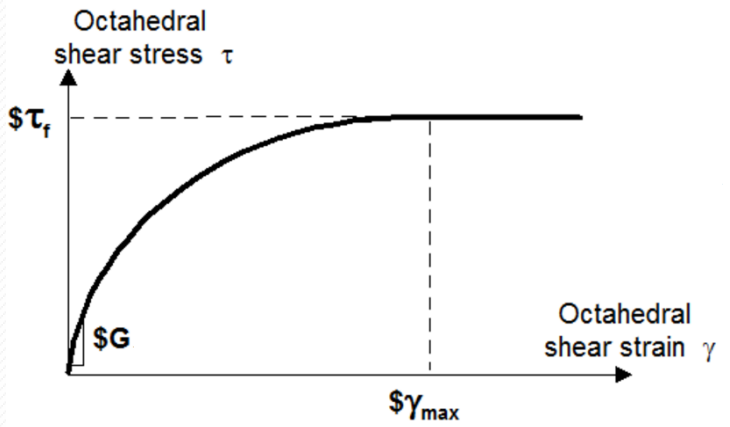
  - Soil Characterization
  - Monotonic and Cyclic Multi-axial Tests

Numerical Study

- Finite Element Analysis of Soil-Pipe Interaction
- Cohesionless material is assumed.
- Pressure Dependent material in OpenSees is used (PressureDependMultiyield02).
- Material strength τ_f and shear modulus G is increased when effective confining pressure p' is increased (failure surfaces expanding when pressure increases)
- Shear modulus is decreasing hyperbolically when shear deformation γ occurs
- Shear strength function of friction angle φ



$$G = G_r \left(\frac{p'}{p_r'}\right)^d$$



$$\tau = \frac{G \cdot \gamma}{1 + \frac{\gamma}{\gamma_r}\left(\frac{p'}{p_r'}\right)^d} \qquad \tau_f = \frac{2\sqrt{2}\sin\varphi}{3 - \sin f}\, p_r'$$

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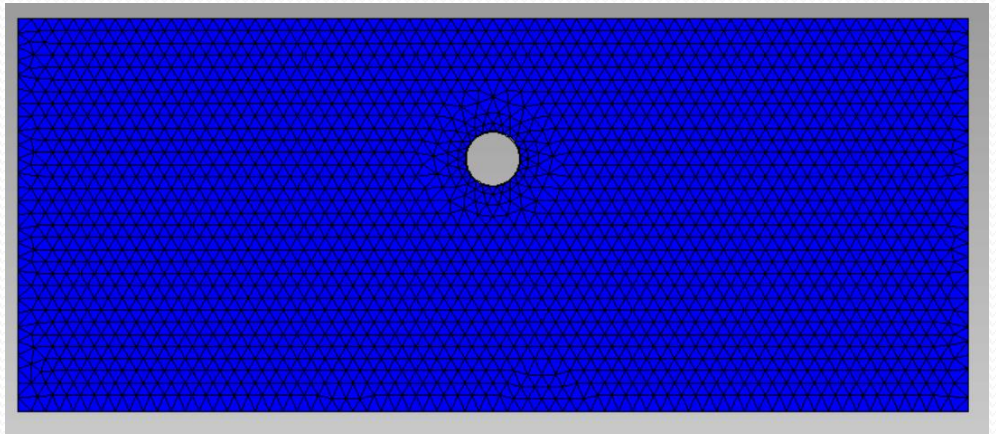
Numerical Study

- Finite Element Analysis of Soil-Pipe Interaction
  - Plane Strain Conditions
  - Pipe diameter D = 0.5 m
  - Material: PressureDependMultiyield02. Material calibrated in Nevada sand.
  - Soil Elements: Triangular elements with size of 0.075 m
  - Pipe Elements: Quad: 24 Quadrilateral elements along the perimeter (rigid)



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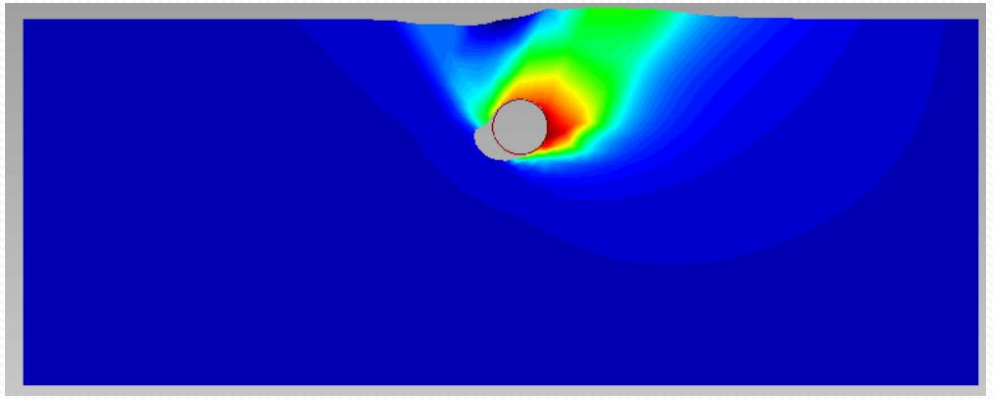

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Experimental Study

- Soil Characterization
  - Grain size distribution - Sieve Test (ASTM D6913 – 04)
  - Specific Gravity of solids (G_s) - Water pycnometer test (ASTM D854 -02)
  - Minimum unit weight (γ_{min}) - Mold method (ASTM D4254 -00)
  - Maximum unit weight (γ_{max}) - Mold method-Vibratory table method (ASTM D4253 -02)
  - Peak friction angle (φ_p) - Direct Shear Test
- Monotonic and Cyclic Multi-axial Tests
  - Monotonic and cyclic Tests in horizontal direction
  - Pipe Diameters: 50 mm and 100 mm
  - Experiments in 2 soil states: Loose and Dense soil
  - Transparent Plexiglass to have visibility inside the box
  - Fix the pipe in the reaction frame while the soil box moves with the shake table
  - Soil Box Dimensions: Length: 1.70 m, Height: 1.20 m, Width: 0.20 m

Experimental Study

- Specific Gravity of solids (G_s) - Water pycnometer test (ASTM D854 -02)

  Average $G_{s,20^\circ}$: 2.603

- Minimum unit weight (γ_{min}) - Mold method (ASTM D4254 -00)

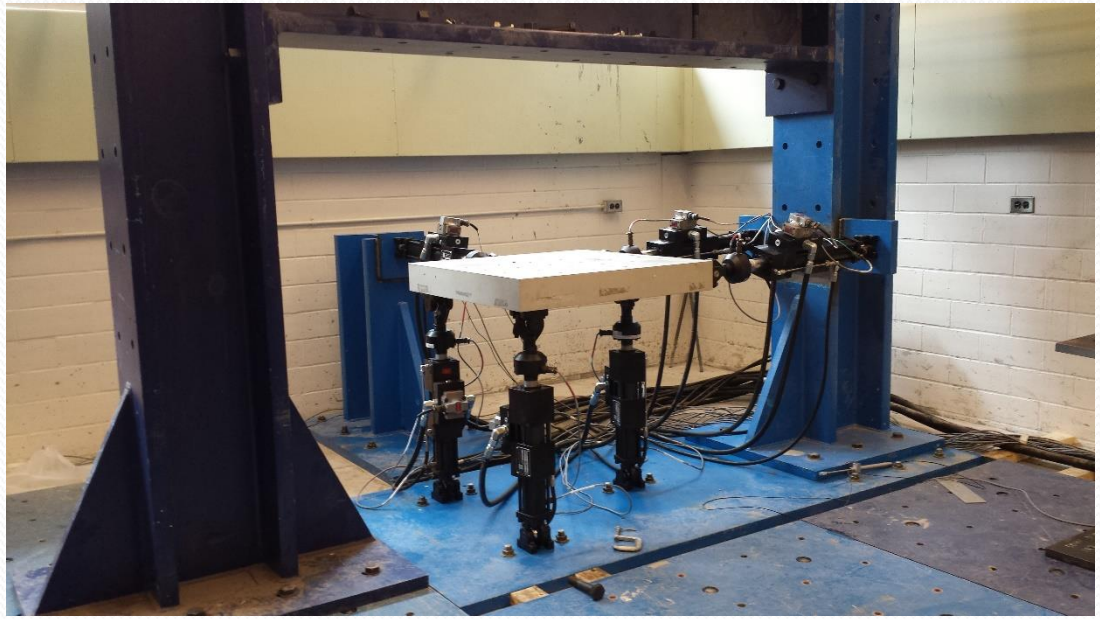
  γ_{min}: 13.89 KN/m^3, e_{max}: 0.839

- Maximum unit weight (γ_{max}) - Mold method-Vibratory table method (ASTM D4253 -02)

  γ_{max}: 16.55 KN/m^3, e_{min}: 0.543

Experimental Study

- Monotonic and Cyclic Multi-axial Tests
  - Control parameters
    - Loading type (monotonic, cyclic)
    - Boundary conditions: D/H ratio
    - Scale effect: Two different pipe diameters
    - Boundary effect: Two different soil thickness
    - Multi-axial loading conditions
      - Horizontal cyclic
      - Vertical cyclic



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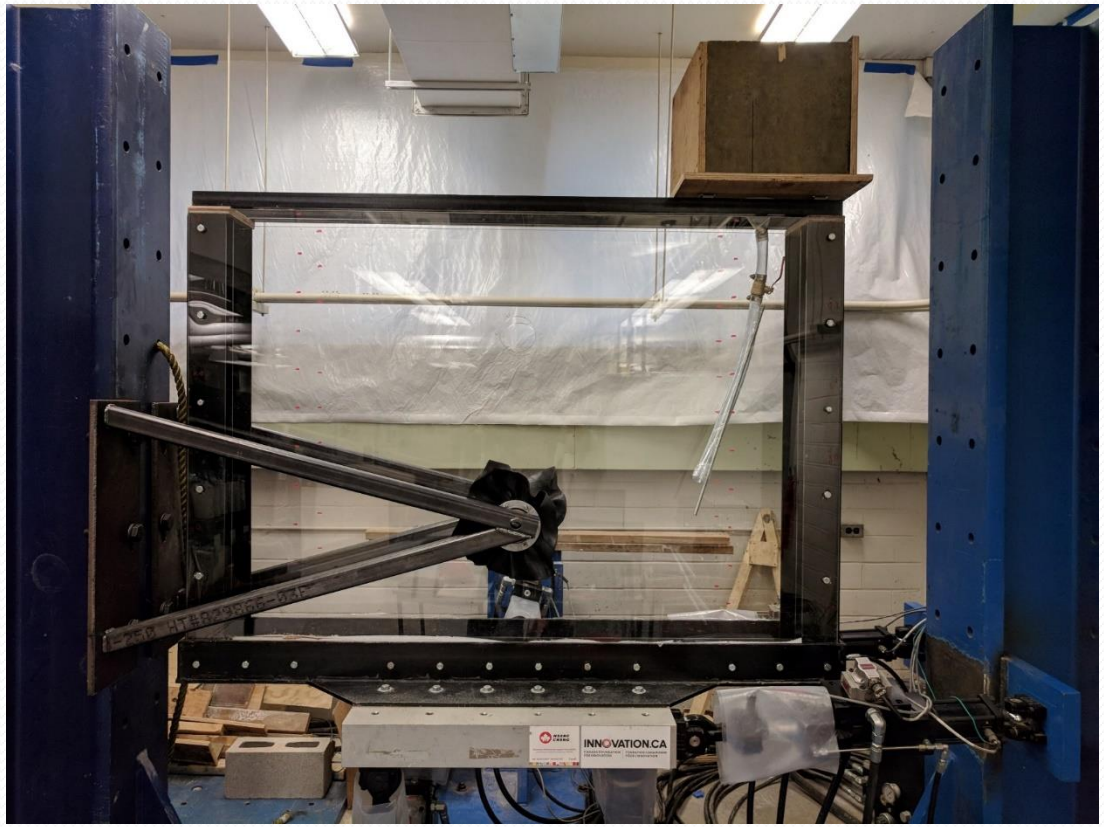

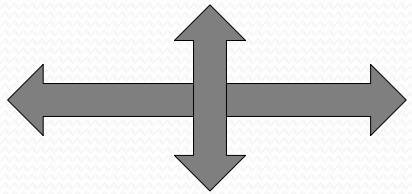

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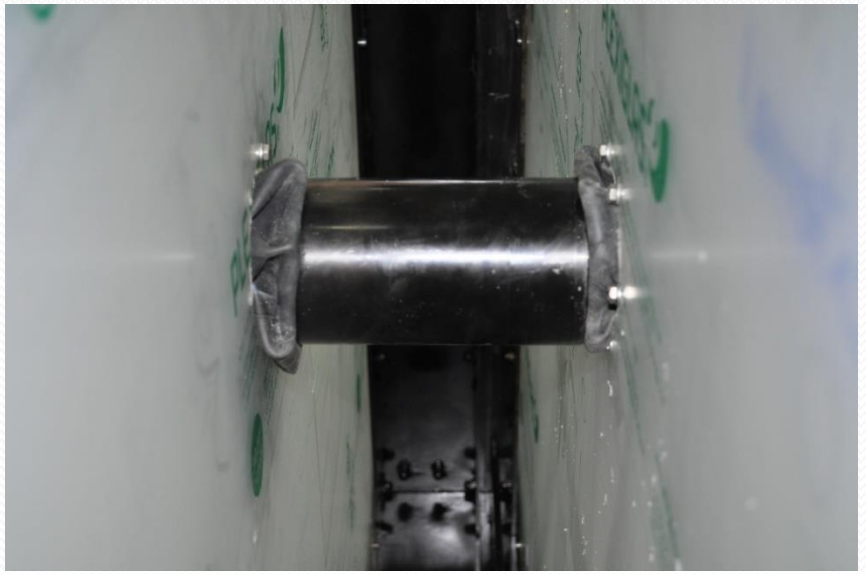

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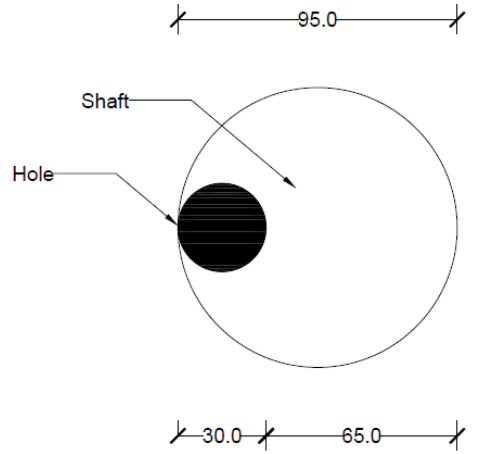
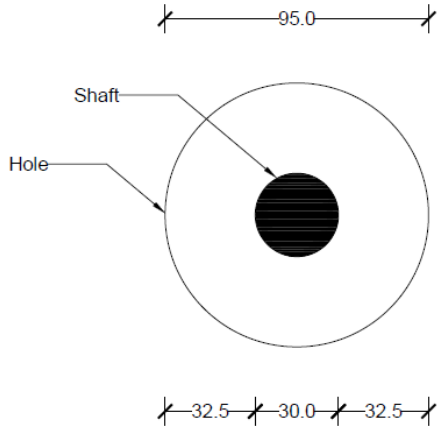
For Monotonic Loading

Hole 95 mm : Available stroke 65.0 mm



For Cyclic Loading

Hole 95 mm : Available stroke 32.5 mm



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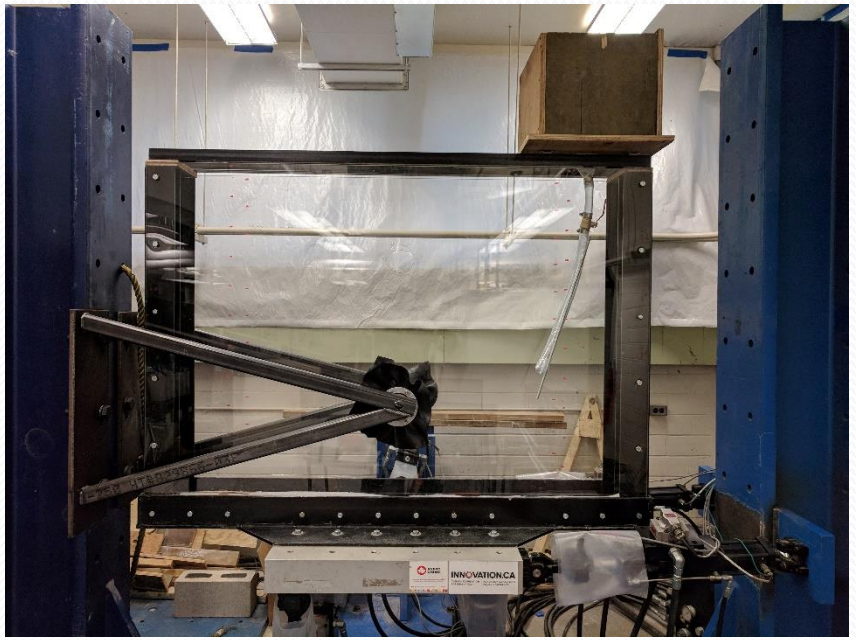
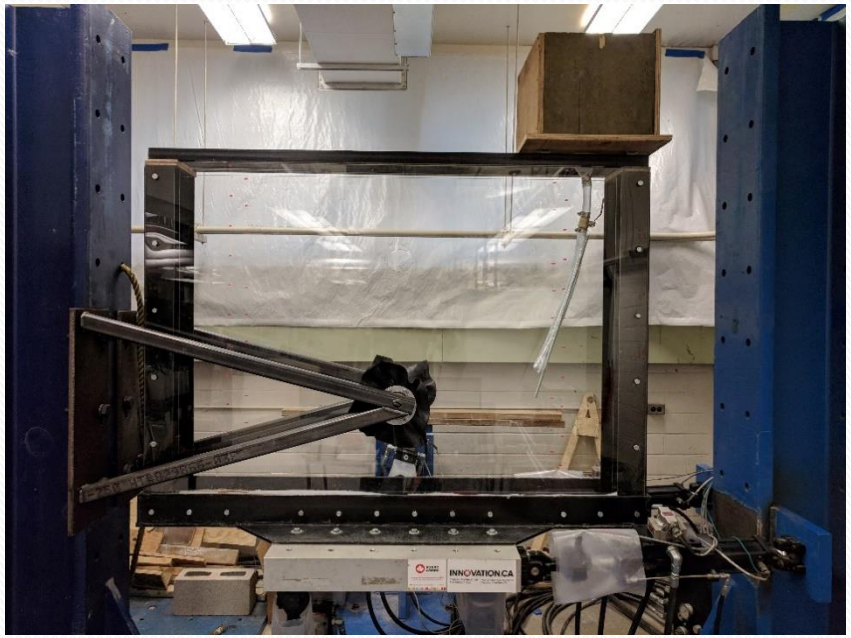
Experimental Study

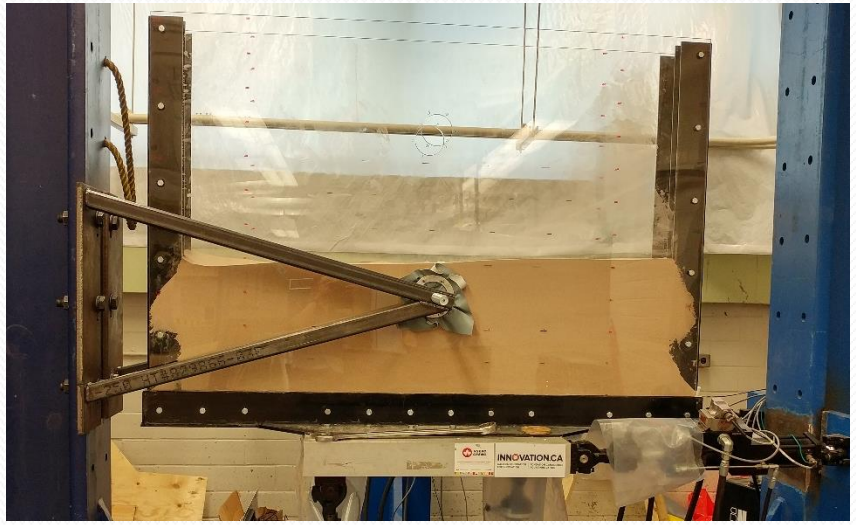
- Monotonic and Cyclic Multi-axial Tests
  - Minimum relative density
    - Using a small box with rollers, rails, funnel and tube
    - Pour the soil from an average height of 20 cm to control density
      - Unit weight: γ_d = 14.40 KN/m^3
      - Void Ratio: e= 0.773
      - Relative Density: D_r =22%



Experimental Study

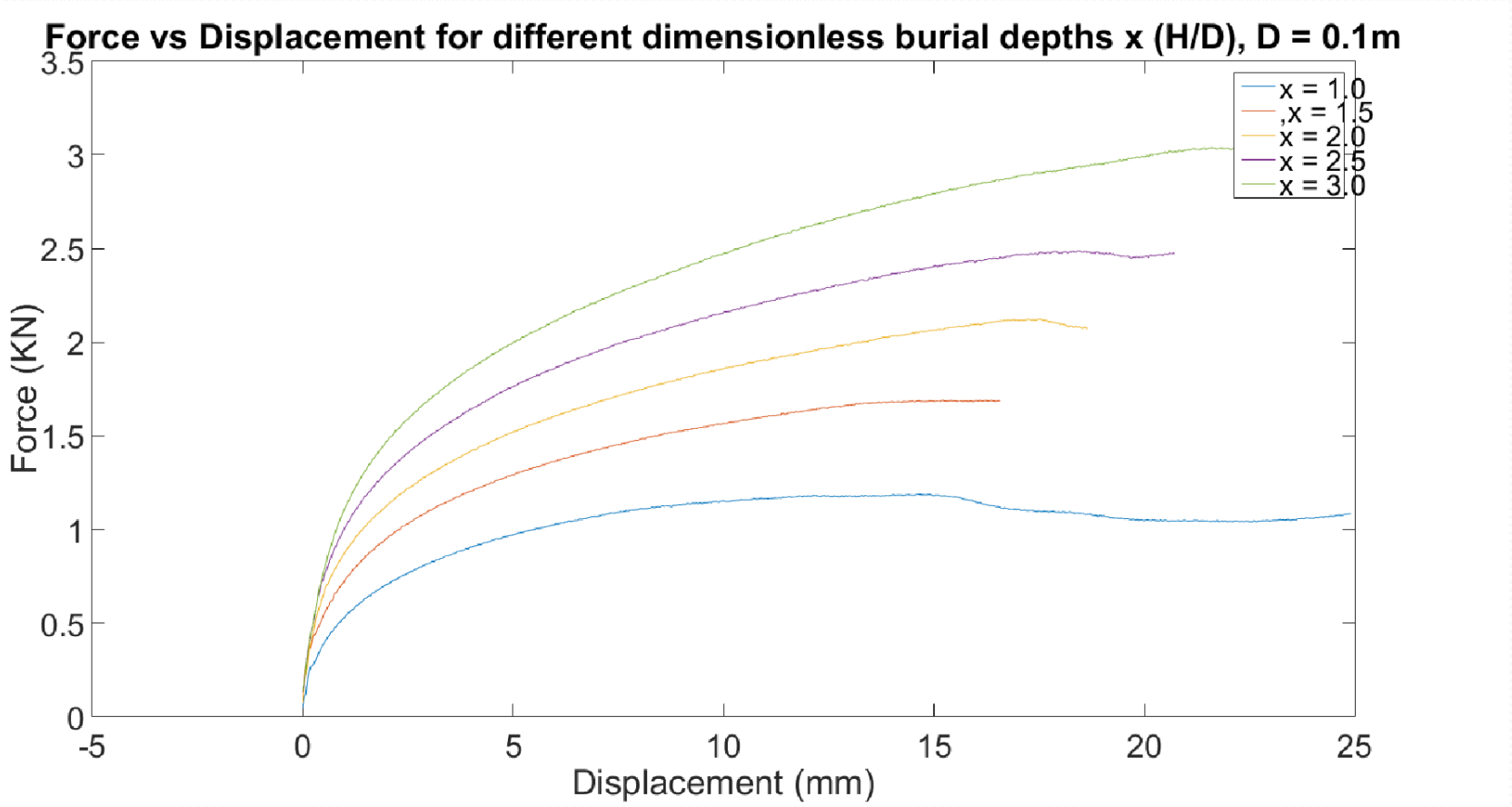
- Monotonic and Cyclic Multi-axial Tests
  - Maximum relative density
    - Using the shake table as a vibrator machine
    - Vibrate in 25 Hz and amplitude 0.5 mm
    - Densify in layers of 5 cm to achieve uniform densification
    - Load soil surface of 1 KPa to make the surface plane
      - Unit weight: γ_d = 16.55 KN/m^3
      - Void Ratio: e= 0.543
      - Relative Density: D_r =100%





Experimental Study

- Monotonic and Cyclic Multi-axial Tests
  - Preliminary results – Monotonic test with different burial depths.



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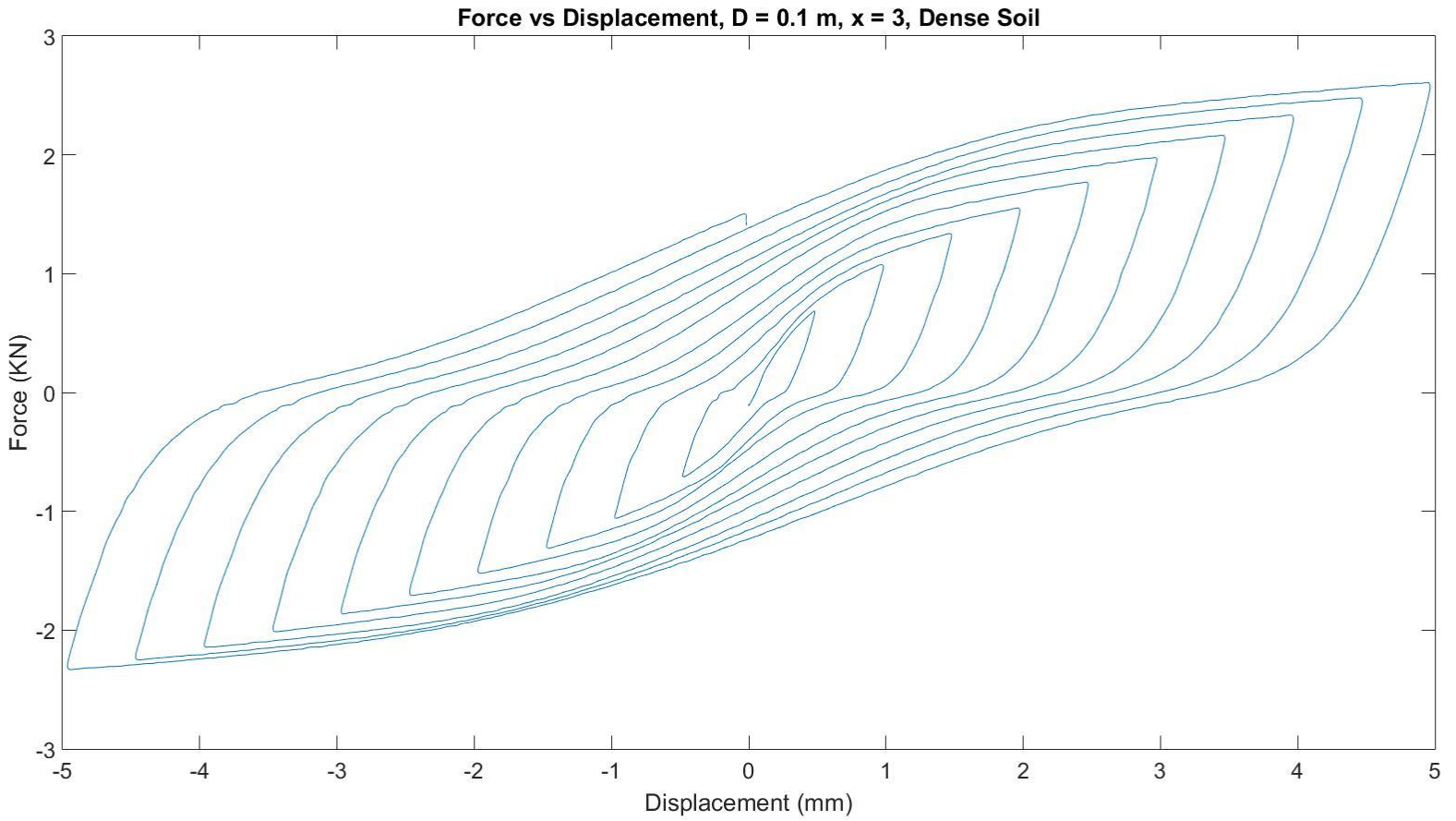
  - Preliminary results – Cyclic test



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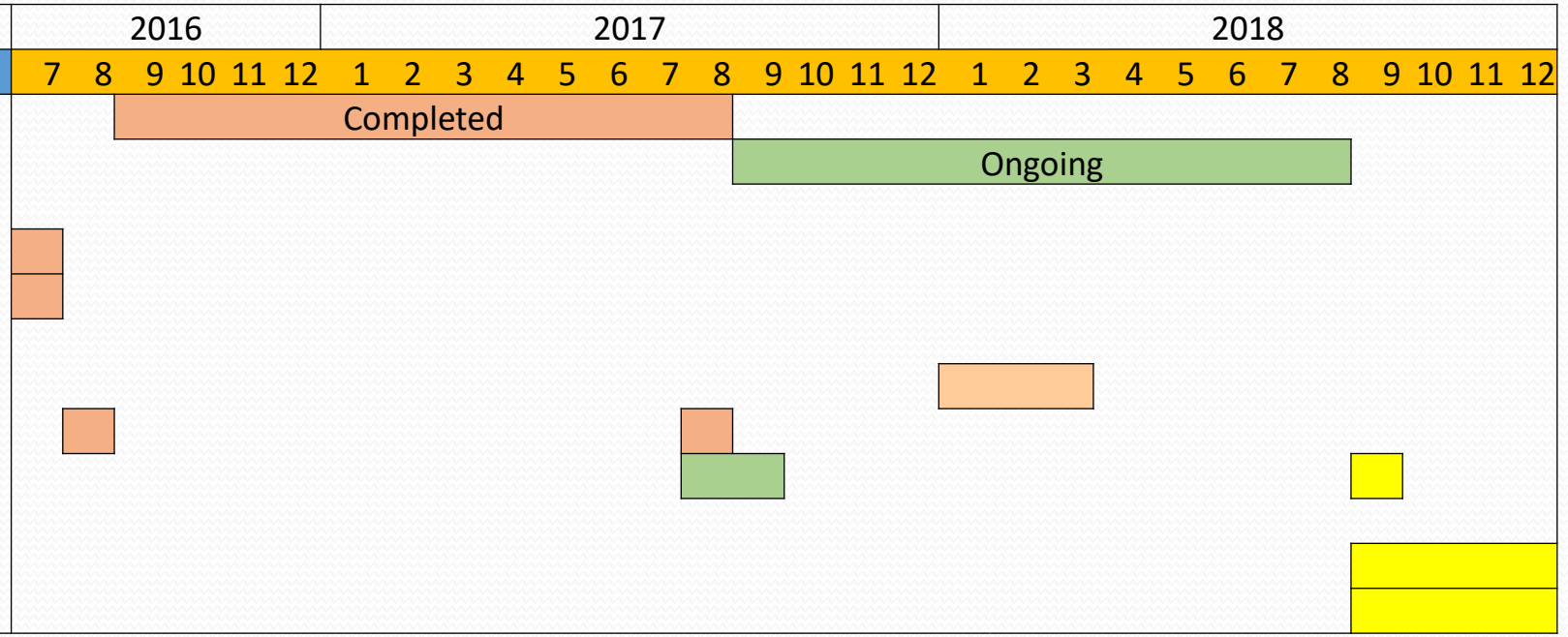
Remaining Tasks

- Extensive parametric studies (June ~ July)
- Development of a computationally efficient numerical model based on multi-axial plasticity theory
- Calibration of the model against experimental results

Completed, Ongoing, or Planned Secondments

Institution	Title	Name
UOB	Ph.D. student	Nikos Psyrras
UPAT	Ph.D. student	Kyriakos Tryfonos
UPAT	Dr.	Stathis Bousias
UOB	Dr.	Flavia De Luca
UOB	Dr.	Raffaele De Risi
AUTH	Dr.	Savvas Papadopoulos
UNAP	Dr.	Daniel Pohoryles
USAN	Dr	Luigi Di Sarno
UNAP	Dr.	Georgios Baltzopoulos
CAU	Ph.D. student	Binod Kafle
UNAP	Ph.D. student	Vasileios Makos
UNAP	Ph.D. student	Marietta Eleni Kolokytha



Kyriakos Tryfonos: Development of soil-pipe interaction model (p-x interaction) through multi-DOF controlled experiments

Flavia De Luca, Raffaele De Risi: Post-earthquake risk assessment for buried gas pipelines at regional scale; advanced empirical vulnerability of NG pipelines through machine learning approach

Georgios Baltzopoulos: Development of small-scale testing equipment for verification of hybrid simulation method before full-scale hybrid simulation

Nikos Psyrras: Analysis of effects of seismic ground motion on the stability of high-pressure natural gas pipelines buried in non-uniform sites

THANK YOU

FOR YOUR ATTENTION!!