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Design of Energy Piles Considering Soil-Structure Interaction and Unsaturated Soil Effects

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Presentation Overview

- Background on Thermo-Mechanical Response of Drilled Shaft Foundations used as Heat Exchangers (Energy Piles)
- Thermo-Mechanical Analyses and Issues to Consider
  - Finite element analysis
  - Thermal load-transfer (T-z) analysis
- Case History 1: US Air Force Academy Building
- Case History 2: Denver Housing Authority Building
- Case History 3: Centrifuge Modeling of Energy Piles in Sand and Unsaturated Silt
- Calibration of Load Transfer Analysis for Design Purposes

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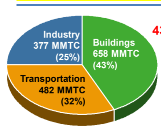
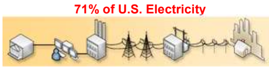
Motivation: High Energy Usage by Buildings

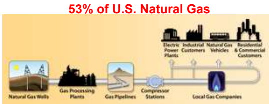


43% of U.S. Carbon Emissions

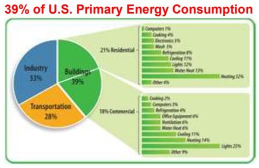
71% of U.S. Electricity



53% of U.S. Natural Gas



39% of U.S. Primary Energy Consumption



EIA (2008)

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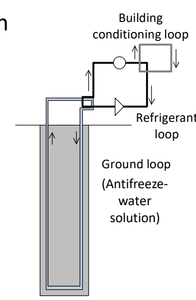
Concept of Ground Source Heat Pumps (GSHPs)

- GSHPs exchange heat between the ground and a building
- Do not generate energy, but move it from one place to another
- Exploit the heat pump cycle
- Can function in any location if designed properly and used properly (slower response)



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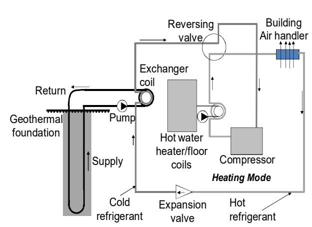
Heat Pump-Ground Loop Connection



Typical entering ground loop fluid temperatures:
Building heating: -1 to 4 °C
Building cooling: 20 to 35 °C
Ground temperature: 10 to 15 °C

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Conventional Borehole-Type GSHPs

- Require drilling of boreholes
- Require space outside building footprint
- Additional excavation of trenches below frost depth
- May require an exterior vault
- Must link loop field with building

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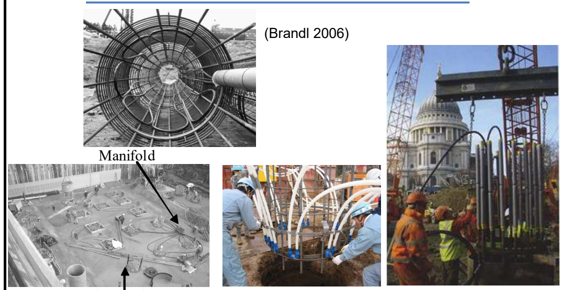
Energy Piles



(Brandl 2006)
(Ooka et al. 2007)
(Amis 2009)

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Thermal Design of GSHP Systems

- Goals of GSHP system design:
  - Install sufficient length of heat exchanger so that heat pulses can be absorbed by the surrounding soil via conduction
  - Avoid thermal overlap with other heat exchangers
- GSHP system design rules of thumb:
  - 1 thermal ton = 1200 BTU = 0.35 kWh
  - 3 to 4 thermal tons per 100 m^2 of building footprint
  - 150 m of heat exchanger per thermal ton

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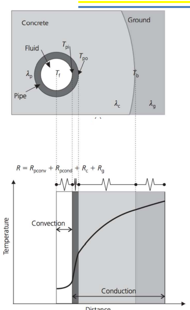
Conductive Heat Transfer in Energy Piles



Material	Thermal Conductivity (W/m°C)	Density (kg/m^3)	Heat Capacity (J/kg°C)
Concrete	1.6	2500	850
Steel Reinforcement	43	7850	490
HDPE Pipe	0.4	1100	1465
Water	0.58	1000	4180
Ethylene Glycol	0.25	1097	2470

Material	Thermal Conductivity (W/m°C)
Dry Sand	0.3-0.8
Dry Gravel	0.3-0.4
Peat	0.2-0.7
Dry Clay/Silt	0.4-1.0
Saturated Clay/Silt	0.9-2.3
Saturated Gravel	1.6-2.0
Claystone/Siltstone	1.1-3.5
Saturated Sand	1.5-4.0
Sandstone	1.3-5.1

Challenge: selection of heat pulses representative of building heating/cooling requirements

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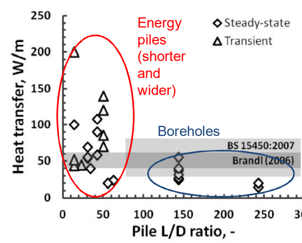
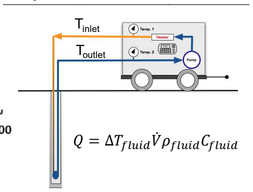
Thermal Response Testing of Energy Piles



Thermal loading	Heat transfer, W/m	
	Cooling mode	Heating mode
Transient	70 – 120	50 – 85
Steady-state	25 – 60	15 – 25



$$Q = \Delta T_{fluid} \dot{V} \rho_{fluid} C_{fluid}$$

Bourne-Webb 2013

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Thermo-Mechanical Design of Energy Piles

- Heating and cooling will lead to thermally-induced displacements
- Restraint provided by soil and overlying structure will lead to axial stresses
- Thermo-mechanical design goals:
  - Ensure axial stresses are within reasonable limits (i.e., with reference to the capacity of the pile and the strength of concrete)
  - Ensure displacements will not cause structural or architectural damage

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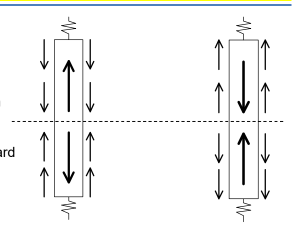
Thermo-Mechanical Soil-Structure Interaction

Sign Conventions
(+) Stress: Compression
(+) Strain: Contraction
(+) Side shear: Upward
(+) Displacement: Downward



Location of point of zero thermal axial displacement (null point)

Heating: Foundation Expands and is Restrained by Mobilized Side Shear Stresses and End Conditions

Cooling: Foundation Contracts and is Restrained by Mobilized Side Shear Stresses and End Conditions

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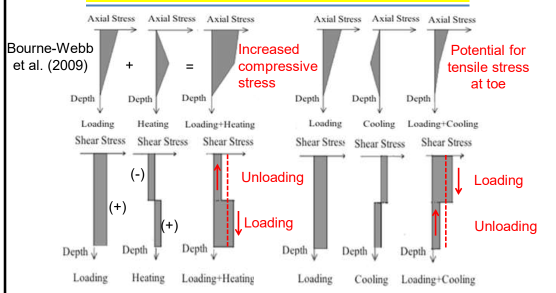
Soil-Structure Interaction for Floating Energy Piles



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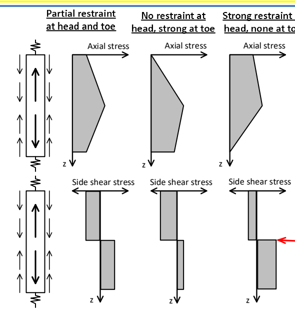
Influence of Top and Bottom Boundary Conditions



Most drilled shaft foundations have end-bearing bottom boundary conditions with strong restraint at toe

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Thermo-Mechanical Analysis Options

- Coupled thermo-hydro-mechanical finite element models
  - Require thermo-mechanical soil and concrete properties
  - Require an interface model
  - Potentially complex geometry that must be simplified
- Thermo-mechanical load transfer (T-z) analyses
  - Require an estimate of the ultimate capacity of the pile (i.e., distribution of ultimate side shear resistance and end bearing capacity), which may be affected by temperature
  - Requires nonisothermal T-z and Q-z curves
  - Should consider the potential effects of radial thermal expansion of the energy pile on the ultimate capacity

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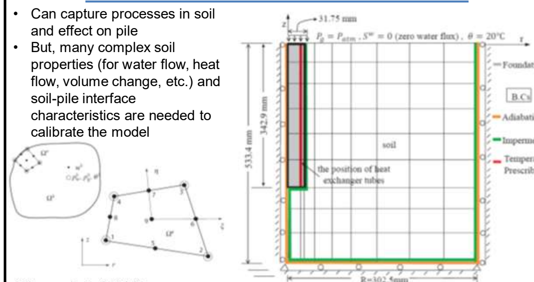
Thermo-Hydro-Mechanical FEA

- Can capture processes in soil and effect on pile
- But, many complex soil properties (for water flow, heat flow, volume change, etc.) and soil-pile interface characteristics are needed to calibrate the model



Wang et al. (2014)

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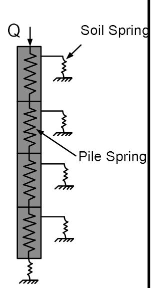
Load Transfer (T-z) Analysis

- Discretization of energy pile into elements
  - Represented by linear springs
- Soil-foundation displacements
  - Represented by non-linear springs
  - ***Ultimate pile capacity and nonisothermal T-z and Q-z curves are required***
- Iterative approach
  - Ensure equilibrium and compatibility of strains in the soil and foundation
- Outputs
  - Predicted load-settlement curve
  - Mobilized side shear with depth
  - Axial thermal stress/strain distribution



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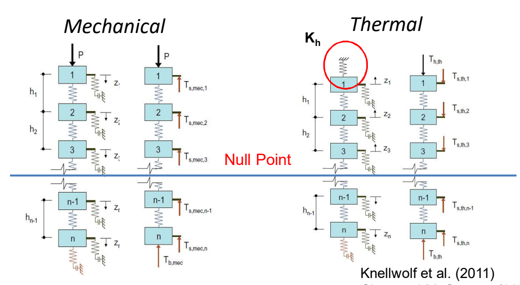
Thermal Load Transfer Analysis



Knellwolf et al. (2011)
Chen and McCartney (2016)

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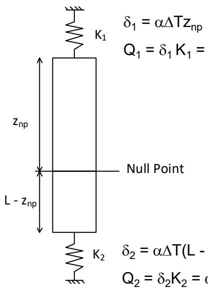
Boundary Conditions: Location of Null Point



$\delta_1 = \alpha\Delta T z_{np}$

$Q_1 = \delta_1 K_1 = \alpha\Delta T z_{np} K_1$

Equilibrium:

$Q_1 = Q_2$

$\alpha\Delta T z_{np} K_1 = \alpha\Delta T(L - z_{np})K_2$

$z_{np} = LK_2 / (K_1 + K_2)$

$\delta_2 = \alpha\Delta T(L - z_{np})$

$Q_2 = \delta_2 K_2 = \alpha\Delta T(L - z_{np})K_2$

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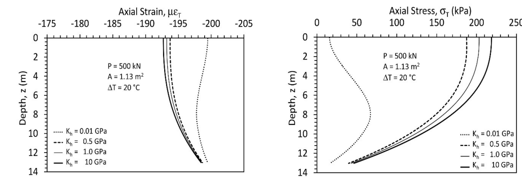
Thermal Load Transfer Results (Semi-Floating)

Plaseied (2011)

Low K_h => Free head movement
High K_h => Constrained head movement



- Stiffness of the spring at the foundation head (K_h) is key to predict thermal axial stress and strain profiles **> Hard to define**
- Displacement at bottom of foundation is associated with Q-z curve
- Possible changes in radial stress and side shear distribution during heating

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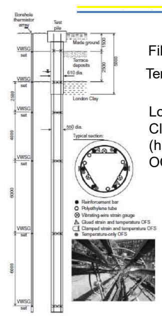
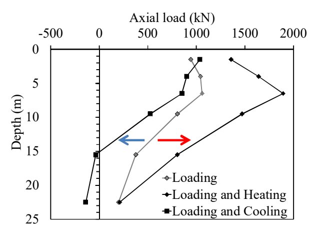
Lambeth College (UK) Case Study



Fill
Terrace
London Clay (high OCR)



Heating from 20 °C to 40 °C
Cooling from 20 °C to -6 °C

(Bourne-Webb *et al.* 2009; Amatya et al. 2012)

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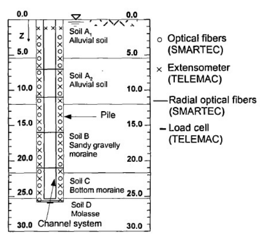
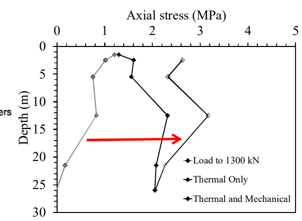
EPFL (Switzerland) Case Study





Heating ΔT = 20 °C

(Laloui et al. 2006; Laloui and Nuth 2006)

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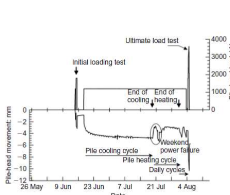
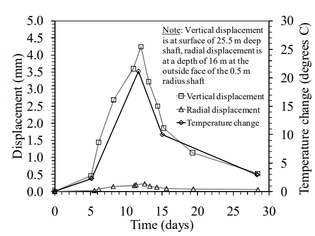
Thermal Deformations of Energy Piles (During Load-Control Proof Tests)



UK: Bourne-Webb et al. (2009)
~2 mm for ΔT = 20 °C over 23 m foundation



Switzerland: Laloui et al. (2006)
~4.5 mm for ΔT = 20 °C over 25 m foundation

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Case History 1: US Air Force Academy Project

Murphy, K.D., McCartney, J.S., and Henry, K.S. (2015). "Evaluation of thermo-mechanical and thermal behavior of full-scale energy foundations." Acta Geotechnica. 10(2), 179-195.

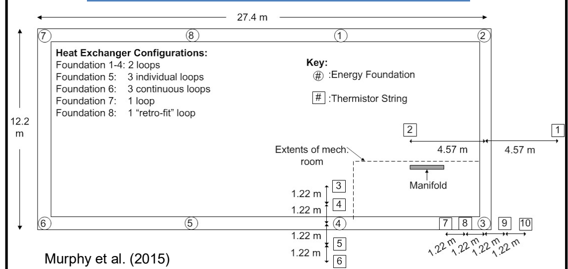
Eight 15.24 m-deep energy piles with different heat exchange configurations under a new shower/shave facility

Site Investigation Details

Layer	Depth to bottom of stratum (m)	Material encountered	SPT N-value (blows/300 mm)	Gravimetric water content (%)	Dry unit weight (kN/m³)
1	1	sandy fill with silt and gravel	70	5	18.4
2	2	dense sands, silt, and gravel	85	7	19.2
3	12+	silty sandstone	50/25.4 mm	N/A	N/A

Drilled shaft construction method: Dry hole approach
Potential Problem: Difficulty in cleaning out toe

USAFA Building Layout



Murphy et al. (2015)

Energy Pile Heat Exchanger Pictures

Lifting Reinforcement Cage

Lowering Reinforcement Cage into Hole

Concrete Placement

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Heat Exchanger Manifold


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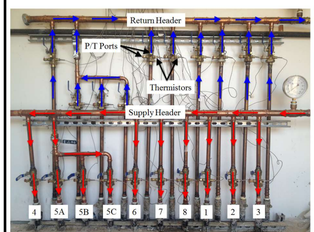
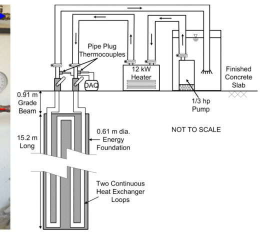
Heat Distribution System





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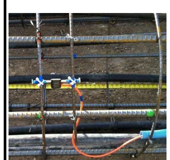
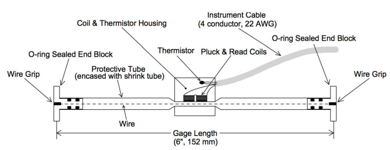
Embedded Vibrating Wire Strain Gauges

$\varepsilon = -Gf^2$ (Geokon 2011)

ε: Axial strain
G: Gauge factor = 3.304 × 10^{-3}
f: Resonant frequency of wire

$\varepsilon_{thermal} = [(\varepsilon - \varepsilon_0)B + (T_i - T_0)\alpha_s]$

ε_0: Mechanical strain
B: Batch factor ~ 1
T = Temperature
α_s: steel coeff. thermal exp.

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Finished Foundation System

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Current Status


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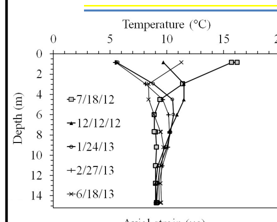
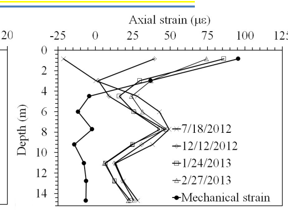
Seasonal Ground Temperature and Axial Strain Profiles





Depth of major fluctuations in temperature: 5 m

Mechanical stress corresponds to axial load of 833 kN (E = 30 GPa)

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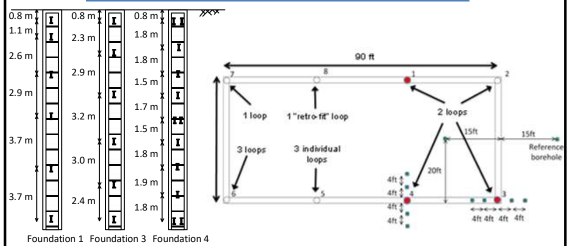
Thermo-Mechanical Characterization



Foundation 3: Corner pile – lower head stiffness due to corner location and due to expansion of adjacent foundations
Foundation 4: Interior pile – more head restraint from grade beam

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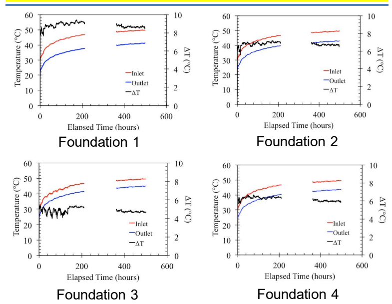
Fluid Temperature Rise Curves



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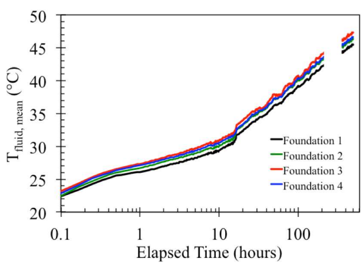
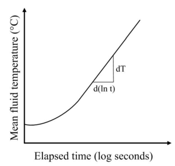
Mean Fluid Temperature Rise Curves





$$\lambda_a = \frac{Q}{4\pi L}\left[\frac{dT}{d(\ln t)}\right]^{-1}$$

$$Q = \Delta T \dot{V} \rho_{fluid} C_{fluid}$$

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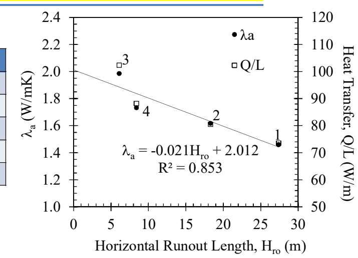
Thermal Conductivity Estimates

$$Q = \Delta T \dot{V} \rho_{fluid} C_{fluid}$$

Parameter	Value
Water-glycol ratio	5:1
Mol. heat cap. (J/molK)	98
Mol. weight (g/mol)	30
Sp. heat cap. (J/kgK)	3267
Density (g/ml)	1.008

$$\lambda_a = \frac{Q}{4\pi L}\left[\frac{dT}{d(\ln t)}\right]^{-1}$$



All four energy piles have identical heat exchanger configuration (2 loops)

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Thermal Response Test Summary

Foundation #	1	2	3	4
Run-out length, H_{ro} (m)	27.4	18.3	6.1	8.4
Effective length, L (m)	42.6	33.5	21.3	23.6
Flow rate (ml/s)	109	119	137	106
Q (W)	3133	2696	2180	2081
Q/L (W/m)	73.5	80.5	102.3	88.2
dT/d(ln t)	4.01	3.96	4.10	4.05
λ_a (W/mK)	1.5	1.6	2.0	1.7
$\lambda_{a, corrected}$ (W/mK)	2.0	2.0	2.1	1.9

- Q/L represents system response and ranges from 73.5 to 102.3 W/m, which is consistent with trends in the literature (L/D = 25)
- $\lambda_{apparent}$ represents system thermal conductivity

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Comparison of TRT Results to Previous Studies

Case	Hamada et al.(2007)	Ooka et al. (2007)	Gao et al. (2008)	Lennon et al. (2009)	Brettmann and Amis (2011)	USAFA
Foundation type	26xD.P.	2xD.S.	1xD.S.	4xD.P.	3xA.C.I.P.	8xD.S.
Foundation length (m)	9	20	25	12-17	18.3	15.2
Foundation diameter (mm)	300	1500	600	244-270	300-450	610
# Heat Exchanger Loops	1,2, Indirect/ Direct Pipe	8	1-3	1	2	1-3
TRT Analysis Method	N/A	N/A	Num. Method	Line Source	Line Source	Line Source
Thermal Conductivity (W/m°C)	N/A	N/A	5.8-6.0	2.4-2.6	2.5-2.6	1.9-2.1 (Found. 1-4)
Heat Exchange Rate (W/m)	54-69 (ext.)	100-120 (rej.) 44-52 (ext.)	57-108 (rej.)	N/A	73-80 (rej.)	72-99 (rej.) (Found. 1-4)

***DS: Drilled shaft, A.C.I.P.: Auger cast in place pile, D.P.: Driven Pile**
**** Rej.: Heat rejection into foundation, Ext.: Heat extraction from pile**

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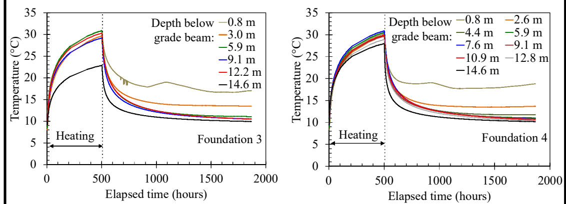
Energy Pile Temperatures During TRT



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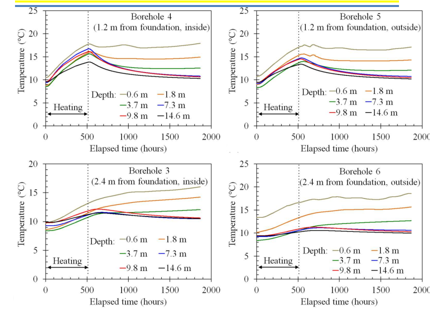
Borehole Temperatures During TRT



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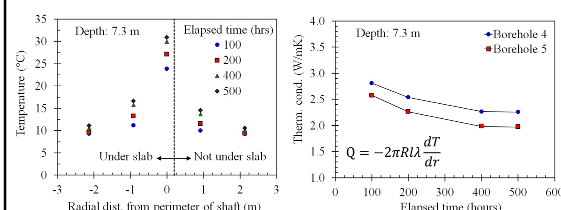
Thermal Conductivity from Conduction Analysis



Less heat is transferred to the subsurface outside of the building footprint (insulating effect of slab enhances heat transfer)

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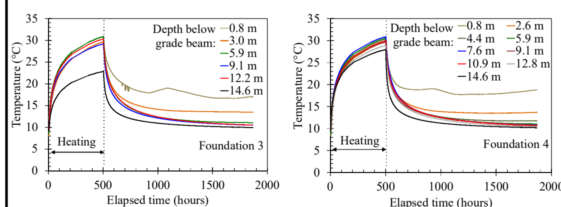
Energy Pile Temperatures During TRT (Revisited)



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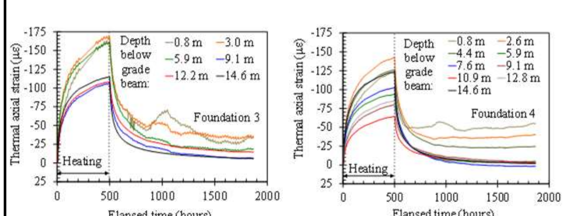
Energy Pile Thermal Axial Strains During TRT



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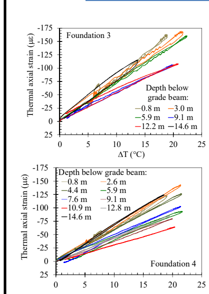
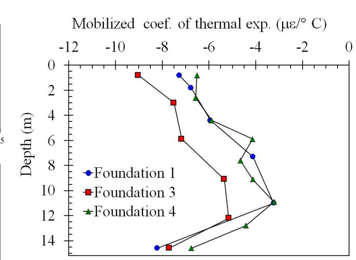
Mobilized Coefficient of Thermal Expansion





$\alpha_{concrete} = \alpha_{free\text{-}expansion} = -12\ \mu\varepsilon/°C$

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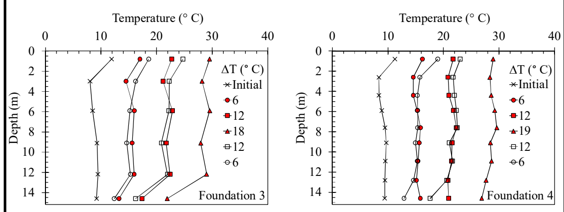
USAFA Foundation Temperature Profiles



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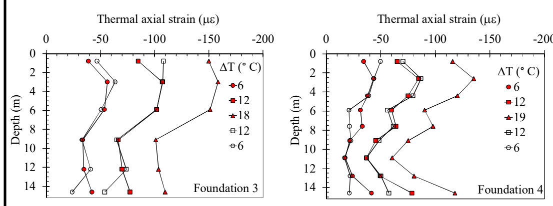
USAFA Thermal Axial Strain Profiles



$\varepsilon_{thermal} = \varepsilon_{measured} - \varepsilon_{mechanical} + \alpha_{steel}\Delta T$

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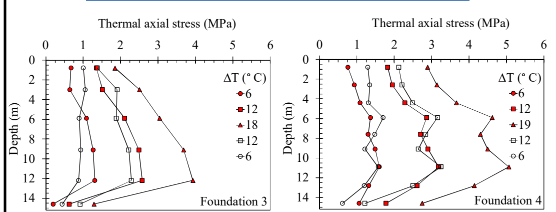
USAFA Thermal Axial Stress Profiles



$\sigma_{thermal} = E(\varepsilon_{thermal} - \alpha_{concrete}\Delta T)$

$\alpha_{concrete} = \alpha_{free\text{-}expansion}$ = -12 με/°C and E = 30 GPa

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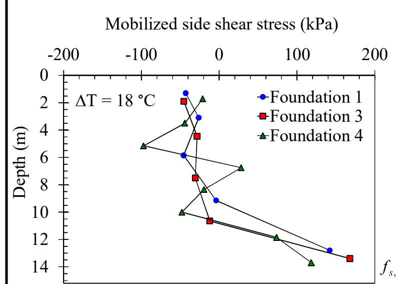
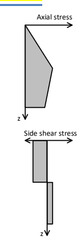
USAFA Mobilized Side Shear Stress Profiles





$$f_{s,mob}(z_j) = \frac{(\sigma_{T,j-1} - \sigma_{T,j})D}{4(z_j - z_{j-1})}$$

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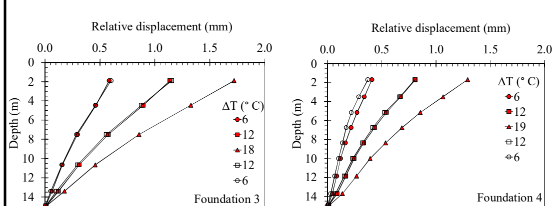
USAFA Thermal Axial Displacement Profiles



$$\delta_{therm,i} = \delta_{therm,i-1} + \frac{1}{2}(\varepsilon_{tm,i-1} + \varepsilon_{tm,i})\Delta l$$

(displacements are relative to unknown toe displacement)

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Evaluation of Head Displacement Data

Structure	Tolerable Distortion	Qualifications
circular steel tank with a fixed top	1/125	tanks have flexible base
circular steel tank with a floating top	1/500 to 1/333	ditto
tracks for overhead cranes	1/333	measured along the length of the track
tall structures	1/500	
jointed concrete pressure pipe	1/67	change in slope at a joint
steel frame warehouses with flexible walls	1/167 to 1/125	consider separately over-head cranes, forklift trucks, utility lines
one or two story houses with brick walls	1/500 to 1/333	use larger value if settlement occurs before construction of the more brittle elements
structures with brittle finishes like plaster, ornamental stone, and tile	1/1000 to 1/500	use larger value if settlement occurs before construction of the more brittle elements
flexible buildings with insensitive wall finishes like dry wall, moveable panels, and glass panels	1/500 to 1/333	consider the frame separately
heavy multistory structure on a rigid concrete mat	1/667	consider wall finishes separately

Bjerrum (1963)

δ/L ~ 1/6000
(No problem)

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Case History 2: Denver Housing Authority (DHA)

- Denver Housing Authority Senior Center Facility
- Includes a conventional geothermal system to provide heating/cooling
- 2 drilled shafts converted to energy piles
- Groundbreaking: Sept. 27, 2010
- Completion: January 2012

Murphy, K.D. and McCartney, J.S. (2015). "Seasonal response of energy foundations during building operation." Geotechnical and Geological Engineering. 33(2), 343-356.

McCartney, J.S. and Murphy, K.D. (2017). "Investigation of potential dragdown/uplift effects on energy piles." Geomechanics for Energy and the Environment. 10(June), 21-28. DOI: 10.1016/j.gete.2017.03.001.

Milender White Construction Co.

DHA DENVER HOUSING AUTHORITY THE BUSINESS OF HOUSING

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Conventional GSHP System at the DHA Building

40 conventional geothermal boreholes installed in the parking lot

- Depths: 470 ft
- Diameters: 4 inch boreholes, 1.75 inch PEX tubing
- Backfill: Sand-bentonite grout
- Total thermal energy to heat pump: 75 thermal tons (263.5 kW)
- Design fluid temperatures: 32.2 °C (cooling) 1.7 °C (heating)

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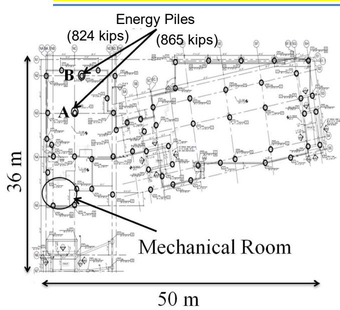
Building Foundation Plan



60 Drilled Shafts
L > 14 m

Diameters from 0.46 to 0.91 m

Minimum 1.6 m socket into bedrock

Energy piles chosen for proximity to mechanical room and large diameter (0.91 m)

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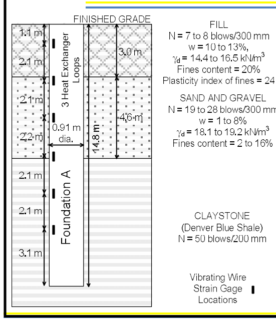
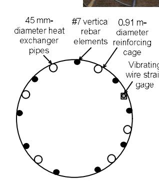
DHA Heat Exchange Tubing & Soil Profile



Foundation A:
3 loops
14.8 m deep



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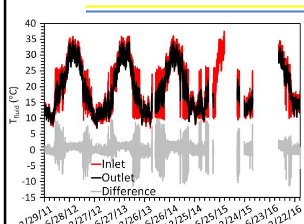
DHA Temperatures during Heat Pump Operation



Interior Foundation A
Q/L_{ave} ≈ 91 W/m

$$\dot{Q} = \Delta T \dot{V} \rho_{fluid} c_{fluid}$$

- Flow rate of 20 ml/s was estimated
- 20% methanol solution was used
- High values in spring/fall are due to stagnant water flow in the system, leading to increases in ambient fluid temperature
- Similar response for A and B so only A is discussed here

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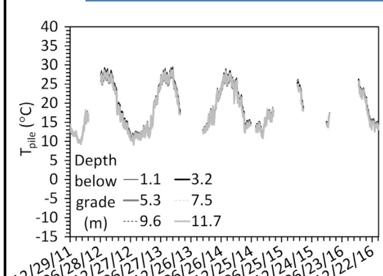
Pile Temperatures with Depth



- Temperatures range from 10 to 30 °C
- Temperatures are relatively consistent with depth
- Temperatures trends follow heat exchanger fluid temperatures

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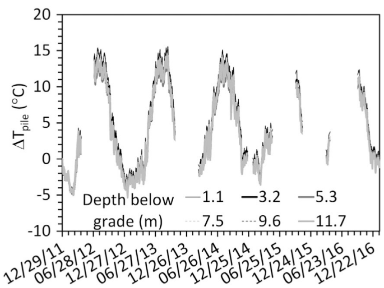
Pile Changes in Temperature with Depth



- ΔT range is about 20 °C
- Initial cooling followed by a significant heating event (not balanced about zero)
- Cycles are similar over each year but depend on demand

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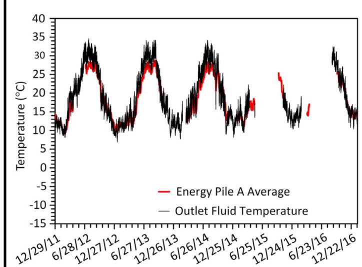
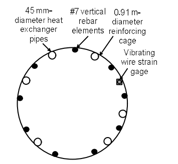
Energy Pile and Fluid Temperatures





- Bulk energy pile temperature is up to 4°C different from the fluid temperature
- This will cause differential strains across the pile area

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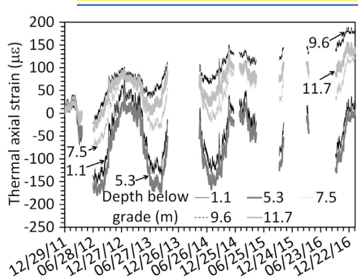
DHA Thermal Axial Strains



- Thermal strains are expected to follow the sinusoidal temperature trends
- Strains near the bottom of the pile indicate that there may be compressive strains developing over time superimposed atop the thermal strains (dragdown…)

$\varepsilon_{thermal} = \varepsilon_{measured} - \varepsilon_{mechanical} + \alpha_{steel}\Delta T$

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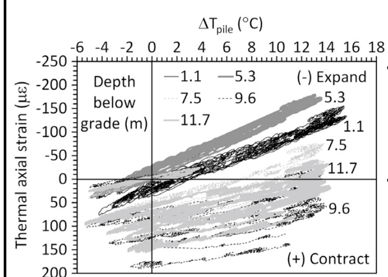
Mobilized Coefficient of Thermal Expansion



- Hysteresis loops are generally linear (expected for thermo-elastic materials)
- However, a downward shift is observed over time

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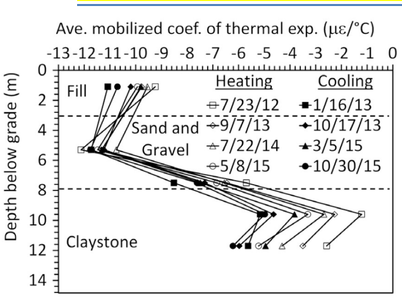
Mobilized Coefficient of Thermal Expansion



- Closed markers are the slopes of the ε_{aT} vs. ΔT curves for the cooling seasons
- Open markers are the slopes of the ε_{aT} vs. ΔT curves for the heating seasons
- Variations do not show a significant temporal effect

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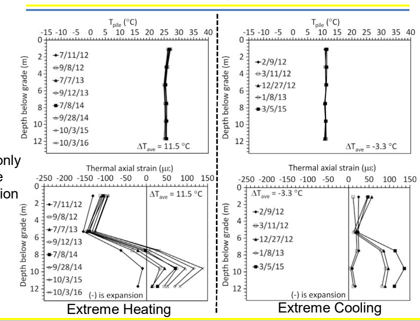
Extreme Heating/Cooling Events

Should expect only negative (expansion strains)



Should expect only positive (contractile strains)

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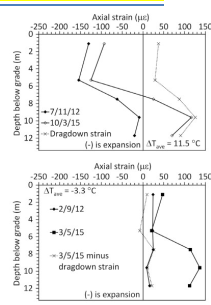
Dragdown Strain Evaluation

- Evaluate the difference in the thermal axial strains after several years of extreme heating to the same temperature
- The difference in thermal axial strain can be attributed to dragdown
- This dragdown strain can be subtracted from the thermal axial strains during cooling to verify the observed trend



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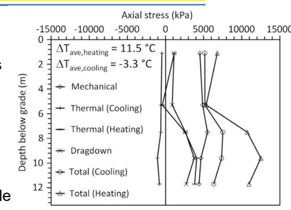
Thermo-Mechanical Axial Stresses

Isolation of the dragdown strains permits a rational interpretation of the total thermo-mechanical stresses in the pile due to mechanical loading, heating effects, and dragdown effects

Dragdown will not occur in all soil deposits, but it should be carefully considered as it adds stress to the pile



$$\sigma_{thermal} = E(\varepsilon_{thermal} - \alpha_{concrete}\Delta T)$$

$$\alpha_{concrete} = \alpha_{free\text{-}expansion} = -13\ \mu\varepsilon/°C \text{ and } E = 30\text{ GPa}$$

$$\sigma_{dragdown} = E\varepsilon_{dragdown}$$

$$\sigma_{total} = \sigma_{dragdown} + \sigma_{thermal} + \sigma_{mechanical}$$

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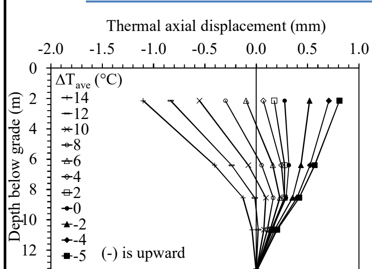
Thermal Axial Displacements



- Nonlinear distribution in displacements is noted with depth
- Magnitude of thermally-induced displacements is relatively small and is not sufficient to cause architectural damage

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Case	Laloui et al. (2006)	Bourne-Webb et al. (2009)	USAFA Murphy et al. (2014)	DHA McCartney and Murphy (2012); Murphy (2013)
Load mechanism at foundation head	Building dead load	Load control frame	Building dead load	Building dead load
Foundation diameter (m)	0.88	0.56	0.61	0.91
Foundation length (m)	25.8	23	15.2	14.8 (A), 13.4 (B)
Maximum mechanical load during heating test (kN)	0, 1300	1200	400	3840 (A), 3640 (B)
Range of ΔT (°C)	+21, +13	-19 to +29	+22	-5 to +14
Depth of max. thermal axial stress during heating (m)	21.0	17.0	11.6	11.6
Maximum thermal axial stress (kPa)	2100	-800 to 1900	5200	-? to 4500
Maximum increase in thermal axial stress with temperature (kPa/°C)	104	192	252	265
Estimated range in head displacement (mm) (negative is upward)	-4.2, not measured	4.0 to -2.0	-1.75	0.8 to -1.5

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Case Study 3: Centrifuge Modeling

- Measure empirical parameters for soil-structure interaction analyses for different boundary conditions
- Properties of scale-model piles and soil layers can be carefully controlled and independently characterized
- Different configurations can be considered for lower costs that full-scale testing in the field
- Incorporation of dense instrumentation arrays to capture thermo-mechanical effects in the energy pile as well as thermo-hydro-mechanical effects in the surrounding soil
- Scale-model energy piles can be loaded to failure to destructively characterize the effects of temperature on the load-settlement curve to back-calculate the ultimate side shear resistance and end bearing
- Effects like unsaturated soil conditions can be considered

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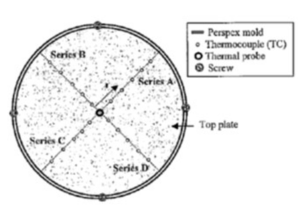
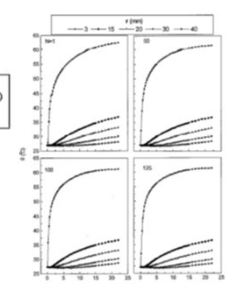
Heat Flow in Stiff Soils in the Centrifuge





Krishnaiah and Singh (2004)

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Scaling Conflict

- Temperature distribution is the same regardless of g-level
- Geometric similitude indicates that the time for heat flow in the centrifuge will be N^2 times faster in the centrifuge
- Strategies to overcome conflict:
  - Perform numerical simulations in model scale
  - Use quasi steady-state results in prototype scale and consider the results as representing a worst-case scenario
    - Heat flow has a larger zone of influence comparing the centrifuge prototype to a real system in the field
    - This means that any thermal effects (stresses associated with constrained thermal expansion, thermal expansion/contraction, etc.) will be greater in the centrifuge prototype
    - Perform tests after reaching steady state foundation temperature

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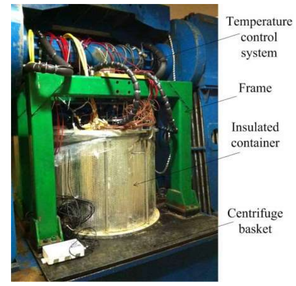
Centrifuge Modeling of Soil-Structure Interaction



Testing Phases:
1. Evaluate impact of temperature on strain distribution and deformation
2. Evaluate impact of temperature on ultimate capacity

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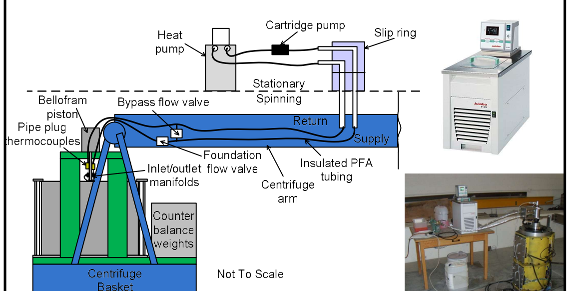
Temperature Control System



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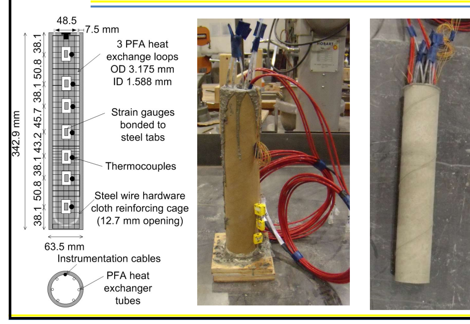
Scale-Model Energy Pile



N = 24 g

D_p = 1.5 m

L_p = 8.4 m

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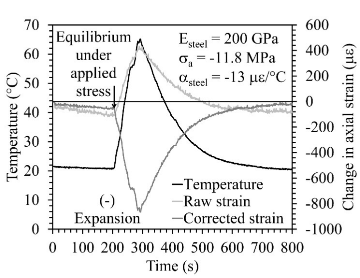
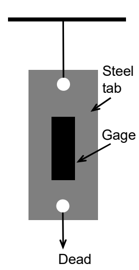
Calibration of Strain Gages Bonded to Steel Tabs





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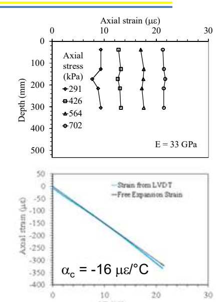
Energy Pile Characterization



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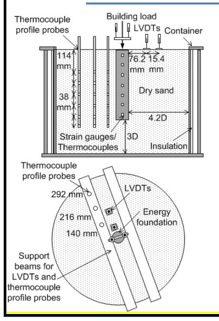
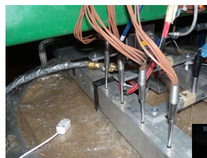
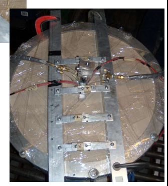
Container and Instrumentation







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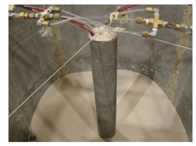
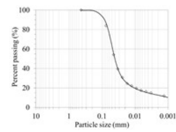
Materials: Dry Nevada Sand





Parameter	Nevada Sand
D_{10}	0.09 mm
D_{30}	0.11 mm
D_{50}	0.16 mm
% Passing No. 200 Sieve	0
Specific gravity, G_s	2.65
Effective friction angle, ϕ'	35°
Initial void ratio, e_0	0.75
Saturated hydraulic conductivity, k_s	1×10^{-4} m/s
Thermal conductivity, λ	0.25

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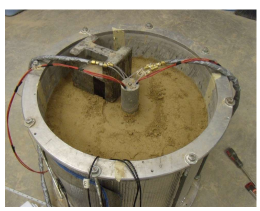
Materials: Bonny Silt

- Low plasticity silt PI = 4
- High fines content
- Unit weight = 17 kN/m^3
- Gravimetric water content = 12.5 %
- Prepared using compaction in 38.1 mm-thick lifts



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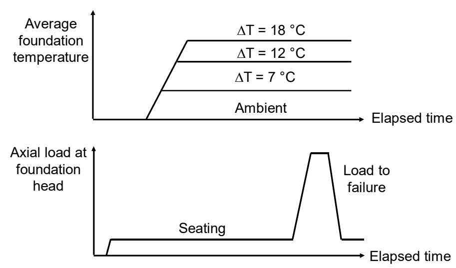
Testing Sequence



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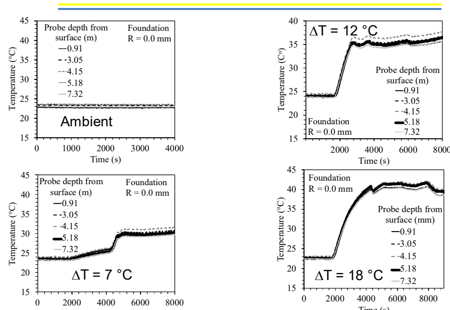
Energy Pile Temperatures



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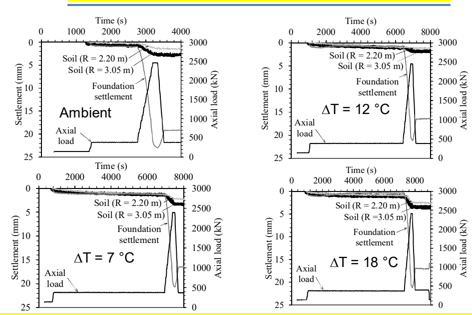
Load and Displacement Time Series



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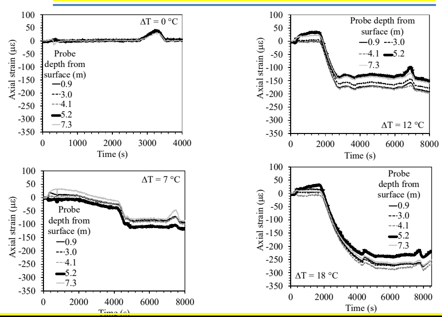
Axial Strain Time Series



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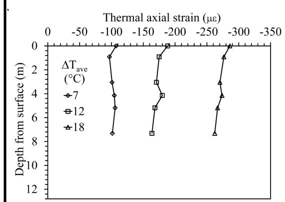
Thermal Axial Strain Profiles



- Head is free to expand so theoretical free thermal expansion strain is shown at a depth of zero ($\varepsilon_{free} = \alpha_c \Delta T$)
- Thermal axial strains are very close to free expansion strain
- Relatively uniform with depth
- Little soil-structure interaction in dry sand with semi-floating boundary conditions

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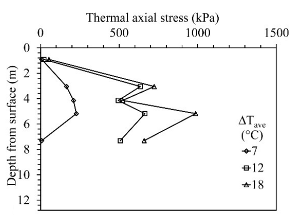
Thermal Axial Stress Profiles



$$\sigma_T = E(\varepsilon_T - \alpha_c \Delta T)$$

α_c = -16 με/°C and E = 33 GPa

- Nearly triangular distribution in thermal axial stress with some variability
- Thermal stresses are relatively small compared to those observed in the field for end-bearing conditions

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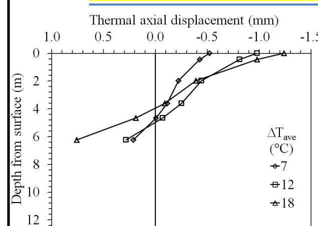
Thermal Axial Displacement Profiles



$$\delta_{T,i} = \delta_{therm,i-1} + \frac{1}{2}(\varepsilon_{T,i-1} + \varepsilon_{T,i})(z_i - z_{i-1})$$

- Displacement at foundation head is known from LVDT measurements
- Thermal axial strains are integrated and subtracted from the head displacement
- Null point is displacement of zero thermal axial displacement
- Null point shifts upward with temperature

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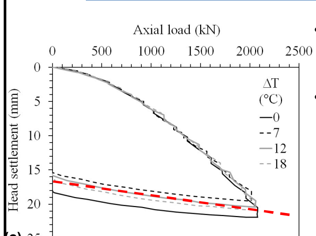
Load-Settlement Curves for Energy Piles in Dry Sand



- No increase in axial capacity was observed with temperature
- Loads were applied to the capacity of the system
  - Approximately reaches Davisson's criterion
  - Displacement was less than 0.1 of the pile diameter
  - Negligible radial expansion effects

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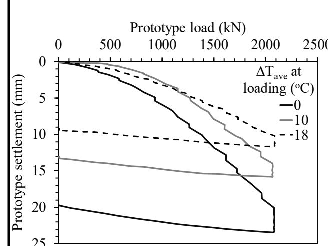
Load-Settlement Curves for Energy Piles in Unsaturated Silt



- An increase in capacity seems to be observed in the results
- However, this is likely due to thermally-induced water flow away from the soil-pile interface
- This leads to an increase in effective stress and interface shear strength

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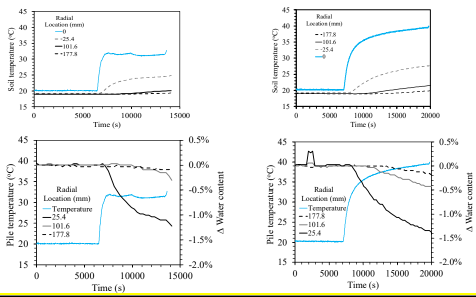
Reasons for Increase in Capacity for Energy Piles in Unsaturated Silt



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Load Transfer Calibration using Centrifuge Data

McCartney and Rosenberg (2011)
Chen and McCartney (2016)

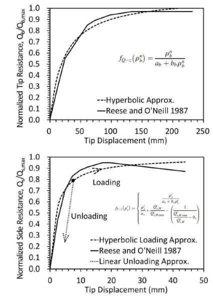
- *Ultimate End Bearing*:

$Q_{b,max} = f(\phi, \text{shape})$

- *Ultimate Side Shear*:

$Q_{s,max} = \beta A_s \sigma_v'$

β = Side shear reduction factor
= $\tan\phi'[K_o + (K_p - K_0)\kappa\varepsilon_{T,free}]$
κ = Weighting factor (close to 0)
$\varepsilon_{T,free}$ = Free radial thermal strain = $\alpha_T \Delta T$
K_p = Coefficient of passive earth pressure
K_0 = Coefficient of earth pressure at rest



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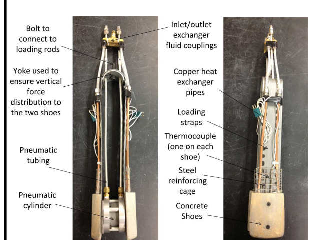
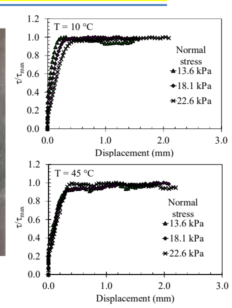
T-z Curves to Use in Analysis



Thermal Borehole Shear Device
(Murphy and McCartney 2014)



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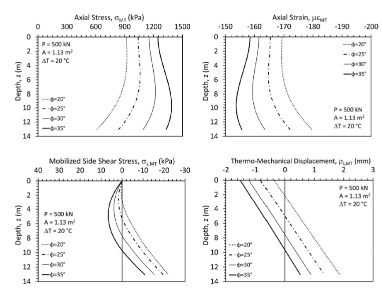
Load Transfer Analysis: Drained Soils



Chen and McCartney (2016)

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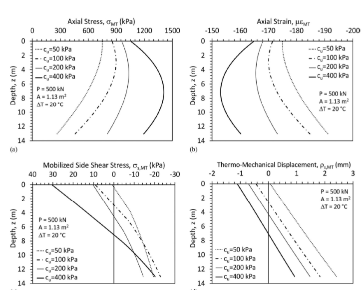
Load Transfer Analysis: Undrained Soils



Chen and McCartney (2016)

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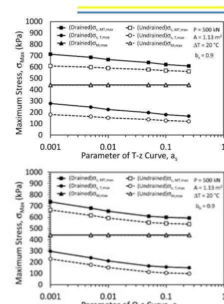
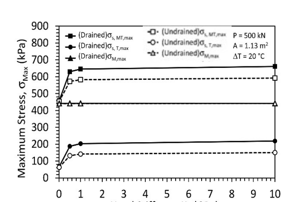
Parametric Evaluation Examples





Chen and McCartney (2016)

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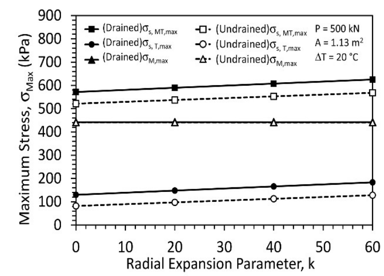
Parametric Evaluation Examples



Chen and McCartney (2016)

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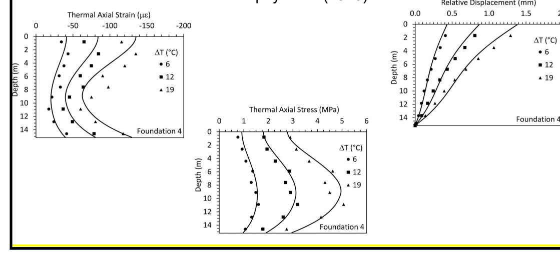
Load Transfer Analysis Results

Chen and McCartney (2016):
Air Force Academy Pile 4 Calibration Results from Murphy et al. (2015)



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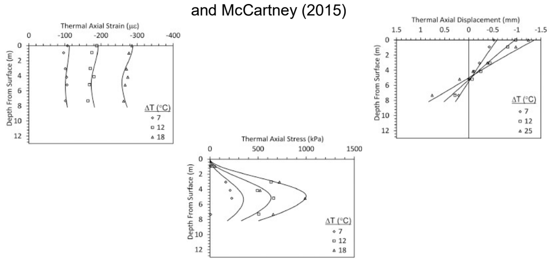
Load Transfer Analysis Results

Chen and McCartney (2016):
Semi-Floating Energy Pile in Nevada Sand Results from Goode and McCartney (2015)



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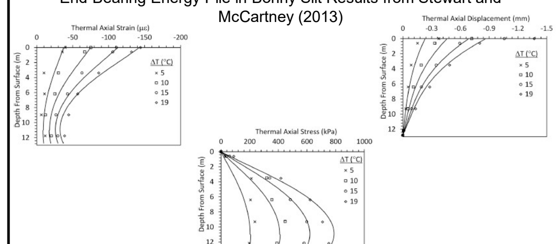
Load Transfer Analysis Results

Chen and McCartney (2016):
End-Bearing Energy Pile in Bonny Silt Results from Stewart and McCartney (2013)



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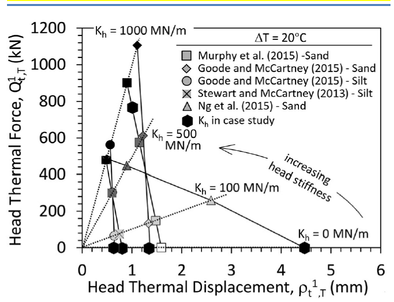
Calibrated Parameter Evaluation



Chen and McCartney (2016)

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Final Comments

- Implementation of energy piles is a potential strategy to decrease installation costs for GSHPs
- Energy piles can provide the base thermal load for a building without causing major structural issues:
  - Thermo-mechanical stresses are less (5-10 MPa) than compressive strength of concrete (~21 MPa)
  - Thermal deformations should be well characterized, but are not expected to have a major impact on buildings (angular distortions less than 1/5000)
- Impacts of heat exchange on soil behavior should be carefully considered, as they may lead to:
  - Change in heat transfer
  - Change in capacity or deformation response (dragdown)

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Acknowledgements and Questions?

Field-Scale Testing
- Prof. Karen Henry (USAFA)
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- Joseph Goode III

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- C.J. Coccia
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- Abdalla El Tawati

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- Diming Chen (T-z Analysis)

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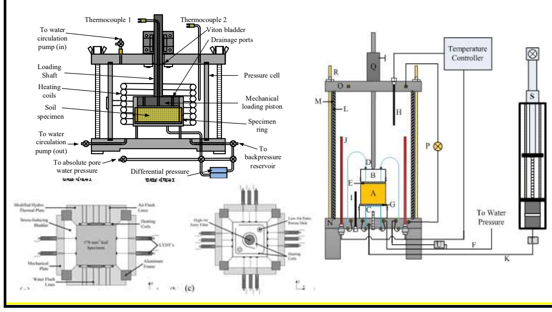
Thermal Evaluation of Soil Properties



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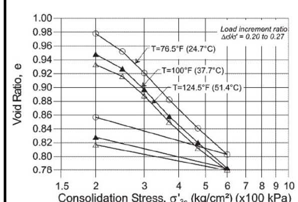
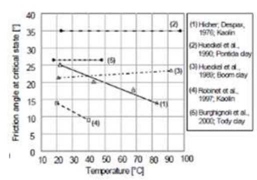
Effects of Temperature on Soil Properties



No effect on compression index

Campanella and Mitchell (1968)



No major effect on critical state friction angle

Laloui (2001)

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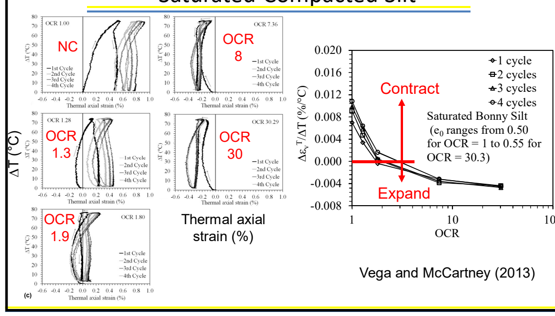
Impact of Temperature on Soil Volume Change: Saturated Compacted Silt



Vega and McCartney (2013)

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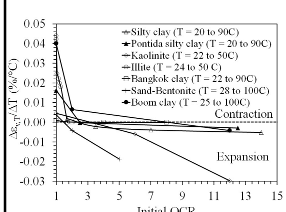
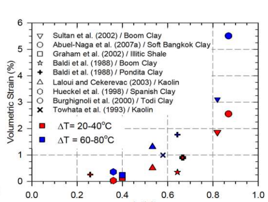
Thermal Volume Change: Saturated Soils





Towhata et al. (1993) Baldi et al. (1998)
Cekeravac and Laloui (2004) Plum and Esrig (1967)
Abuel-Naga et al. (2008) Graham et al. (2001)
Sultan et al. (2002)

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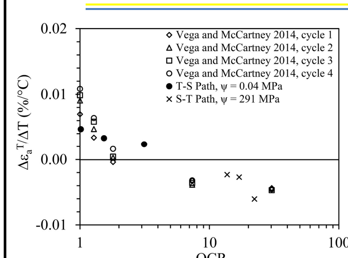
Impact of Temperature on Isotropic Volume Change: Unsaturated Soils

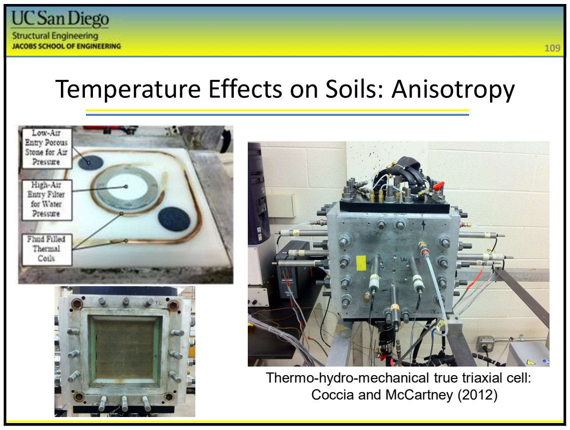


McCartney et al. (2014)

$OCR = \sigma'_{max}/\sigma'_{current}$

σ' from Lu et al. (2010)

- Behavior is similar to saturated soils, but mechanisms of volume change differ
- Saturation plays an important role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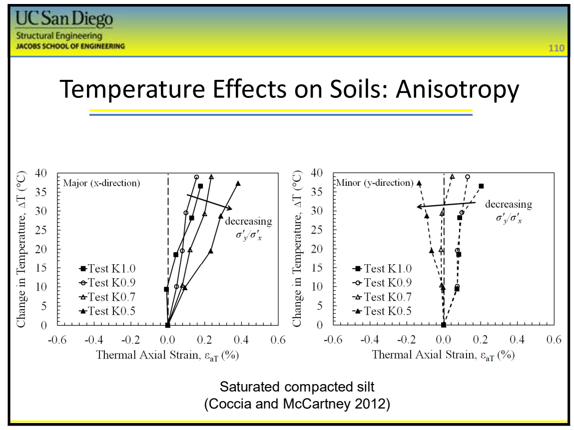
Temperature Effects on Soils: Anisotropy
Low-Air Entry Porous Stone for Air Pressure
High-Air Entry Filter for Water Pressure
Fluid Filled Thermal Coils
Thermo-hydro-mechanical true triaxial cell:
Coccia and McCartney (2012)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Temperature Effects on Soils: Anisotropy
Major (x-direction)
Minor (y-direction)
decreasing σ'y/σ'x
Test K1.0
Test K0.9
Test K0.7
Test K0.5
Change in Temperature, ΔT (°C)
Thermal Axial Strain, εaT (%)
Saturated compacted silt
(Coccia and McCartney 2012)