Energy Piles - Background and Geotechnical Engineering Concepts

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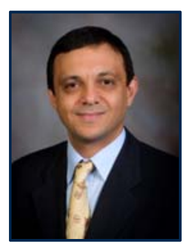
Guney Olgun : Biographical Sketch



- BS and MS degrees on Civil Engineering from Bogazici University in Turkey and PhD from Virginia Tech.
- Currently research assistant professor of Civil and Environmental Engineering at Virginia Tech. Ten years experience in research and teaching. Five years of prior experience in geotechnical construction.
- Main research interests include thermo-active foundation systems, seismic performance of improved ground, cyclic vulnerability of fine grained soils, dynamic soil-structure-foundation interaction and advanced numerical modeling.
- Recent funding includes projects on energy foundations and seismic performance of improved ground. Total research funding about $2M over the last four years.

2

Learning Objectives

- Gain background on geothermal heat exchange systems such as geothermal boreholes and horizontal loops
- Identify the basic principles of geothermal heat exchange systems
- Learn about different applications of energy piles and other thermo-active systems
- Learn about the geotechnical issues related to energy piles; temperature induced soil-pile interaction, possible temperature effects on soil behavior
- Gain related insight about recent research on energy piles and recently developed design guidelines

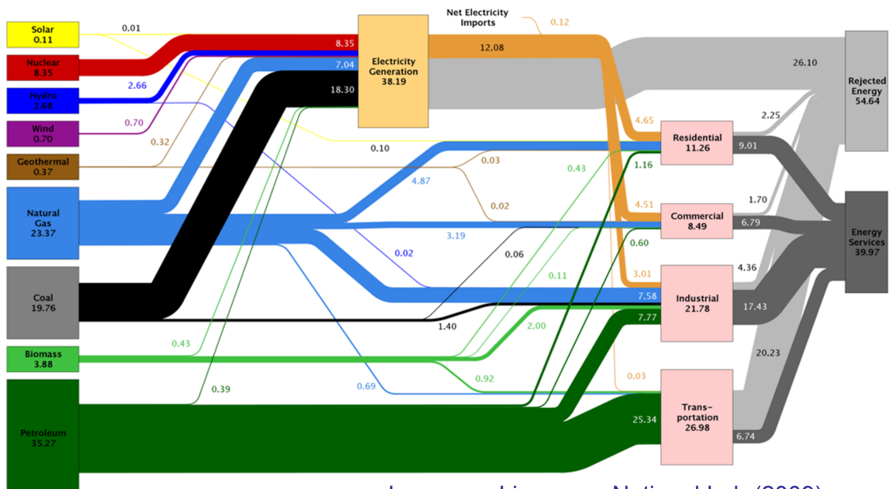
Key References

- Brandl, H. (2006). “Energy foundations and other thermo-active ground structures.” Geotechnique, vol. 56, no. 2, pp.81-122.
- Laloui, L., Nuth, M., Vulliet, L. (2006). "Experimental and numerical investigations of the behaviour of a heat exchanger pile." International Journal for Numerical and Analytical Methods in Geomechanics, vol.30, no.8, pp.763-781.
- Bourne-Webb, P.J., Amatya, B., Soga, K., Amis, T., Davidson, C., Payne, P. (2009) “Energy pile test at Lambeth College, London: geotechnical and thermodynamic aspects of pile response to heat cycles”, Geotechnique, vol. 59, no. 3, pp. 237-248.
- Adam, D., Markiewicz, R. (2009). “Energy from earth-coupled structures, foundations, tunnels and sewers.” Geotechnique, vol. 59, no. 3, pp. 229–236.
- GSHP (2012). “Thermal Pile : Design, Installation and Materials Standards : Issue 1.0” Ground Source Heat Pump Association, October 1, 2012, http://www.gshp.org.uk/GSHPA_Thermal_Pile_Standard.html

Webinar Outline : Energy Piles

- Background and concept
- Geothermal heat-exchange systems, energy piles
- Performance and design considerations
- Issues & geotechnical challenges in energy pile behavior
- Recent and ongoing research
- Design of energy piles
- Summary and conclusions

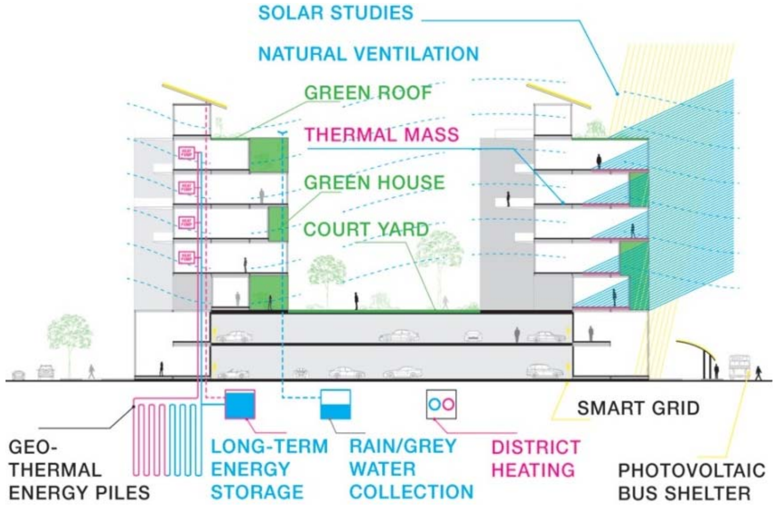
U.S. Energy Flow Chart



Lawrence Livermore National Lab (2009)

Significant energy consumption in buildings mainly for heating and cooling

It is All about Energy!



Courtesy J. Wheeler / Virginia Tech

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Globally Increasing Need for Renewable Energy

- Driving factors – rising global energy demand and need to reduce carbon emissions (i.e., recent UK codes require zero-carbon buildings by 2019)
- Electricity generation is largest source of air pollution in US
- Significant electricity consumption due to heating/cooling
- Commercial and residential buildings consume 71% of US electricity
- Buildings generate 43% of US carbon emissions

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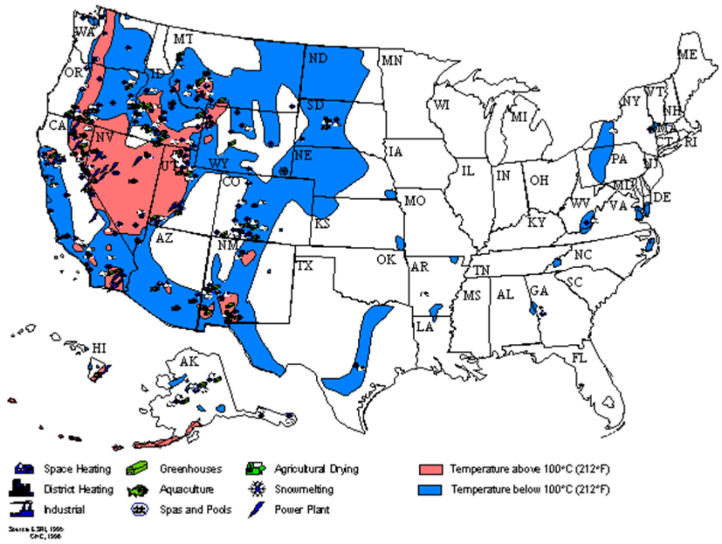
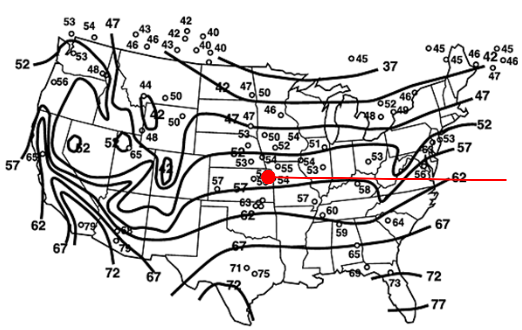
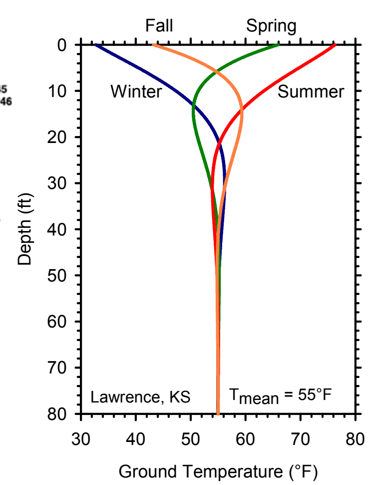
U.S. Geothermal Resources & Projects



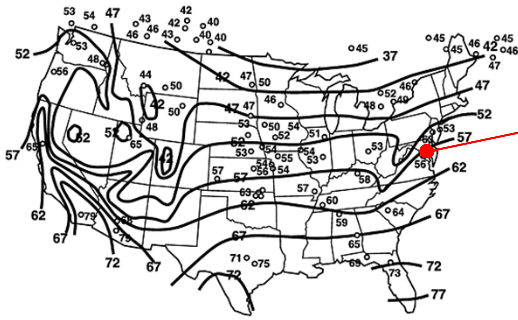
Ground Temperature Profile



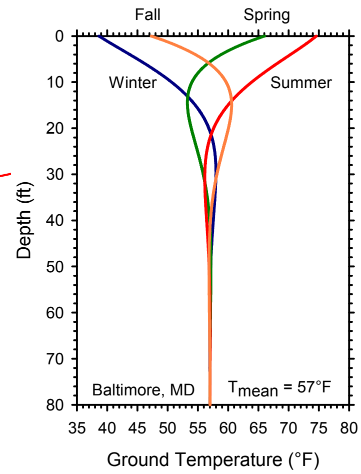
Mean ground temperature



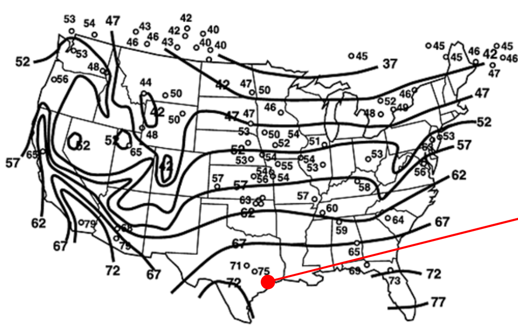
Ground Temperature Profile



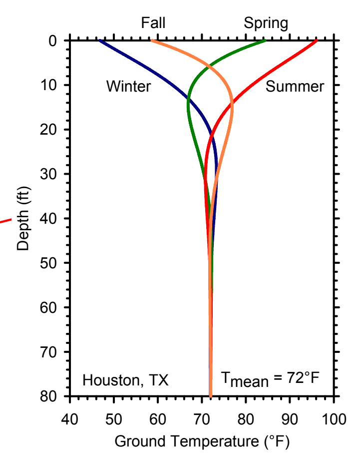
Mean ground temperature



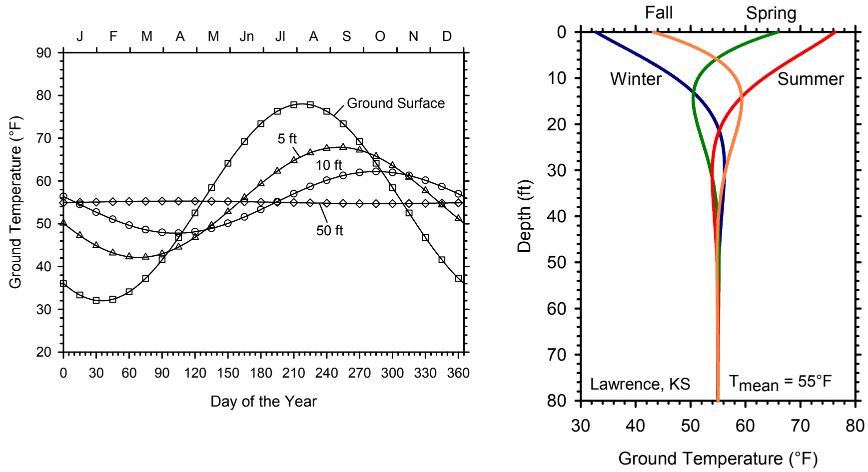
Ground Temperature Profile



Mean ground temperature



Ground Temperature Profile



Ground temperature fluctuations in Lawrence, KS

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Outline : Energy Piles

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Ground Source Heating/Cooling

- Geothermal heat exchange systems provide ground-source energy for heating and cooling
- The use of ground-source systems for heating and cooling has increased exponentially especially in Europe
- Basic idea been around for long time – make use of the heat energy stored in the ground; access this energy using heat exchangers buried in the ground (fluid-filled HDPE loops)
- In ideal conditions these systems can provide majority of required heating/cooling energy and significantly reduce costs and carbon footprint

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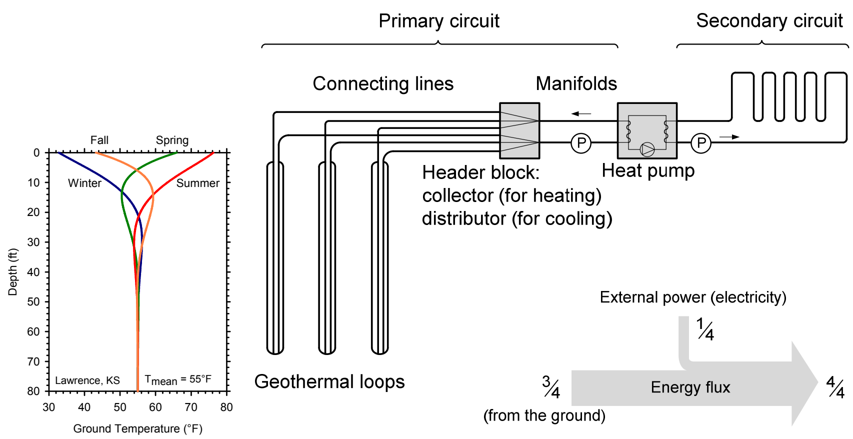
Geothermal Heat-Exchange Systems



Utilize the relatively constant temperature of the ground and use it for heating in the winter and cooling in the summer

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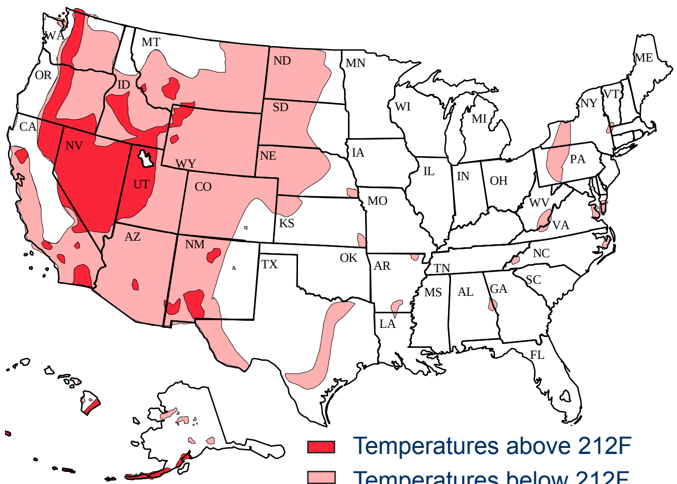
Geothermal Resources



- Temperatures above 212F
- Temperatures below 212F
- Suitable for geothermal heat exchange (entire U.S.)

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Geothermal Heat Exchange Systems

Geothermal Boreholes

Horizontal Loops

Energy Piles

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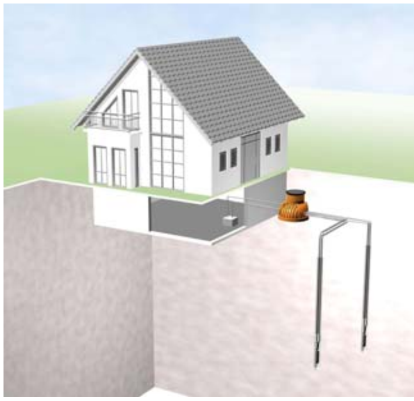
18

Geothermal Borehole Wells



Major cost is drilling and materials

- 4-6 inch diameter borehole
- 200 ft - 500 ft deep
- Small residential to large commercial

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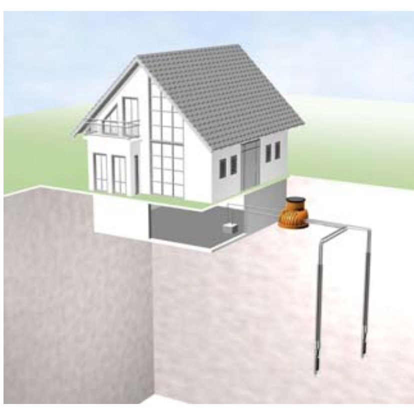
Geothermal Borehole Wells



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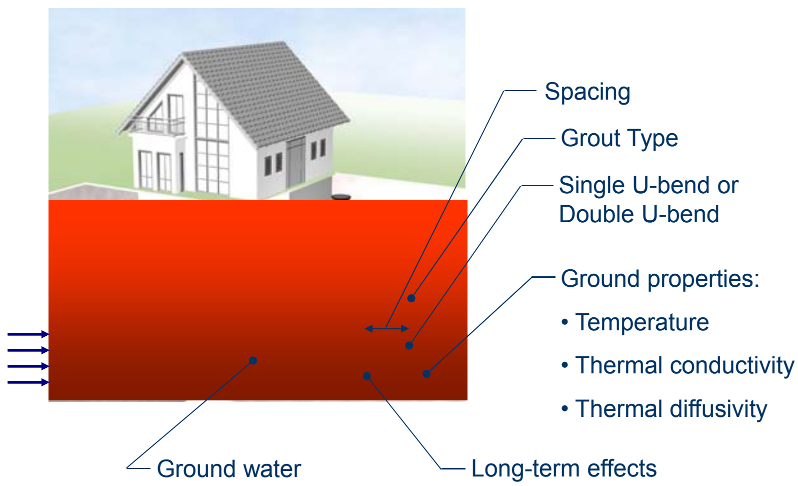
Geothermal Borehole Wells – Design Considerations



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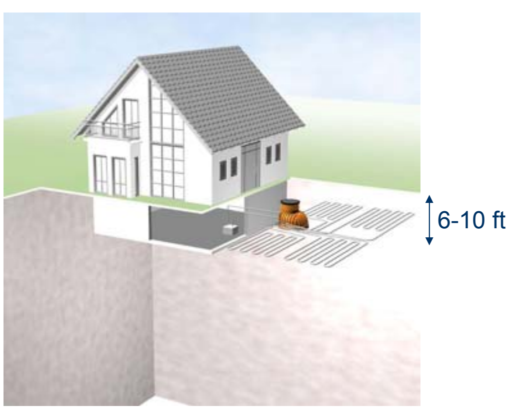
Horizontal Loops



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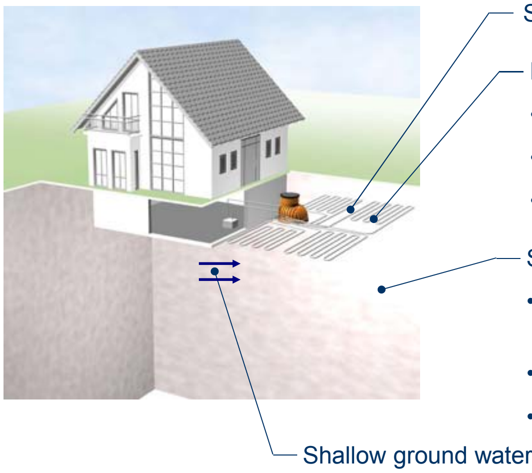
Horizontal Loops



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Horizontal Loops

Recently built house in Blacksburg VA with a trench loop system

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Horizontal Loops

Horizontal loop systems within/beneath slabs

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Horizontal Loops

Energy slab (Messe U2 metro station, Vienna)

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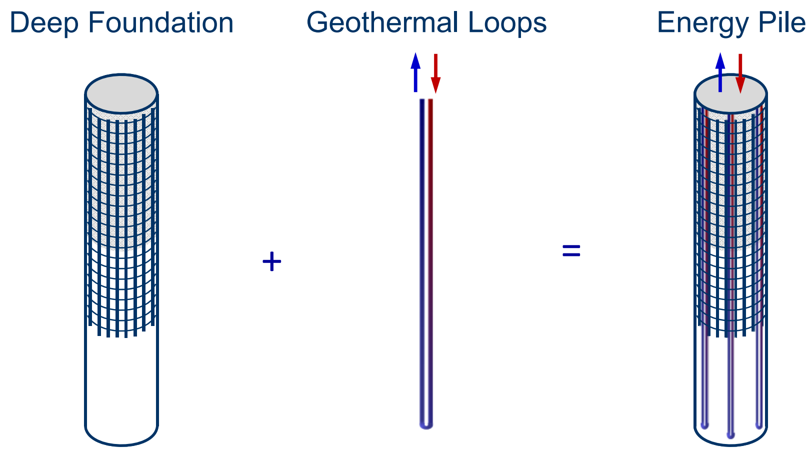
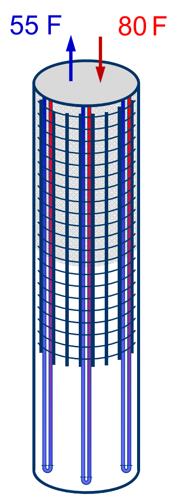
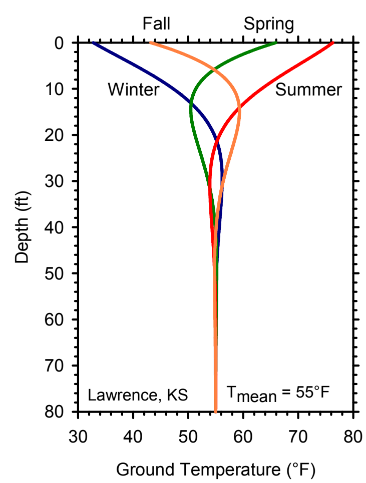
Energy Piles – Dual Purpose Elements



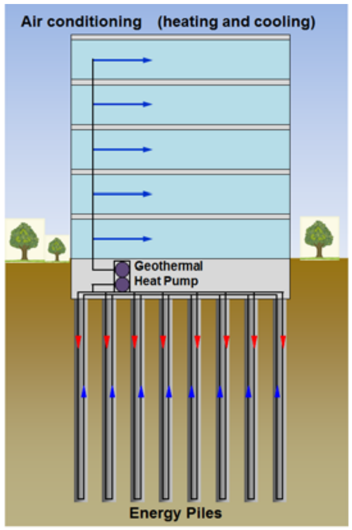
Foundation support (micropile, drilled shaft, CFA) | Heating/cooling (PEX, HDPE) | Foundation support & heating/cooling

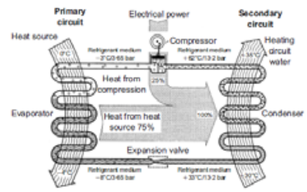
Energy Piles – Dual Purpose Elements

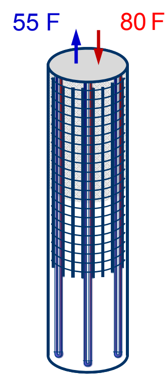




Energy Piles







Energy Piles – Installation

Energy Piles – Installation

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Energy Piles – Installation

Reinforcement cage equipped with circulation loops

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Energy Piles – Installation

Lowering the reinforcement cage with U-tube loops

Completion of tube installation

After concrete

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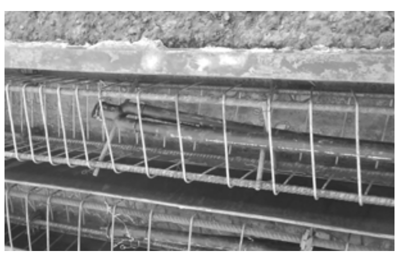
Energy Piles – Driven Precast Concrete



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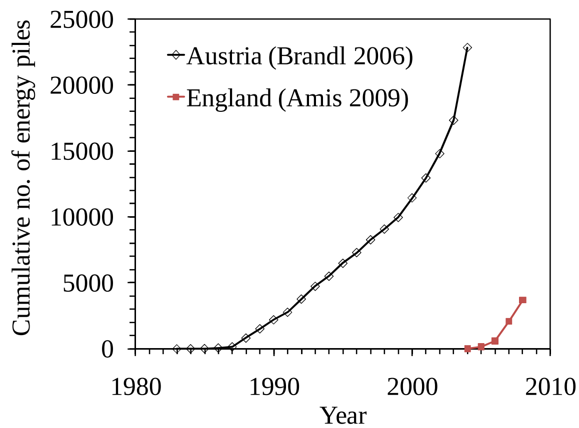
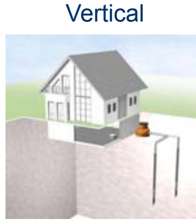
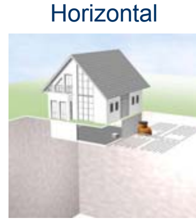
Increasing Use of Energy Piles



Swiss, Austrians, English and Japanese leading the effort since 1990s

Performance of Heat Exchange Systems





	Vertical	Horizontal	Energy Pile
Poor ground quality	8 W/ft	1 W/ft²	8 W/ft
Average ground quality	15 W/ft	2.5 W/ft²	15 W/ft
Excellent ground quality	25 W/ft	4 W/ft²	25 W/ft

1W ~ 3.4Btu/hr

Advantages of Geothermal Heat Exchange Systems and Thermo-active Foundations

- Environmentally-friendly, with relatively little power demand
- Help reduce fossil fuel demand, decreasing CO_2 emissions
- Low maintenance and long lifetime
- Installation in foundation permits heat exchange system to be within building footprint, making more efficient use of material and space
- Offer more opportunities for radiant heating/cooling with better humidity control
- Less vulnerable to variation in energy source than hydropower (droughts), wind, and solar
- Less sensitive to energy price fluctuations

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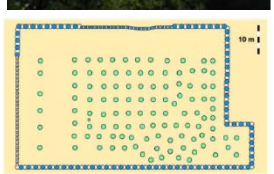
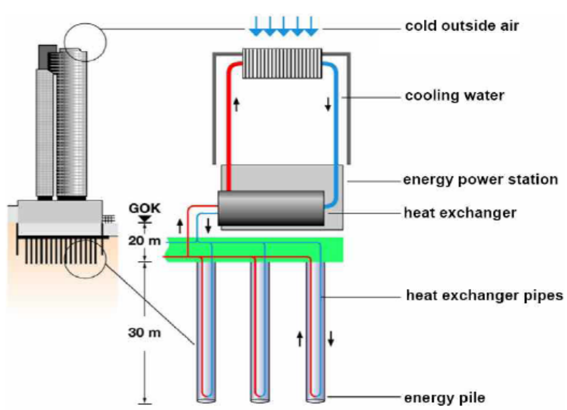
Frankfurt Main Tower





223 Energy piles were installed
Power : 500kW
Courtesy R. Katzenbach TUD

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Keble College, Oxford UK

First Energy Wall Project in the UK
Completion: 2002
Type of Absorber: Pile wall, 61 drilled shafts
Heating Capacity: 45 kW
Cooling Capacity: 45 kW
Courtesy Tony Amis, Geothermal International

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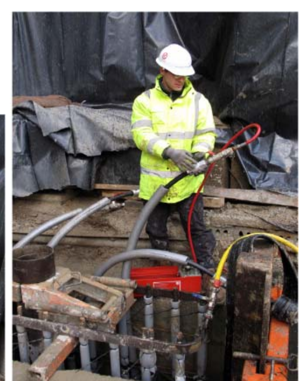
Other Thermo-active Systems



Knightsbridge Palace Hotel – Loop Installation into Energy Wall
(Courtesy Tony Amis, Geothermal International)

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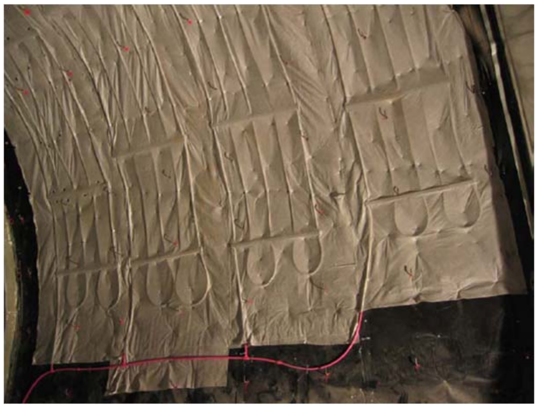
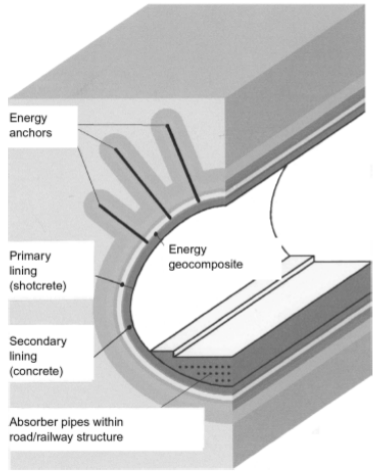
Other Thermo-active Systems





Energy tunnel/anchor systems (Brandl 2006)

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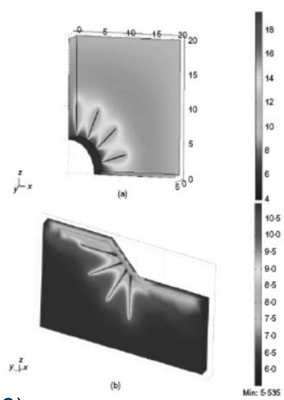
Other Thermo-active Systems



Energy tunnel/anchor systems (Brandl 2006)

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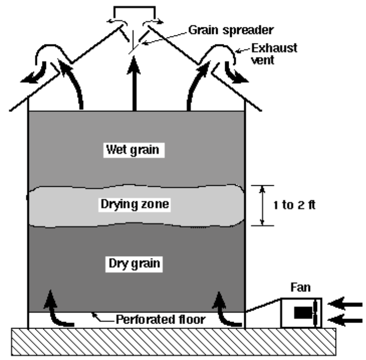
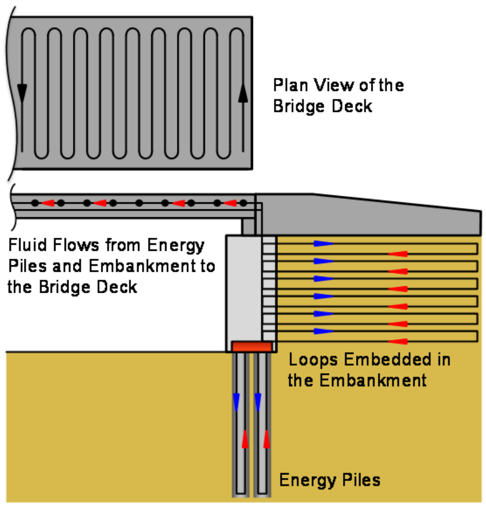
Ground-source Grain Drying



Fan connected to a geothermal borehole system or energy foundation and forces air through grains which eliminates grain moisture

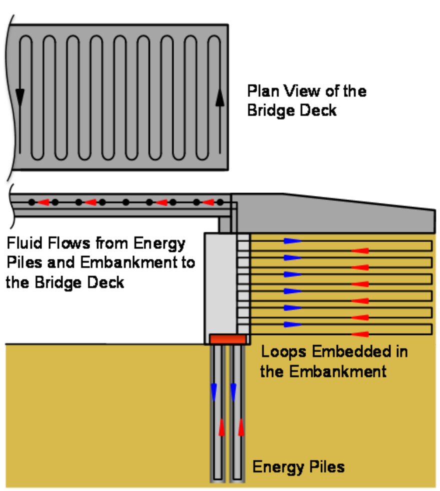
Pavement and Bridge Deck Deicing

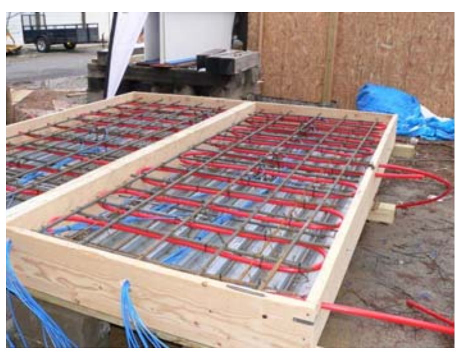
Geothermal Bridge Deck Deicing



- Heat exchanger foundation elements can be used to deice bridge decks in the winter.
- Can reduce bridge deck deterioration and aging.
- Bridge deck and the tubing system can be used for heat collection in the summer.
- Can also utilize the approach embankment as a thermal mass for heat storage and extraction.

Geothermal Bridge Deck Deicing





Small-scale Bridge Deck Slab
(8 ft x 10 ft)

Model Scale Field Experiments

Bridge Deck Deicing Using Energy Piles

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Model Scale Field Experiments

1 inch snow

After snow melting

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Energy Pile Performance

- Performance depends on many site-specific factors, such as soil type (thermal conductivity is key!), ground water depth, initial ground temperature
- Best conditions are saturated sands and clays, especially with ground water flow
- Thermal yield from an energy pile under favorable (i.e. high thermal conductivity) ground conditions ~25W/ft
- Say heating/cooling load for a building is about 150 kW or less
- Assuming good soil conditions, and using 60-ft long piles, 18-in diameter
- We would need about 100 energy piles to supply heating and cooling needs for such a building

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Materials in Geothermal Heat Exchange Systems

- Soil
- Circulation loop – mostly High Density Polyethylene (HDPE), PEXa
- Sand-Bentonite grout (for geothermal loops)
- Concrete (for energy piles)
- Heat exchange fluid (Propylene glycol mix)

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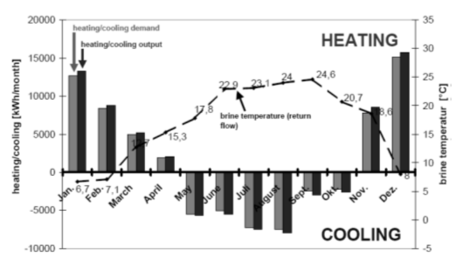
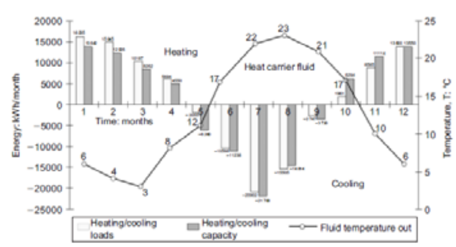
Design Considerations

- Heating/cooling demand





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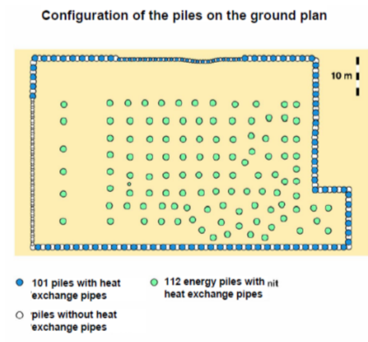
Design Considerations

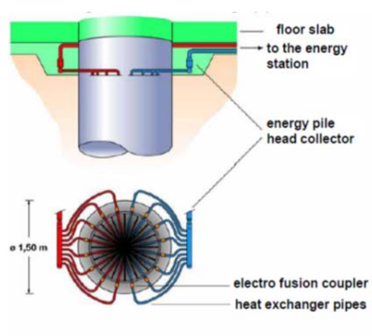
- Heating/cooling demand
- Spacing / pattern

MainTower in Frankfurt



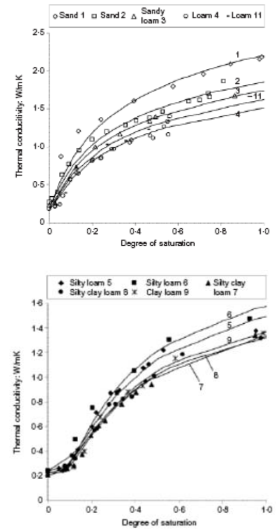
Design Considerations

- Heating/cooling demand
- Spacing / pattern
- Pipe/loop density



Design Considerations

- Heating/cooling demand
- Spacing / pattern
- Pipe/loop density
- Soil properties (thermal conductivity)



from Tarnawski et al. (2009)

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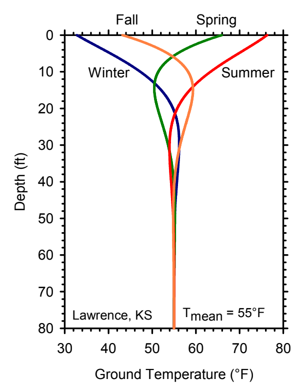
Design Considerations

- Heating/cooling demand
- Spacing / pattern
- Pipe/loop density
- Soil properties (thermal conductivity)
- Initial ground temperature



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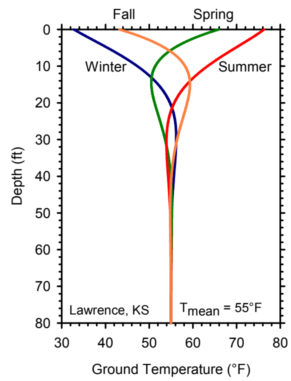
Design Considerations

- Heating/cooling demand
- Spacing / pattern
- Pipe/loop density
- Soil properties (thermal conductivity)
- Initial ground temperature
- Ground water; depth, flow



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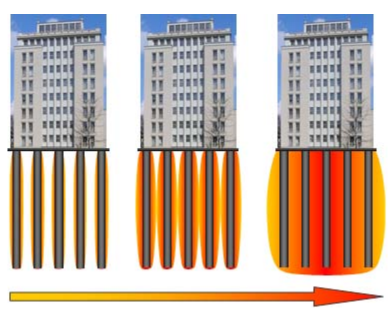
Design Considerations

- Heating/cooling demand
- Spacing / pattern
- Pipe/loop density
- Soil properties (thermal conductivity)
- Initial ground temperature
- Ground water; depth, flow
- Long-term effects



Time evolution of temperatures

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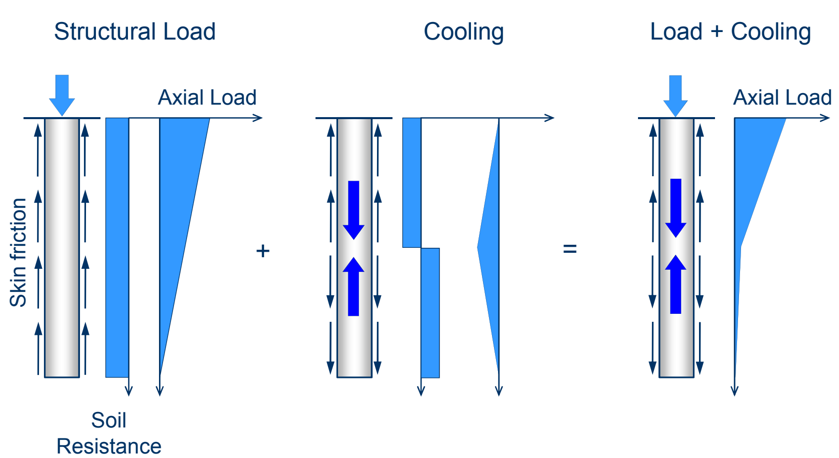
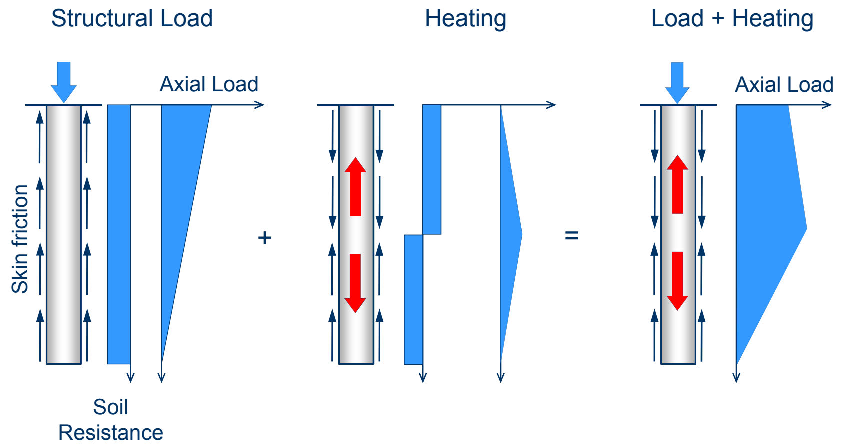
Effect of Ground Cooling



Ground cooling reduces stresses along pile cross-section, can cause tensile stresses

Effect of Ground Heating



Heating can cause increased stresses along pile cross-section

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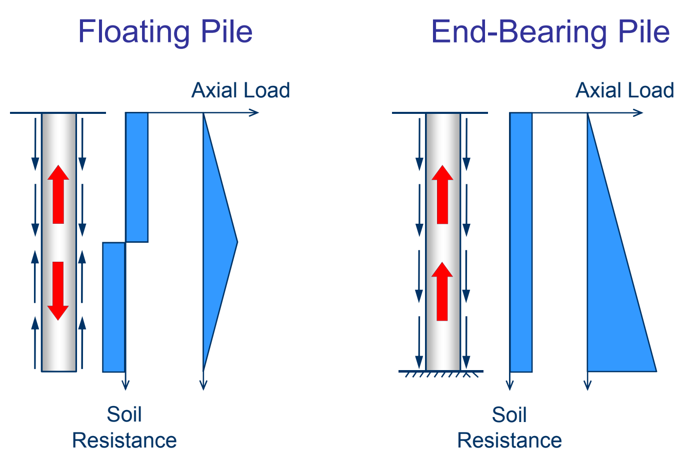
Pile-Soil Interaction – Ground Heating



End restraints (top and bottom of the pile) effect the load transfer mechanism during heating and cooling

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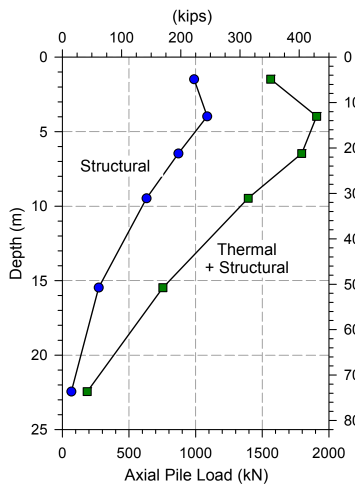
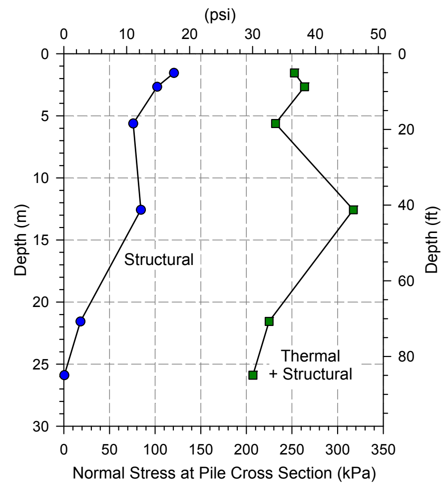
Effect of End Bearing on Thermal Stresses





K. Soga / T. Amis – Lambeth College

L. Laloui - EPFL

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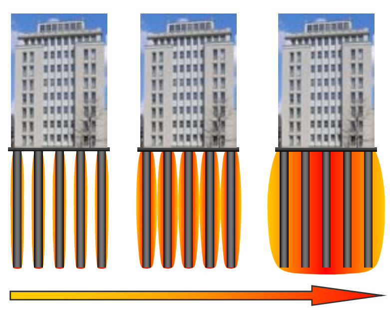
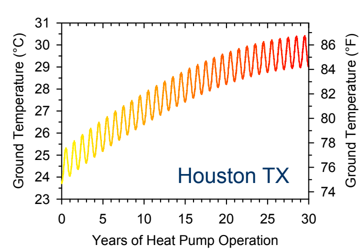
Long Term Performance of Energy Piles





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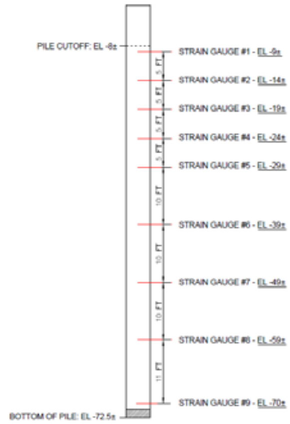
Long Term Monitoring of Energy Piles



Trevor Day School in Manhattan, New York City
Collaboration with Langan, Geothermal International, Geo-Instruments

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Outline : Energy Piles

- Background and concept
- Geothermal heat-exchange systems, energy piles
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- Issues & geotechnical challenges in energy pile behavior : Temperature effects on soil behavior
- Recent and ongoing research
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Temperature Effects on Soil Behavior

- Temperature changes within the soil around the energy pile due to injection of heat in the summer and extraction in the winter.
- The nature of heating/cooling of the soil : slow/drained vs. fast/undrained; seasonally cyclic
- Potential effects on soil strength, compressibility and excess pore water pressure generation.
- Flow and deformation field, soil-pile interaction and performance of the deep foundation system.

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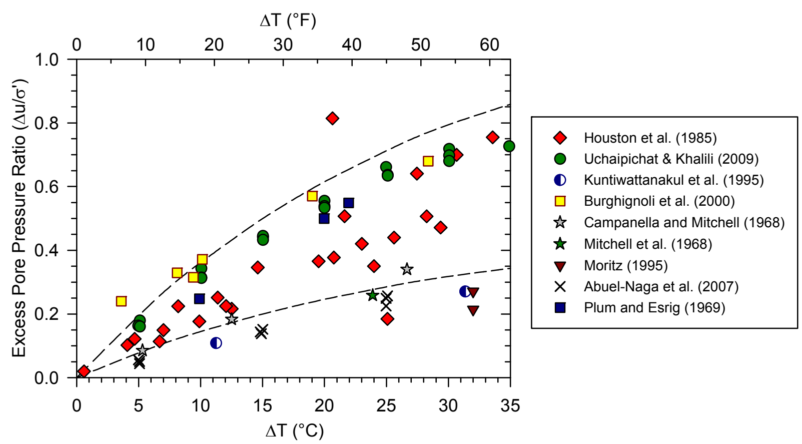
Pore Pressures during Undrained Heating



25-60% excess pore pressure ratio with ΔT = 20°C

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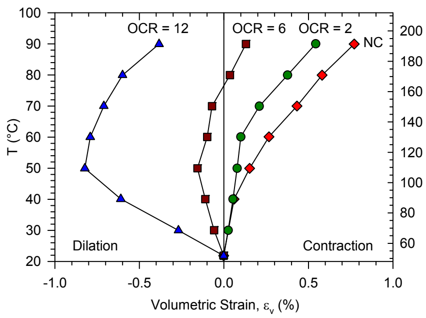
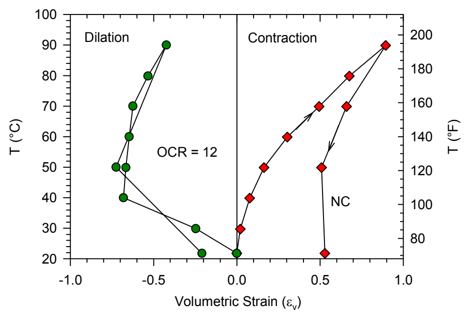
Volume Change during Drained Heating





- Volume change during drained heating highly depends on overconsolidation ratio (OCR).
- As OCR increases, clays tend to be more dilative.
- Overconsolidated clays show elastic, normally consolidated clays show plastic behavior during temperature cycles.

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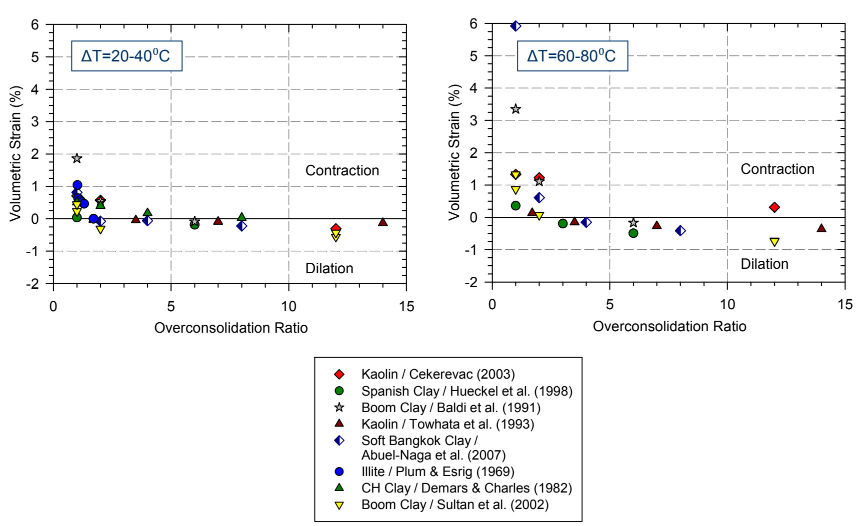
Volume Change during Drained Heating



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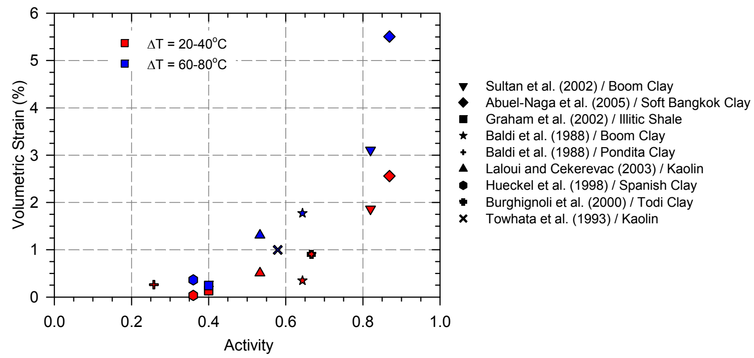
Volume Change during Drained Heating



- Temperature induced volume change potential is a function of plasticity index and clay percentage
- Higher volumetric strain with more active clays

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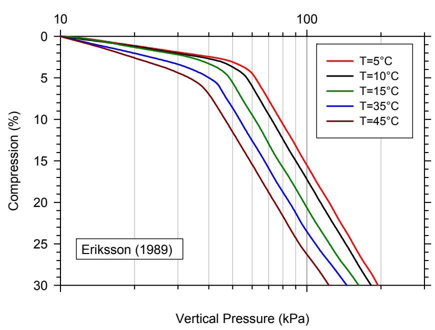
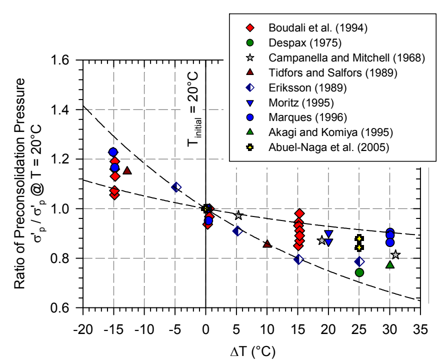
Consolidation Behavior during Heating





- Yield Pressure decreases with increasing temperature (lateral pressures around the energy pile?)
- Compression index remains unchanged

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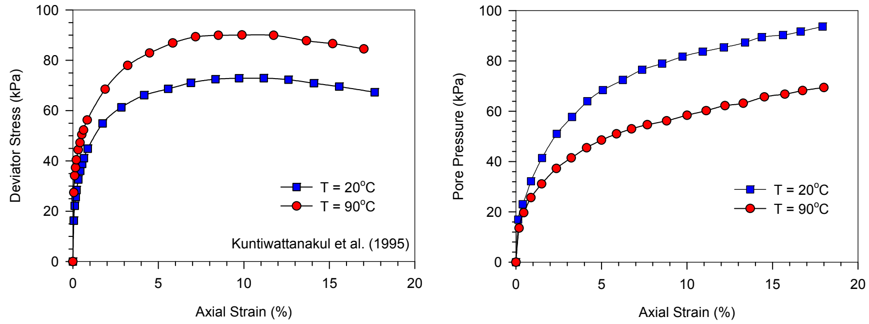
Effect of Temperature on Shear Strength



Stress-strain behavior and pore pressure development during loading at different temperatures

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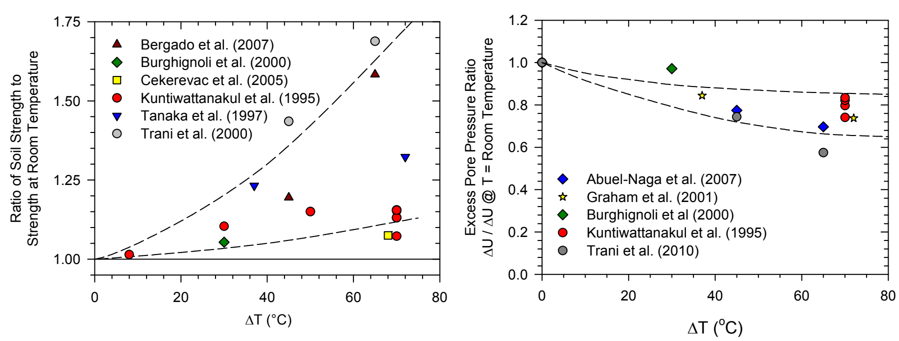
Effect of Temperature on Shear Strength



- Specimen heated drained and then sheared undrained
- Increase in shear strength, decrease in pore pressure are reported

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Outline : Energy Piles

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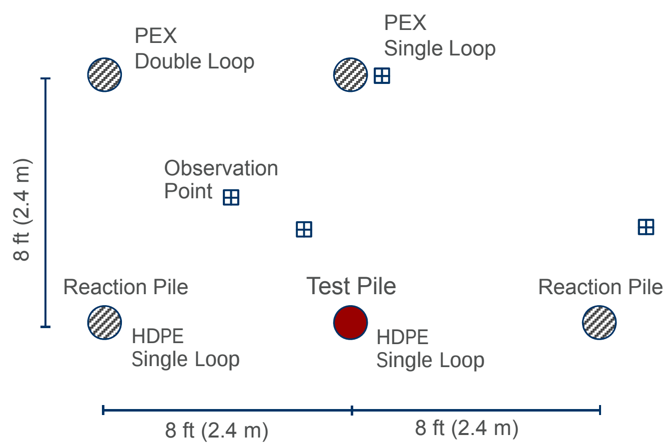
Virginia Tech Energy Pile Field Test Setup



- Four Energy Piles – 10-inch diameter, 100 ft long – instrumented
- Several observation boreholes - thermistors

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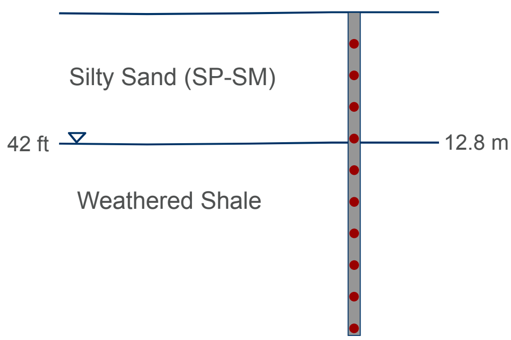
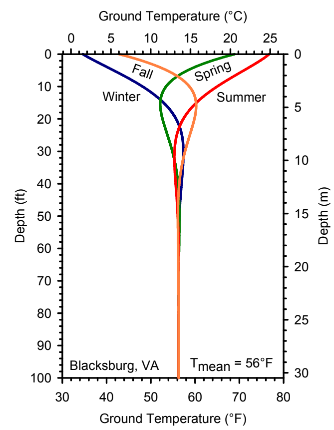
Soil Profile and Ground Temperatures





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Geothermal Circulation Loops

HDPE Geothermal Loop and U-Bend

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Geothermal Circulation Loops

REHAU PEXa Geothermal Loop and U-Bend

Energy Pile Installation

Drilling

Energy Pile Installation


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Energy Pile Installation


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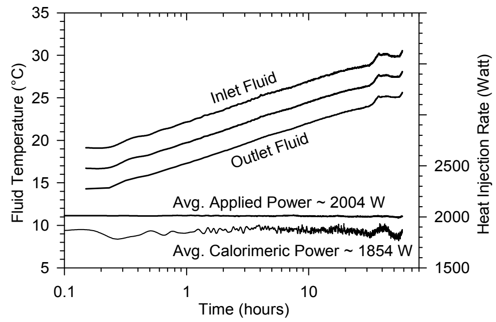
82

Thermal Conductivity Testing



Inject heat into the ground at a constant rate and monitor temperature increase rate to evaluate thermal conductivity

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Thermo-Mechanical Load Test

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Thermo-Mechanical Load Test

Thermo-mechanical Load Test Set-up

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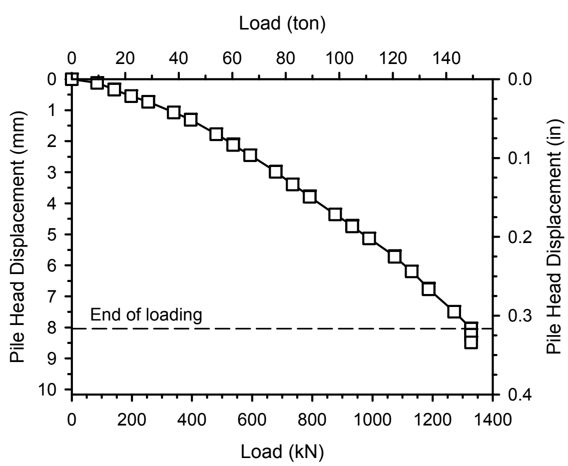
Load Test Results – Prior to Thermal Loading



Pile Loaded to 150 tons (1330 kN) and this load maintained during the later stages of testing

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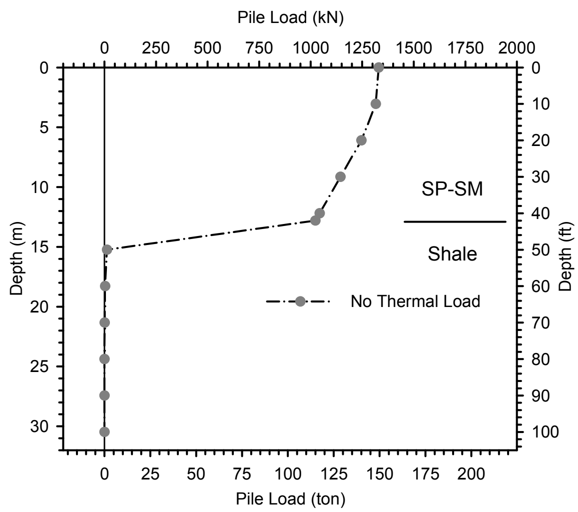
Pile Load – Prior to Thermal Loading



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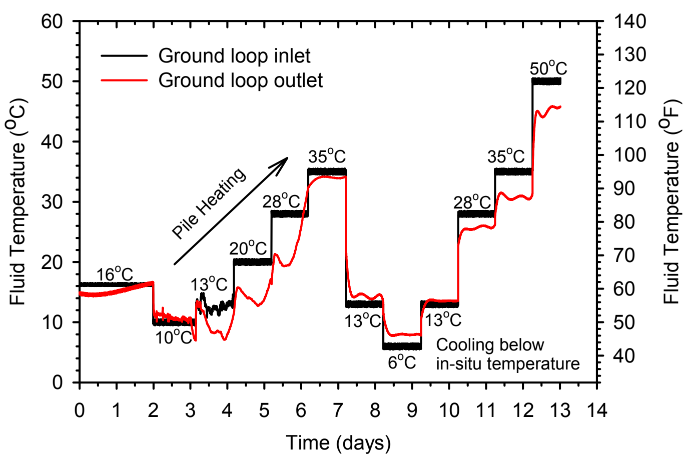
Heating and Cooling Episodes



Temperature cycles applied in stages with a temperature controller

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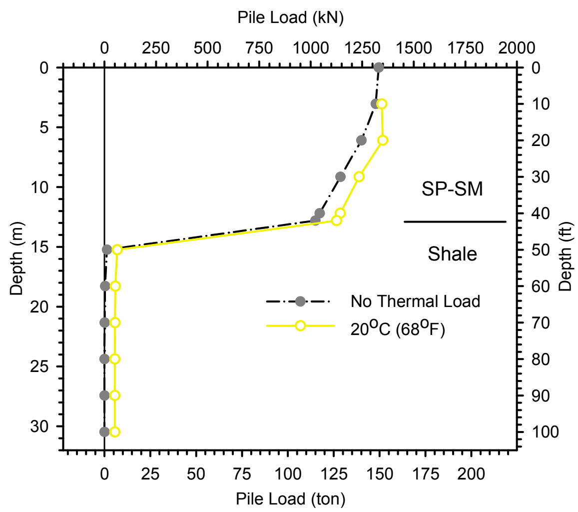
Pile Load during Thermal Loading



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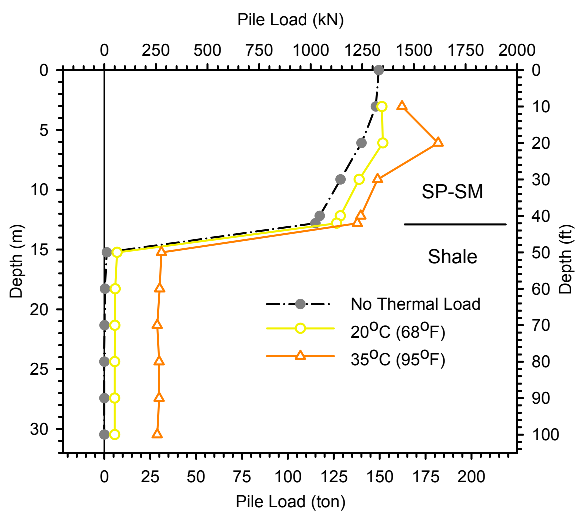
Pile Load during Thermal Loading



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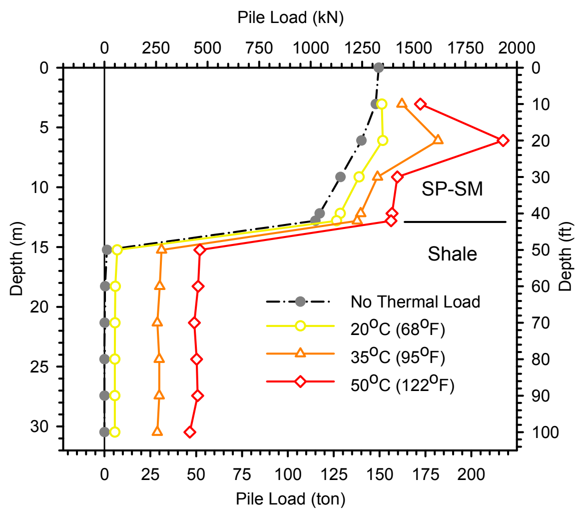
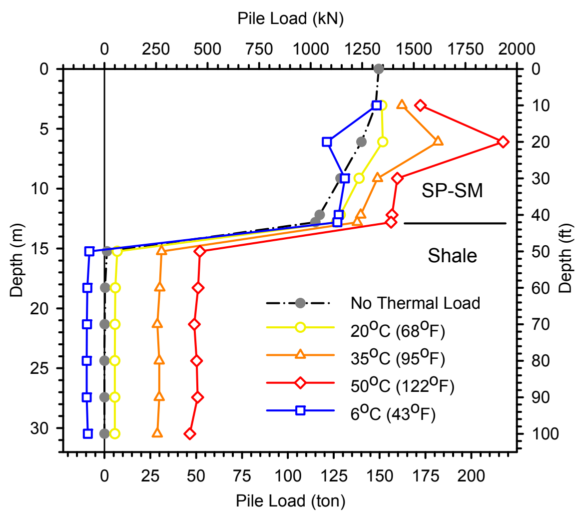
Pile Load during Thermal Loading



Pile Load during Thermal Loading



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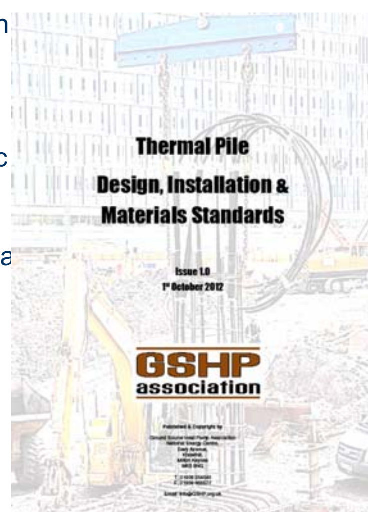
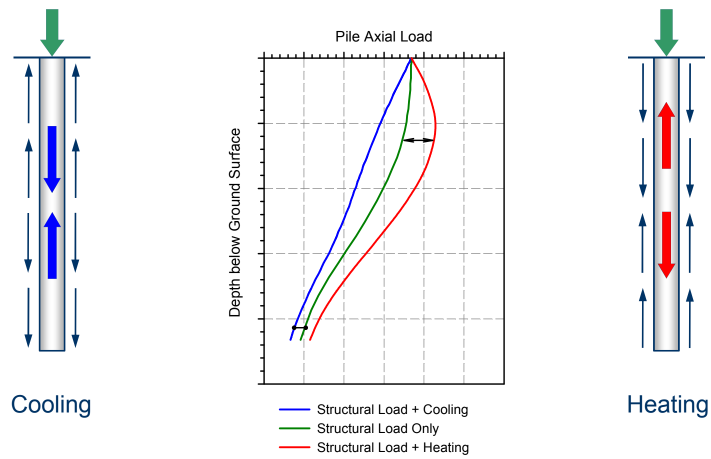
Design of Energy Piles

- Ground Source Heat Pump Association
- Check thermally induced pile stresses
- Pile performance under repeated cyclic cooling)
- Estimate pile settlement due to tempera



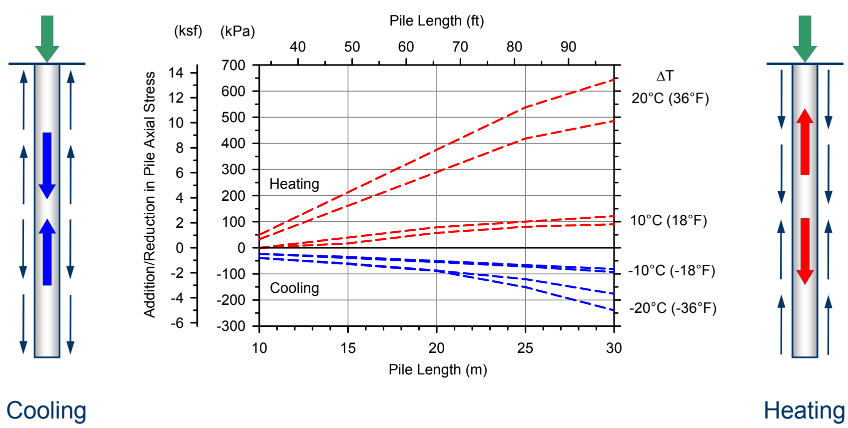
http://www.gshp.org.uk/GSHPA_Thermal_Pile_Standard.html

Temperature Induced Pile Stresses



Check pile stresses due to thermal loading

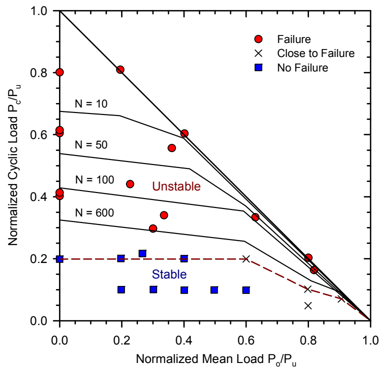
Temperature Induced Pile Stresses



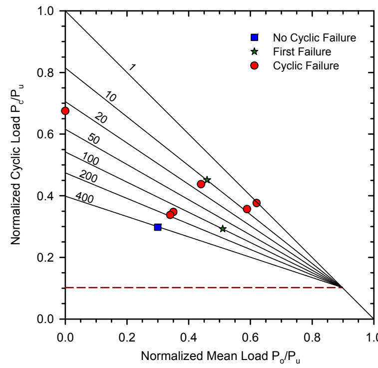
Heating and cooling induced pile stresses

from GSHP Thermal Pile Standard

Pile Performance under Structural and Cyclic Thermal Loads



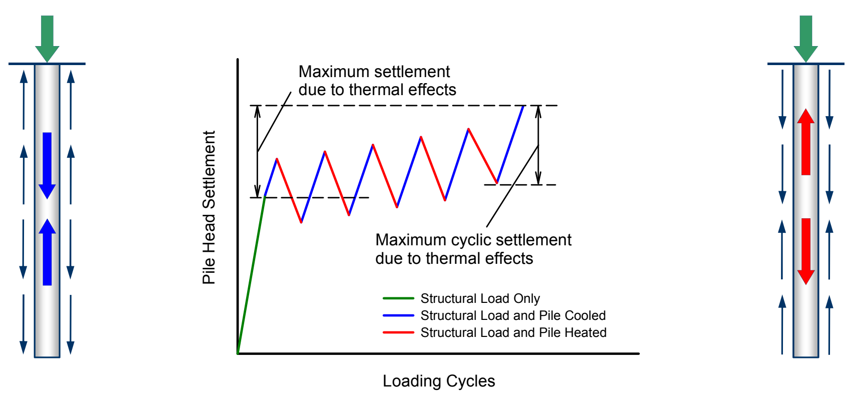
Poulos (1989)



Jardine and Standing (2000)

Check pile capacity under cyclic loading (heating and cooling)

Temperature Induced Pile Head Settlement

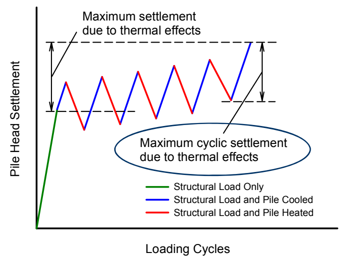


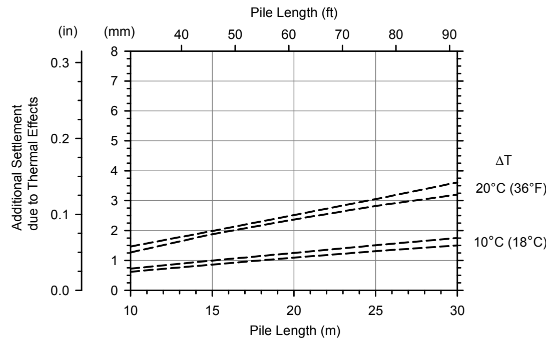
Cooling

Heating

Check pile stresses due to thermal loading

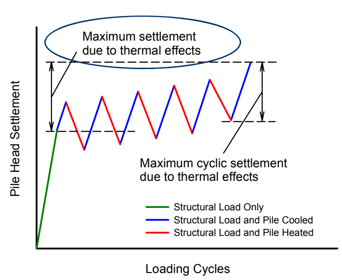
Temperature Induced Pile Head Settlement

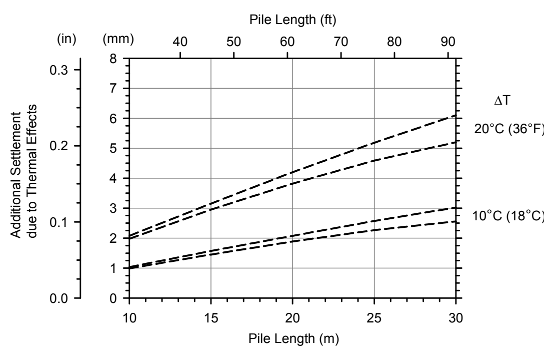




from GSHP Thermal Pile Standard

Temperature Induced Pile Head Settlement





from GSHP Thermal Pile Standard

Summary and Conclusions

- Use of deep foundations as heat exchangers can be an environmental friendly way of deicing bridge decks in the winter.
- Energy pile usage exponential in Europe and Japan; but not common in US
- Need better energy pile design guidelines developed by geotechnical engineers – recently developed by UK group under IGSHP
- Thermal loads can increase stresses in piles but this effect is very small for the level of temperature changes during heat pump operations
- Long term energy pile operation not sustainable for unbalanced thermal loads; must design system to be balanced
- New energy applications such as bridge deck deicing being studied
- Great opportunity for civil engineers, especially geotechnical engineers, but we must move faster

Thank You!

Energy Piles - Background and Geotechnical Engineering Concepts

C. Guney Olgun

Department of Civil and Environmental Engineering, Virginia Tech

e-mail : colgun@vt.edu

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Tue., Aug. 20 – Structural Design	Thur., Aug. 22 – Construction Materials
Tue., Aug. 27 – Geometric Design	Thur., Aug. 29 – Engineering Cost Analysis
Tue., Sept. 3 – Hydraulics	Thur., Sept. 5 - Hydraulics
Tue., Sept. 10 – Waste & Water Treatment	Thur., Sept. 12 – Geomechanics
Tue., Sept. 17 – Foundation Engineering	Thur., Sept. 19 – Construction Scheduling and Estimating

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Tue., Aug.13 – Structural Analysis	Thur., Aug. 15 – Strength of Materials
Tue., Aug. 20 – Structural Design	Thur., Aug. 22 – Construction Materials
Tue., Aug. 27 – Geometric Design	Thur., Aug. 29 – Engineering Cost Analysis
Tue., Sept. 3 – Hydraulics	Thur., Sept. 5 - Hydraulics
Tue., Sept. 10 – Waste & Water Treatment	Thur., Sept. 12 – Geomechanics
Tue., Sept. 17 – Foundation Engineering	Thur., Sept. 19 – Construction Scheduling and Estimating
Mon., Sept. 9 – Water Resource Depth	Mon., Sept. 23 – Structures Depth
Tue., Sept. 24 – Geotechnical Depth	Thur., Sept. 26 – Transportation Depth
Fri., Sept. 27 - Construction Depth	

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Fri., Aug. 16 – Environmental Assessment and Remediation	Fri., Aug. 23 – Hazardous Waste and Emergency Operations
Fri., Aug. 30 – Storm Water	Fri. Sept. 6 – Waste and Water Treatment
Fri., Sept. 13 – Water Quality	Fri., Sept. 20 – Air Quality