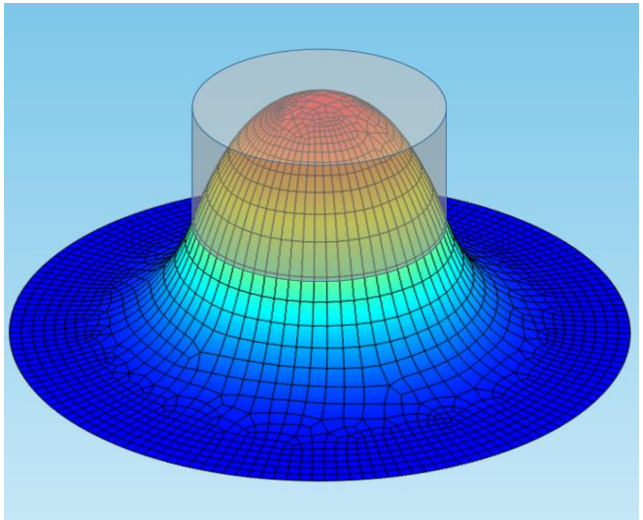
Thermal Integrity Analysis of Concrete Bridge Foundations Using COMSOL Multiphysics® Software



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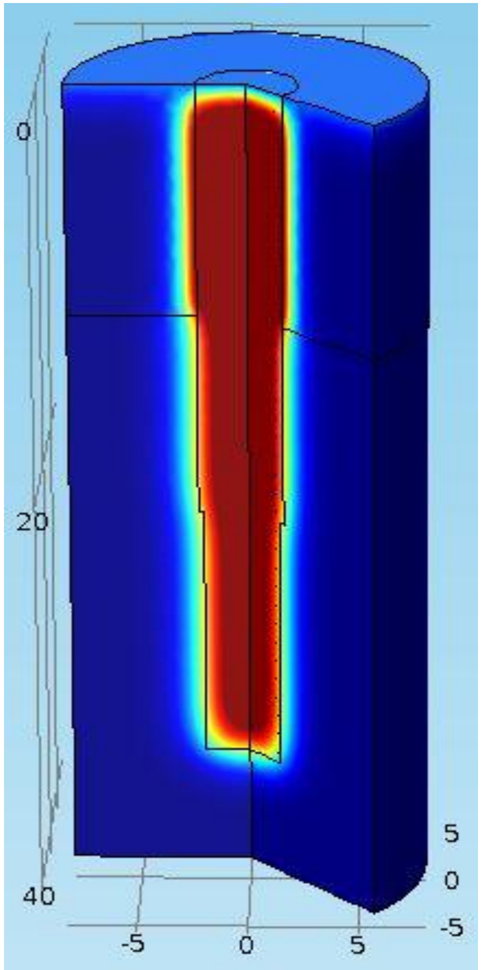
Civil & Environmental Engineering

COMSOL CONFERENCE 2017 BOSTON



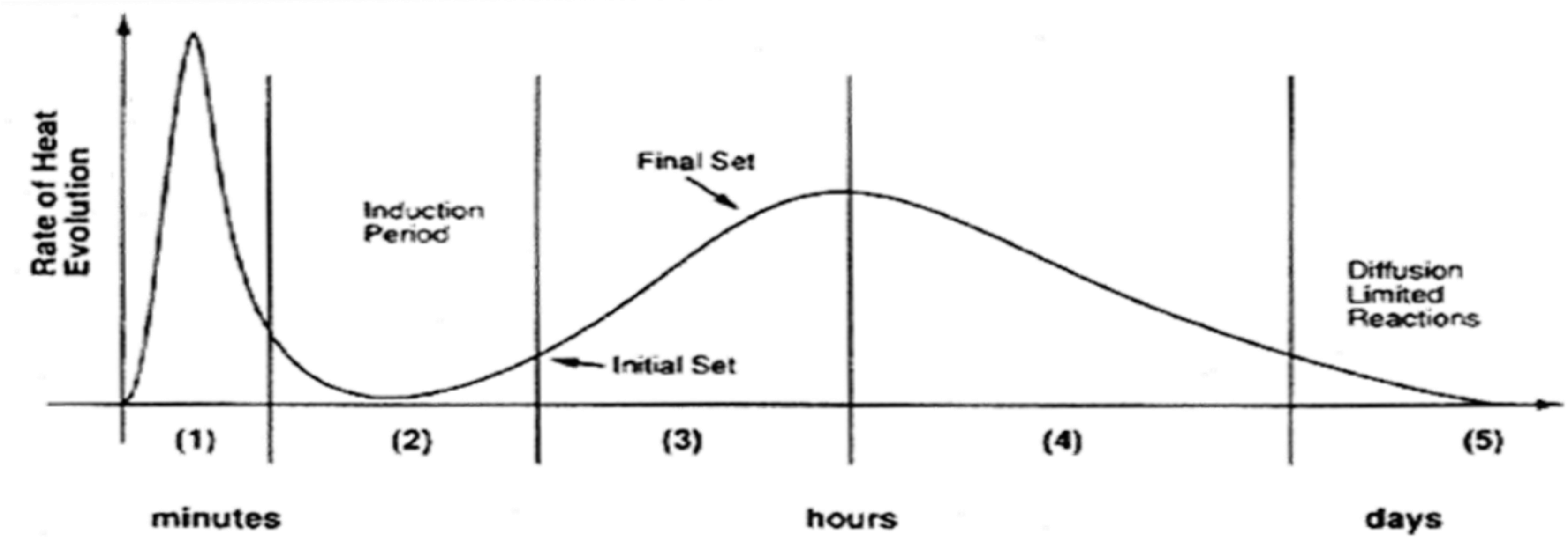
Outline

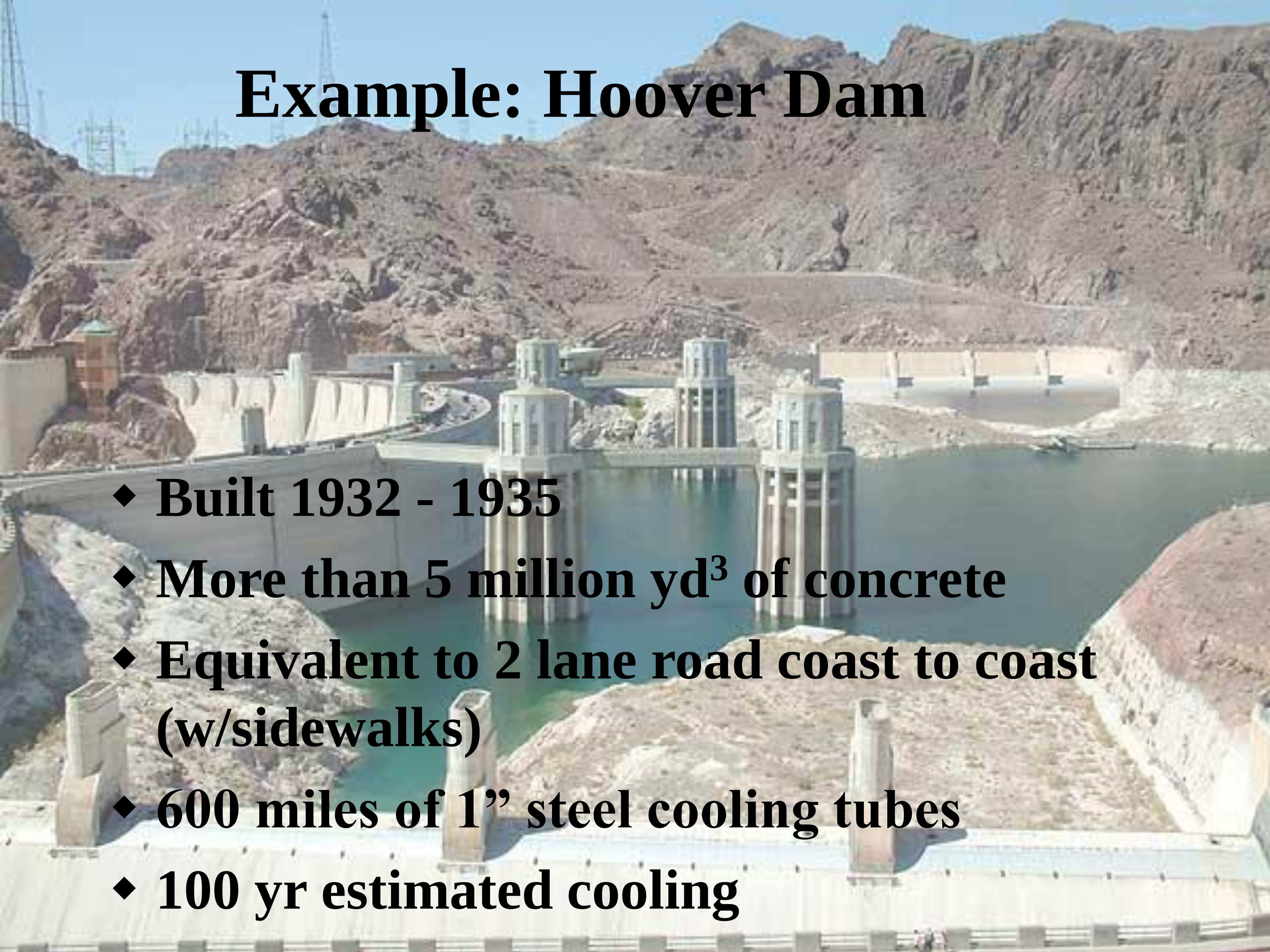
- Concrete Heat of Hydration
- Thermal Integrity Profiling
- Governing Equations
- COMSOL® Model
- Case Study
- Conclusions

Background

Cement hydration is a highly exothermic process

C_4AF C_2S C_3A C_3S $C\overline{S}H_2$ H_2O





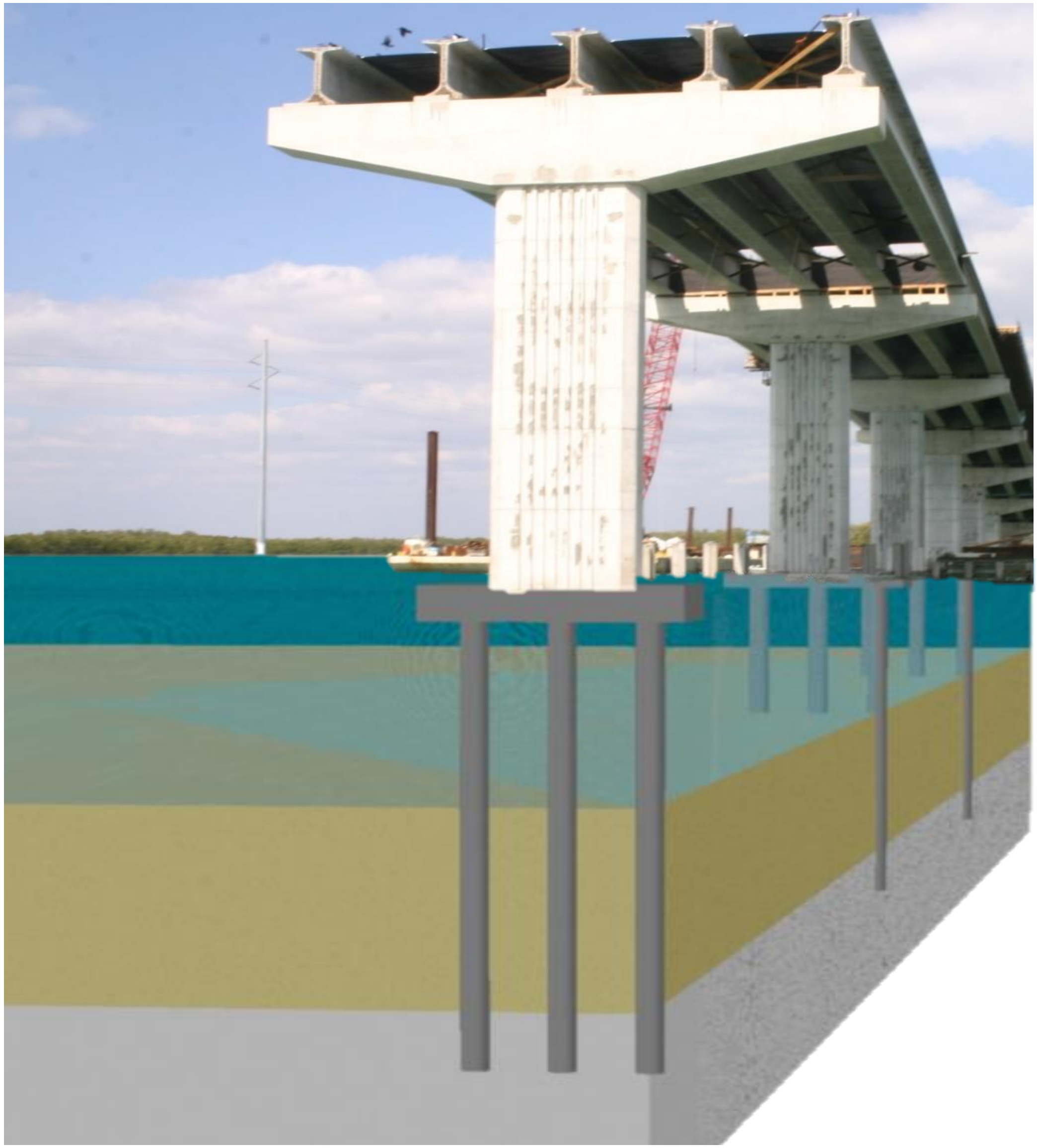
Example: Hoover Dam

- Built 1932 - 1935
- More than 5 million yd^3 of concrete
- Equivalent to 2 lane road coast to coast (w/sidewalks)
- 600 miles of 1” steel cooling tubes
- 100 yr estimated cooling

Background

Drilled Shafts

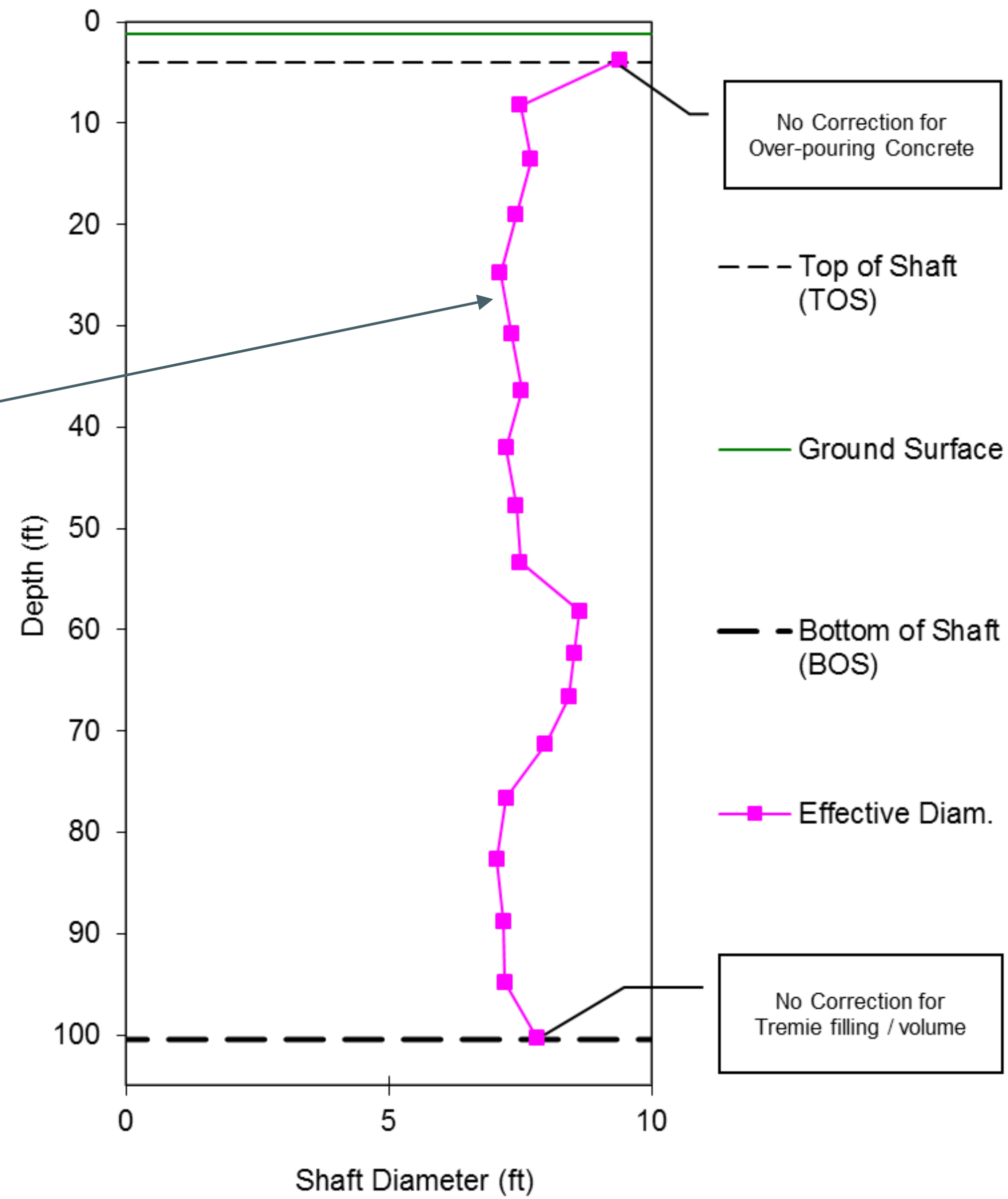
- **Cast-in-place concrete deep foundations**
- ***3 – 30 ft. diameter***
- ***Up to 300 ft. deep***
- ***Group or mono-shaft foundations***

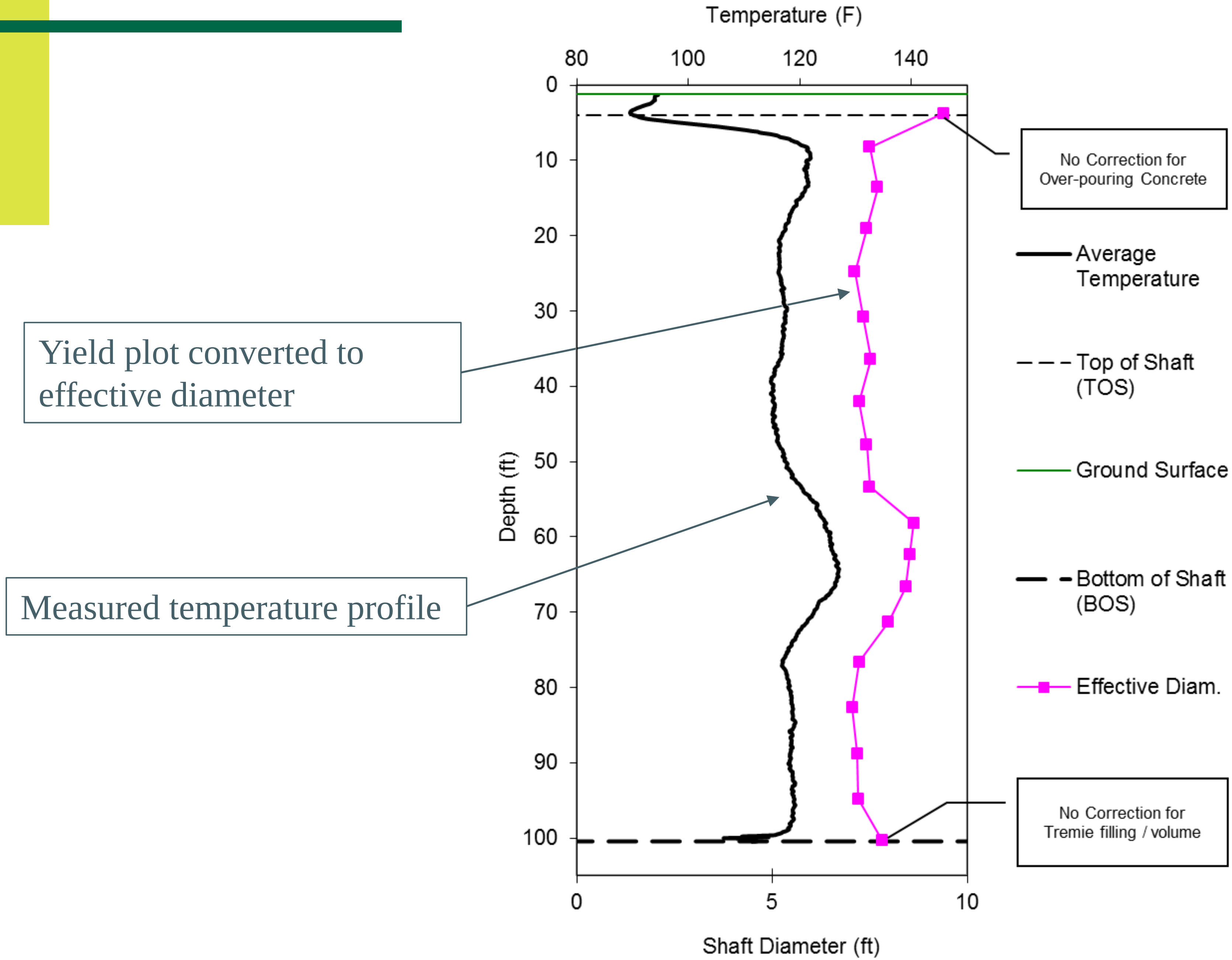


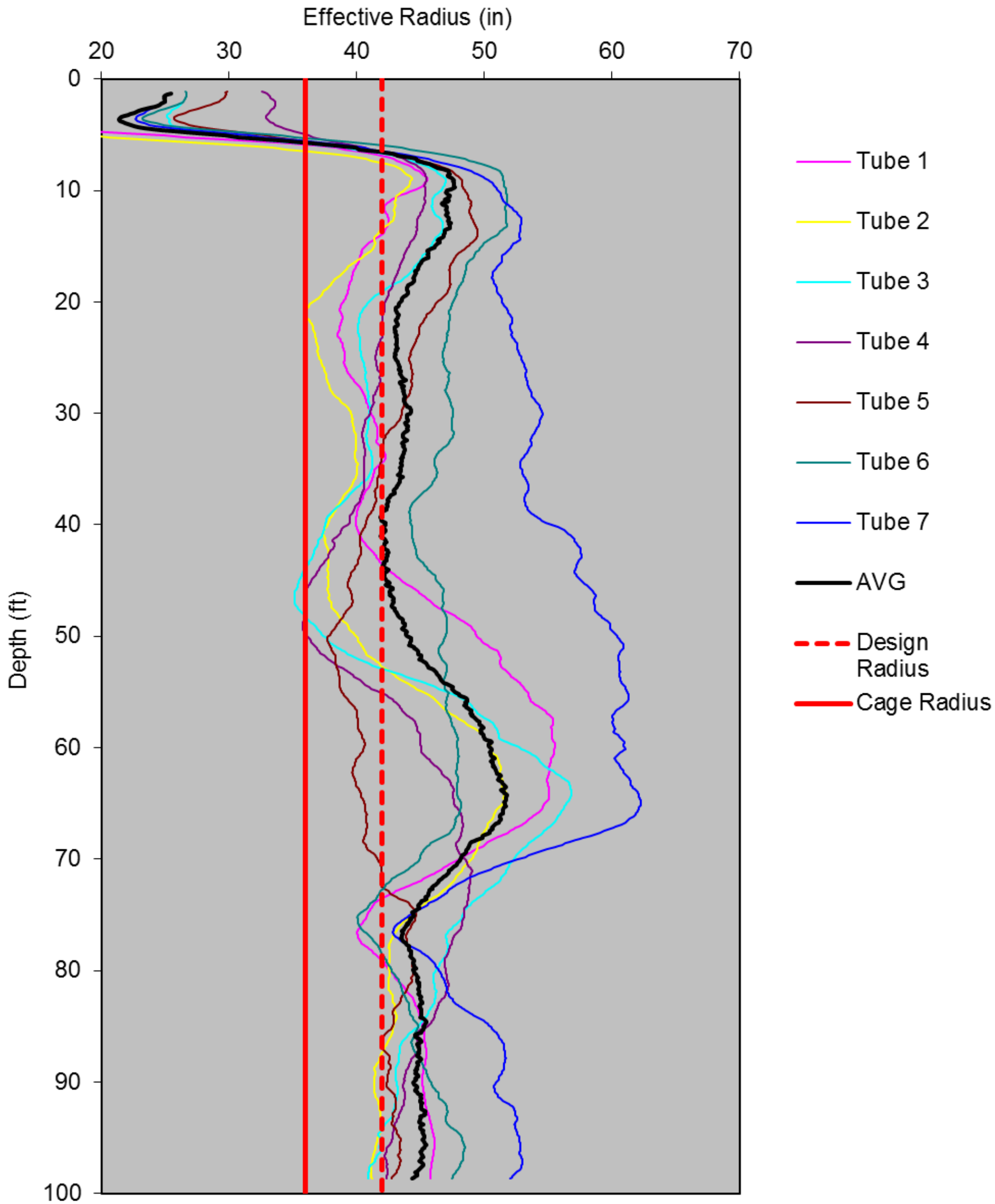
Why Test Shaft Integrity?

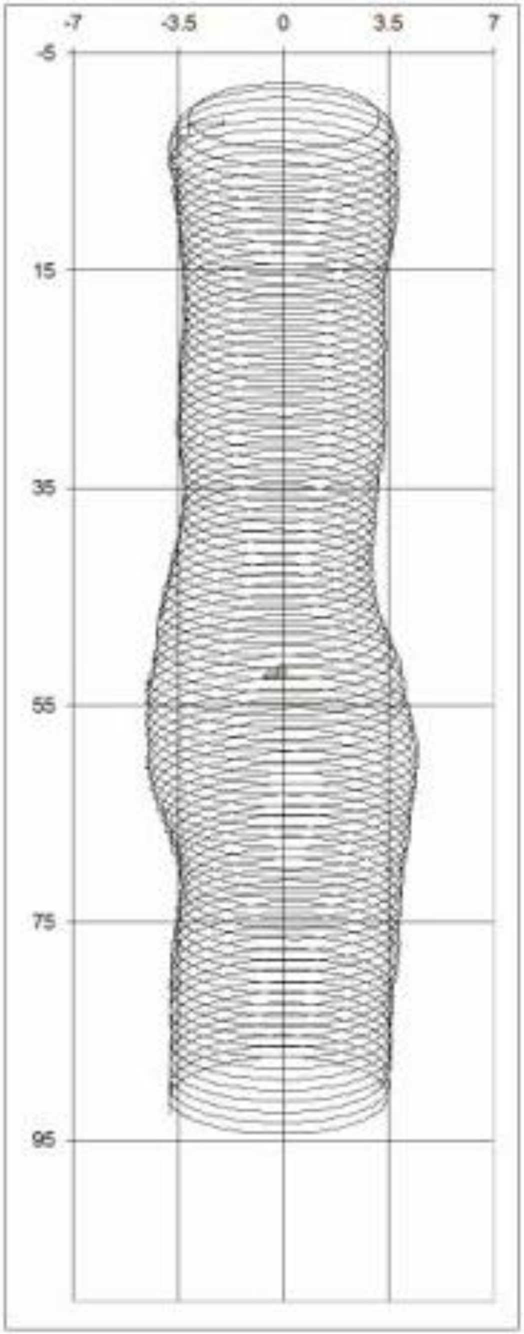
Thermal Integrity Profiling (TIP)

Yield plot converted to effective diameter

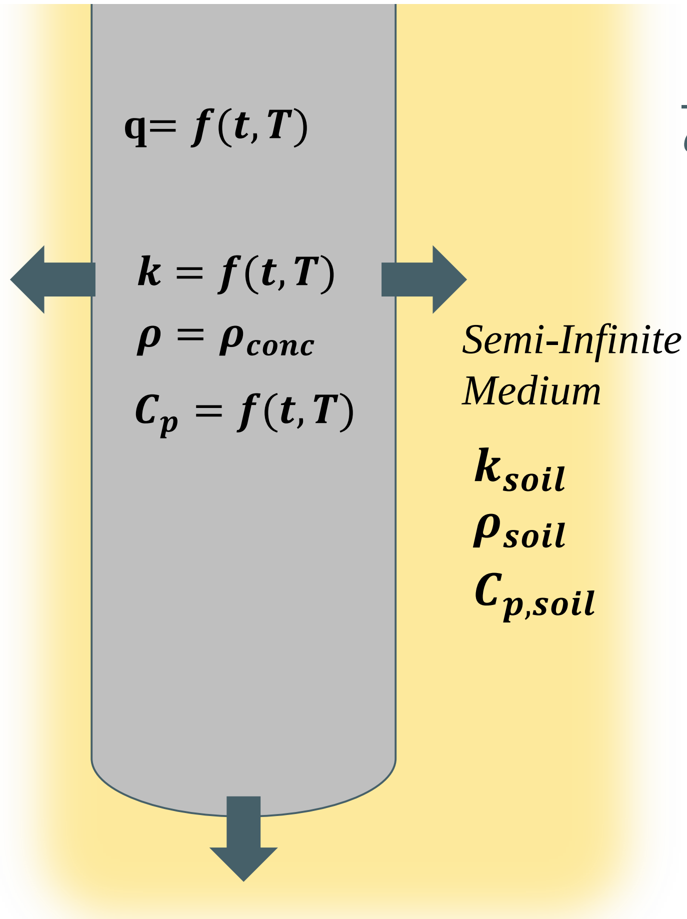



Yield plot converted to effective diameter
Measured temperature profile
Temperature (F)
80
100
120
140
Depth (ft)
0
10
20
30
40
50
60
70
80
90
100
Shaft Diameter (ft)
0
5
10
No Correction for Over-pouring Concrete
Average Temperature
Top of Shaft (TOS)
Ground Surface
Bottom of Shaft (BOS)
Effective Diam.
No Correction for Tremie filling / volume


Effective Radius (in)
20
30
40
50
60
70
Depth (ft)
0
10
20
30
40
50
60
70
80
90
100
Tube 1
Tube 2
Tube 3
Tube 4
Tube 5
Tube 6
Tube 7
AVG
Design Radius
Cage Radius


-7
-3.5
0
3.5
7
-5
15
35
55
75
95

Governing Equations



General Heat Equation

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + q = \rho C_p \frac{\partial T}{\partial t}$$

T = *temperature*

t = *time*

xyz = *rectangular coordinates*

k = *thermal conductivity*

ρ = *density*

C_p = *specific heat*

q = *rate of heat generation*

Concrete Heat Generation

The α−β−τ Model

$$\alpha = degree\ of\ hydration = \frac{H(t)}{H_u} = \alpha_u \cdot \exp\left[-\left(\frac{\tau}{t_e}\right)^{\beta}\right]$$

$$t_e = Equivalent\ Age = \sum_{0}^{t} e^{-\frac{E_a}{R}\left(\frac{1}{T}-\frac{1}{T_r}\right)} \cdot \Delta t$$

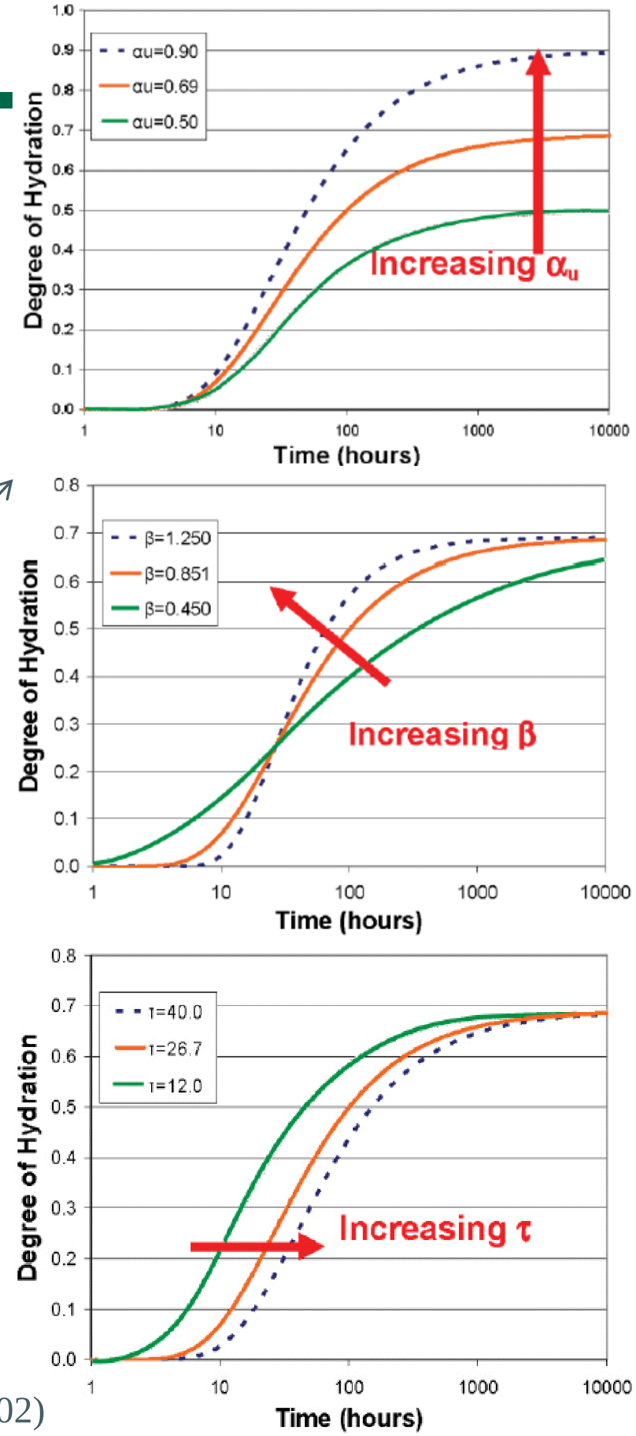
$H_u = Total\ Available\ Heat$

$E_a = Activation\ Energy$

$\left.\begin{matrix}\alpha_u \\ \beta \\ \tau\end{matrix}\right\} = Shape\ Parameters$

$T_r = Reference\ Temperature$

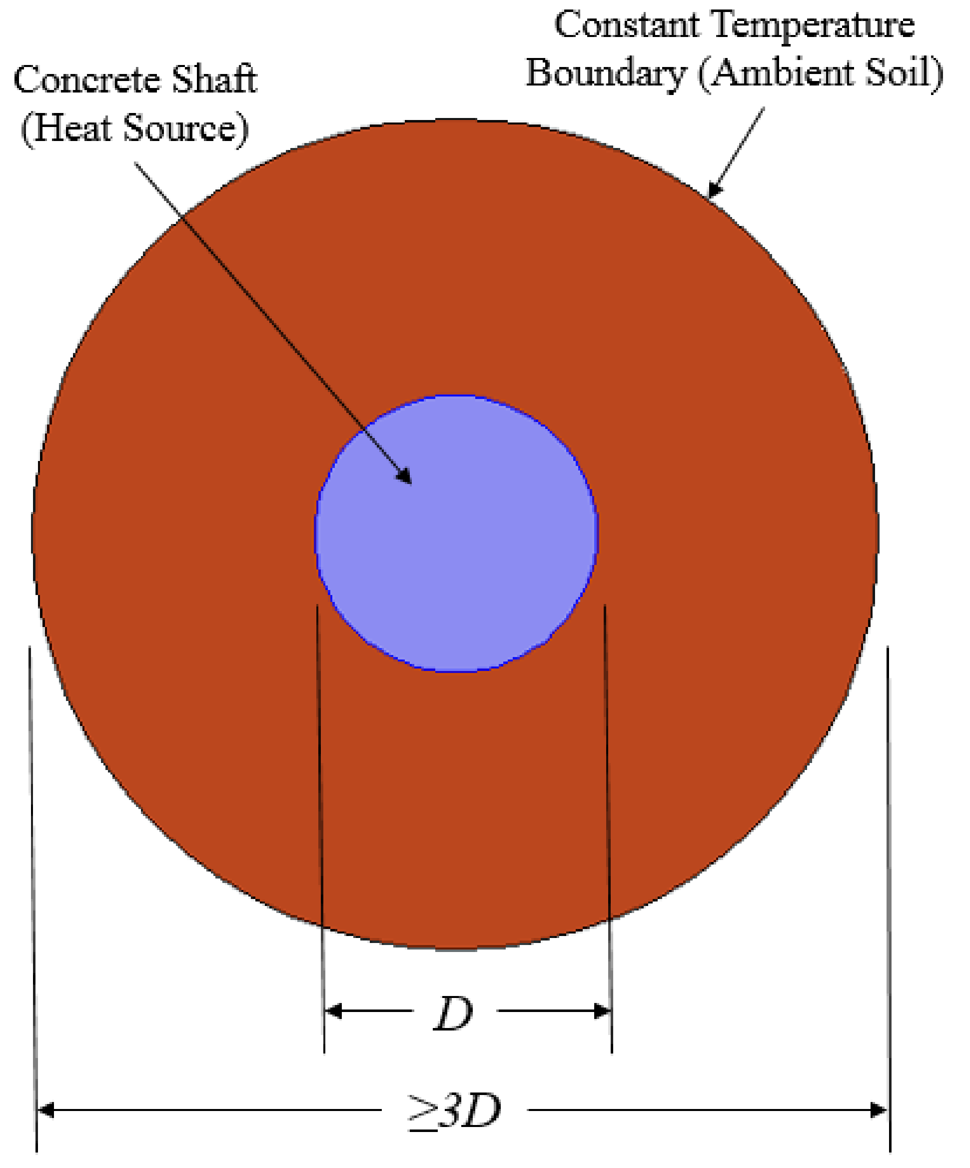
$R = Natural\ Gas\ Constant$



(Schindler & Folliard, 2002)

COMSOL® Model Geometry

Governing equations can be applied to 2-D or 3-D geometries



COMSOL® Model
Materials - Concrete

Empirical correlations used to estimate α-β-τ model parameters:

$$\alpha_u = f({}^{w}/_{cm}, C_4AF, Na_2O_{eq}, FA, WRs)$$

$$\beta = f(C_3A, Slag, WRs)$$

$$\tau = f(C_3S, Na_2O, Slag, FA, WRs, ACCs)$$

$$H_u = f(C_3S, C_2S, C_3A, C_4AF, SO_3, Free\ CaO, MgO)$$

$$E_a = f(C_3A, C_4AF, SO_3, Na_2O_{eq}, Fineness, FA, Slag, SF, WRs, ACCs)$$

(Schindler, 2005; Ge, 2006; Poole, 2007)

COMSOL® Model
Materials - Concrete

- *Density*

$$\boldsymbol{\rho} = (\boldsymbol{W_c} + \boldsymbol{W_a} + \boldsymbol{W_w})$$

- *Thermal Conductivity*

$$\boldsymbol{k} = \boldsymbol{k_{uc}}(\mathbf{1.33} - \mathbf{0.33}\boldsymbol{\alpha})$$

$$k_{uc} = 2 - 3\ \frac{W}{m \cdot K}$$

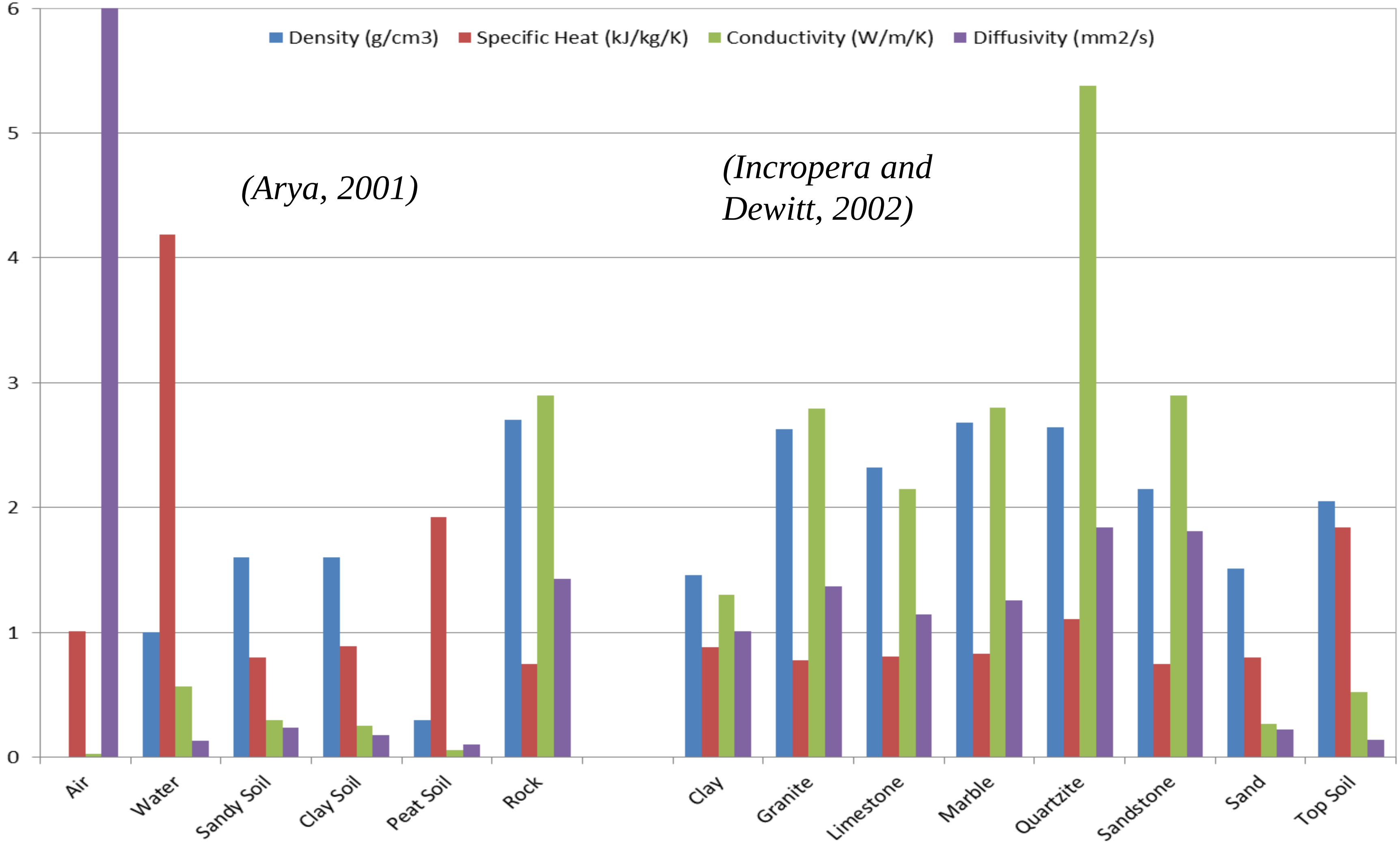
- *Specific Heat*

$$\boldsymbol{C_p} = \frac{\mathbf{1}}{\boldsymbol{\rho}}\left(\boldsymbol{W_c}\boldsymbol{\alpha}\boldsymbol{C_{ref}} + \boldsymbol{W_c}(\mathbf{1} - \boldsymbol{\alpha})\boldsymbol{C_c} + \boldsymbol{W_a}\boldsymbol{C_a} + \boldsymbol{W_w}\boldsymbol{C_w}\right)$$

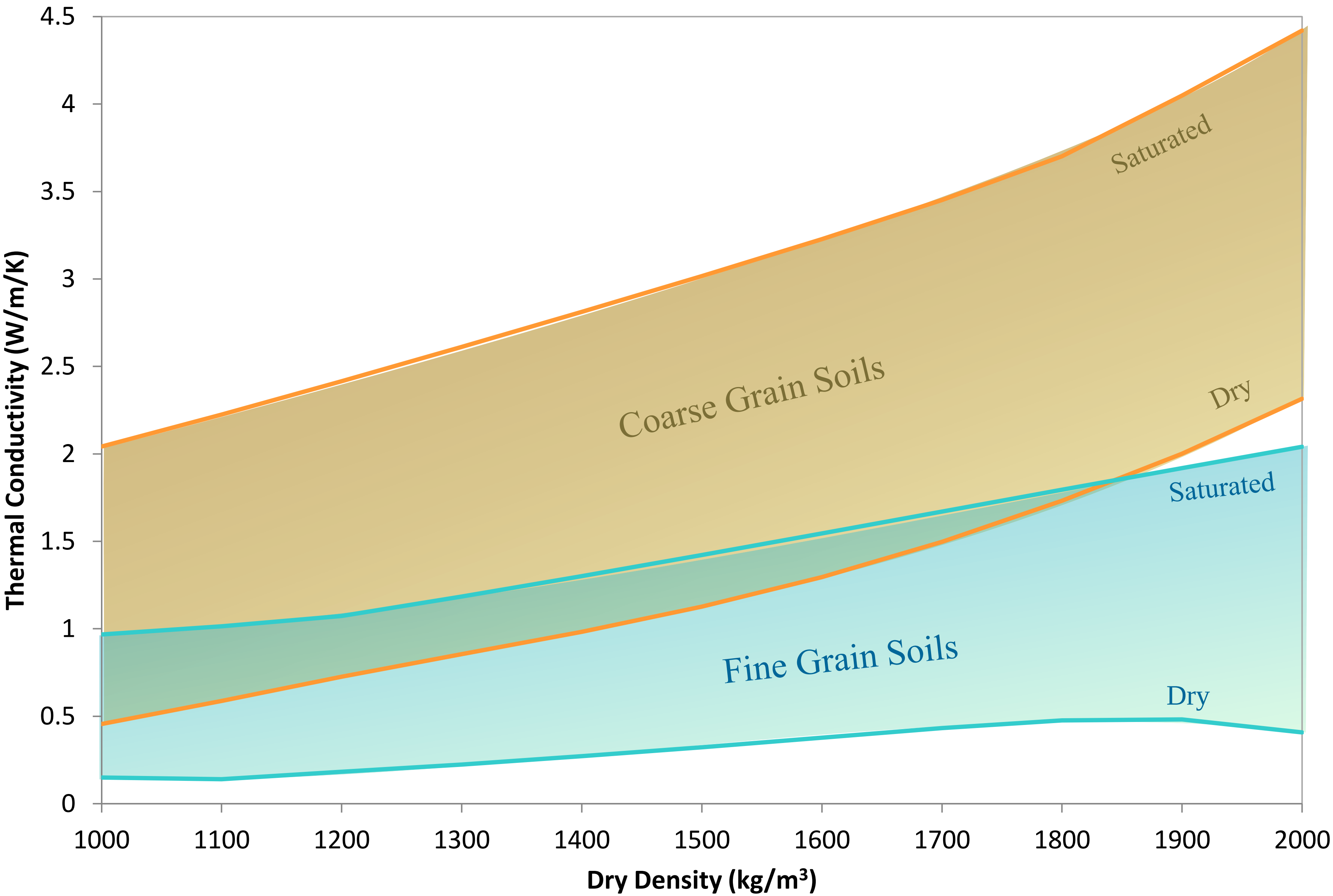
$$C_{ref} = 8.4T + 339$$

(Schindler, 2002)

COMSOL® Model
Materials - Soil



Soil Thermal Properties



COMSOL® Model
Physics – Heat Transfer in Solids

Initial Values

Soil Domain = Ambient soil temperature

Concrete Domain = Ambient air temperature

Boundary Condition

Constant temperature at soil domain edge

Heat Source

Concrete: $q = H_u \left(\frac{\tau}{t_e}\right)^{\beta} \left(\frac{\beta}{t_e}\right) \alpha \frac{E_a}{R} \left(\frac{1}{T_r} - \frac{1}{T_c}\right)$

COMSOL® Model
Physics – Coefficient Form PDEs

PDE 1: $Equivalent\ Age, t_e = \sum_{0}^{t} e^{-\frac{E_a}{R}\left(\frac{1}{T}-\frac{1}{T_r}\right)} \cdot \Delta t$

- Note: Initial values $t_e = 1$ and $\frac{dt_e}{dt} = 1$

PDE 2: $Degree\ of\ Hydration, \alpha = \frac{H(t)}{H_u} = \alpha_u \cdot \exp\left[-\left(\frac{\tau}{t_e}\right)^{\beta}\right]$

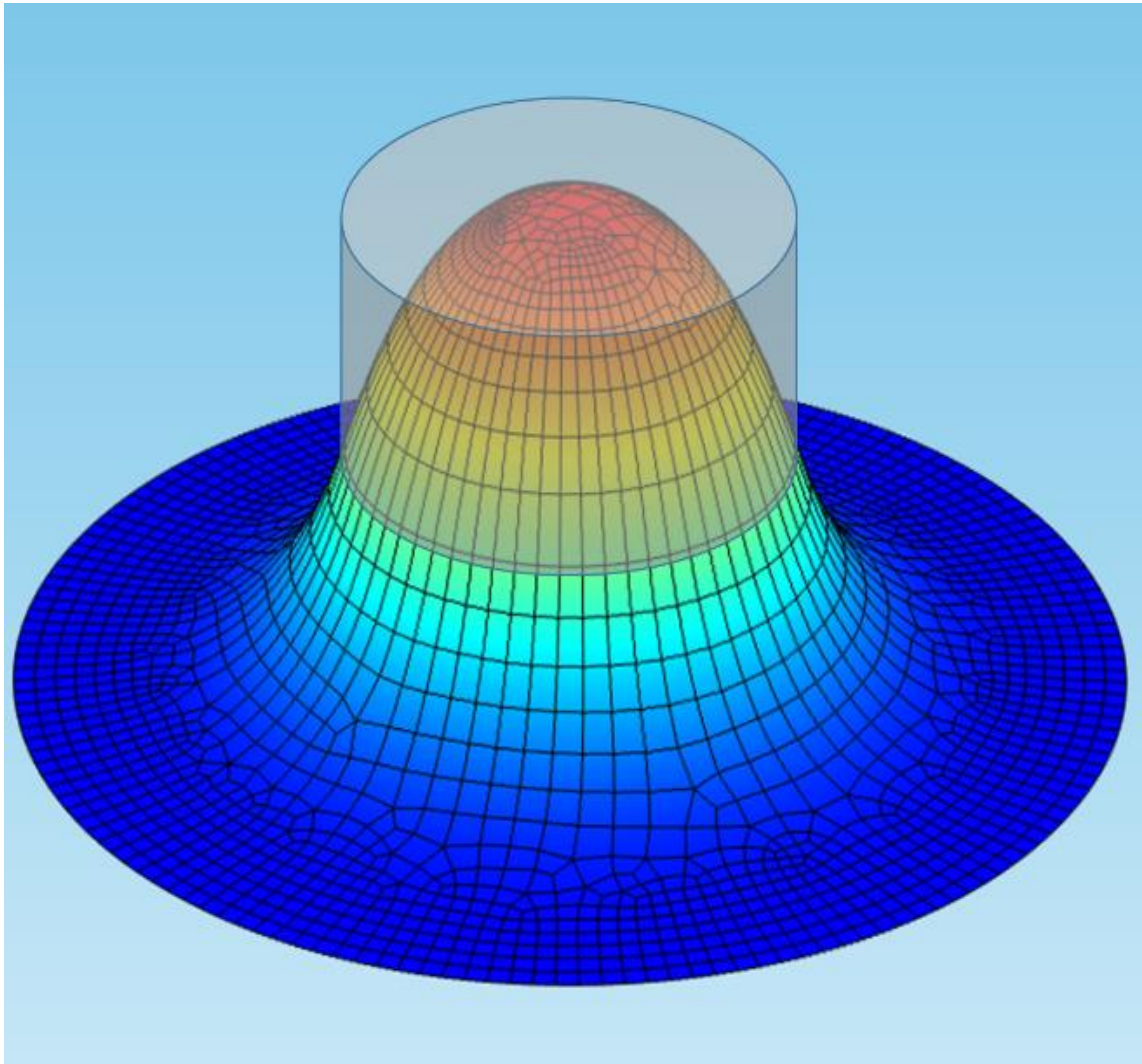
COMSOL® Model
Solver Configuration

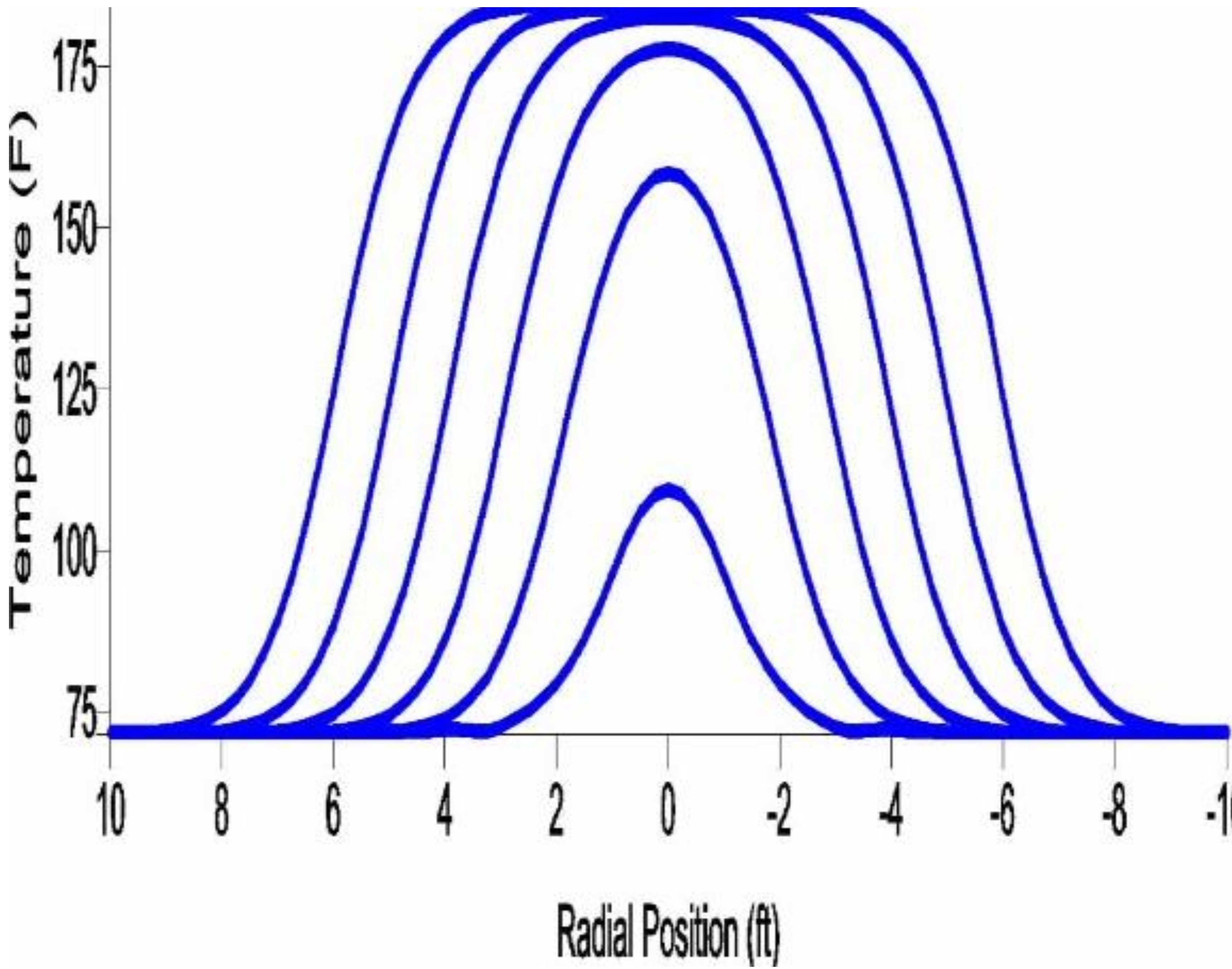
Time Dependent Solver with segregated steps:

- Step 1: Equivalent age, t_e
- Step 2: Degree of hydration, α
- Step 3: Temperature, T

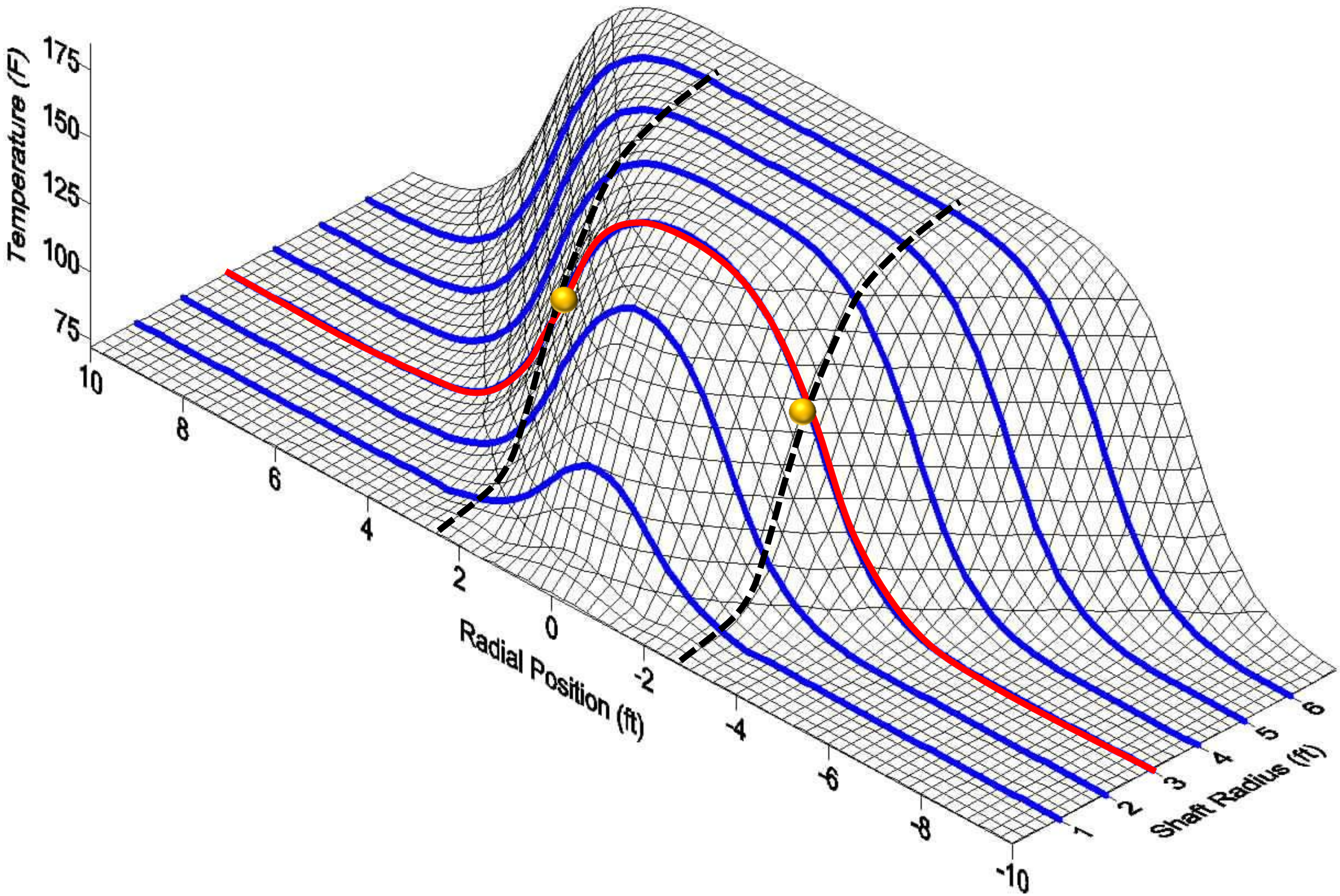
COMSOL® Model Results

Radial heat distribution is bell shaped with peak temperatures occurring at the center of shaft and radiating outwards into the surrounding soil.



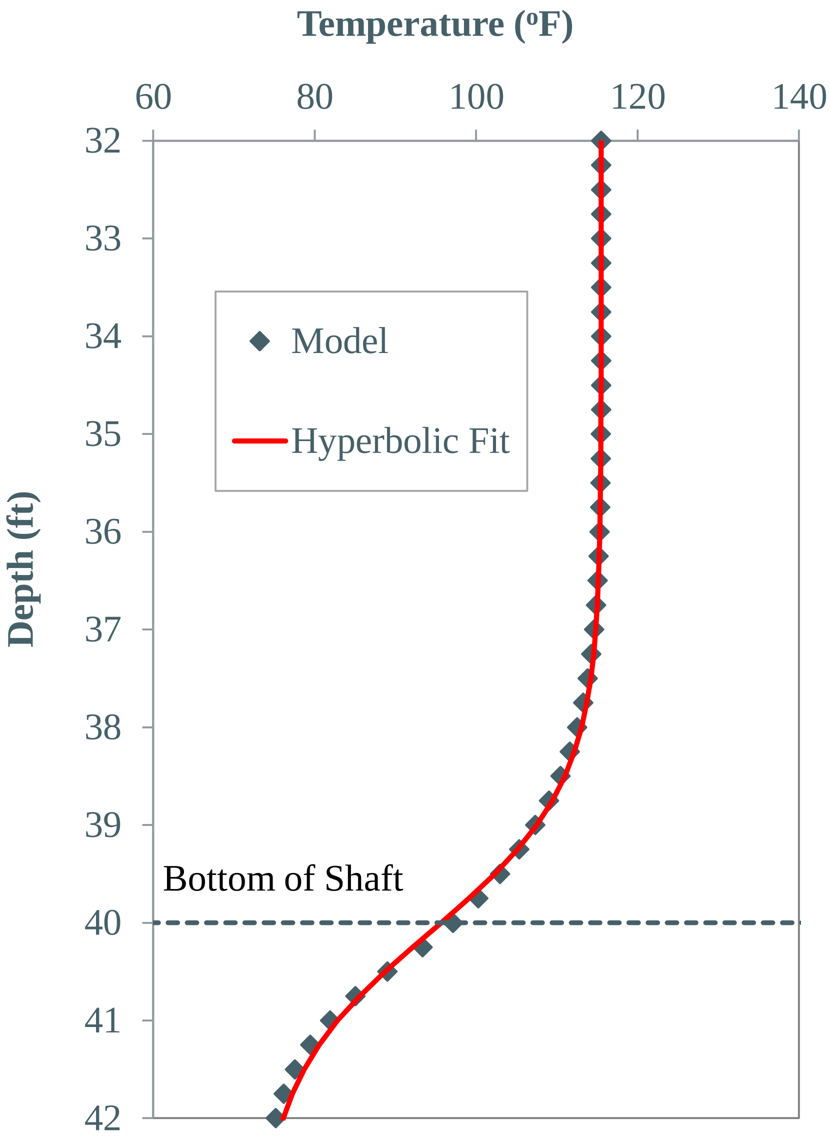


Temperature (F)
175
150
125
100
75
10
8
6
4
2
0
-2
-4
-6
-8
-10
Radial Position (ft)


Temperature (F)
175
150
125
100
75
10
8
6
4
2
0
-2
-4
-6
-8
-10
Radial Position (ft)
1
2
3
4
5
6
Shaft Radius (ft)

COMSOL® Model Results

Model results also show that the longitudinal temperature distributions in a shaft can be closely approximated by a hyperbolic tangent function.



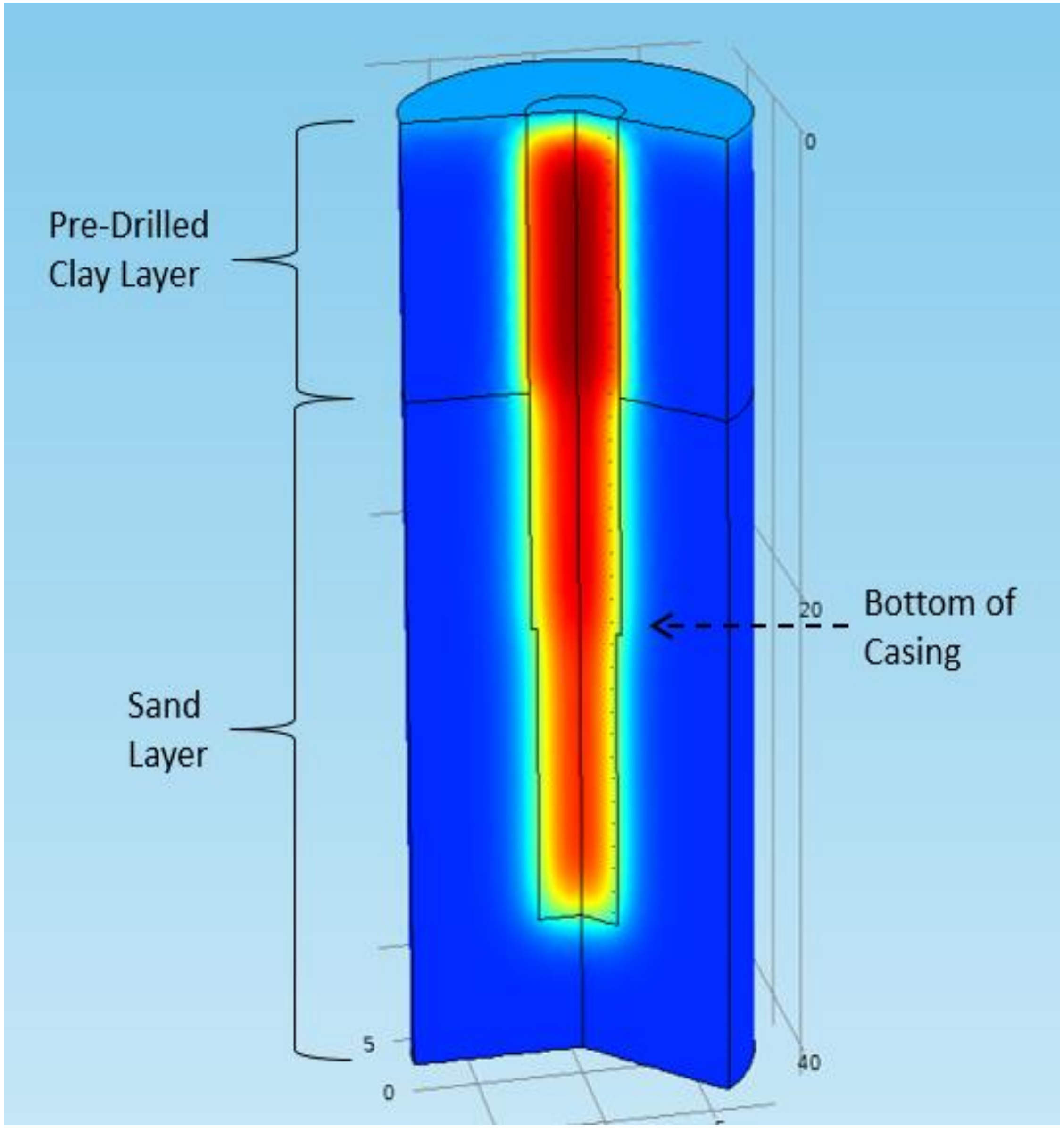
Case Study

Drilled Shaft

Upper Diam. (cased) = 54”

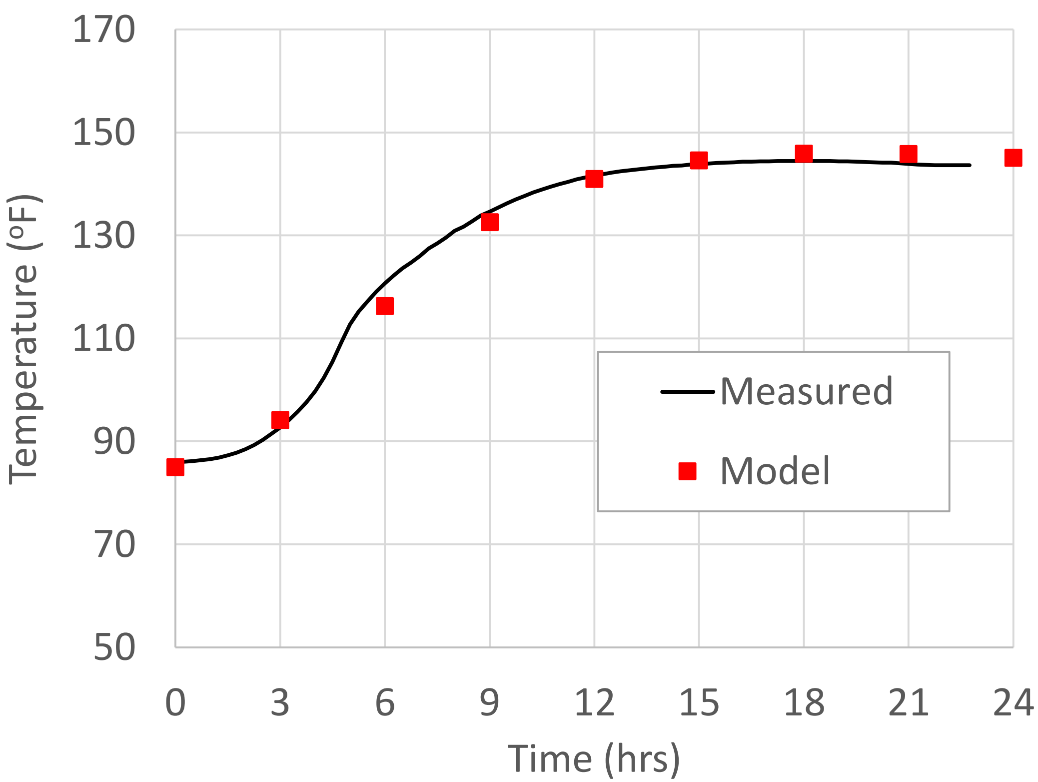
Lower Diam. (uncased) = 48”

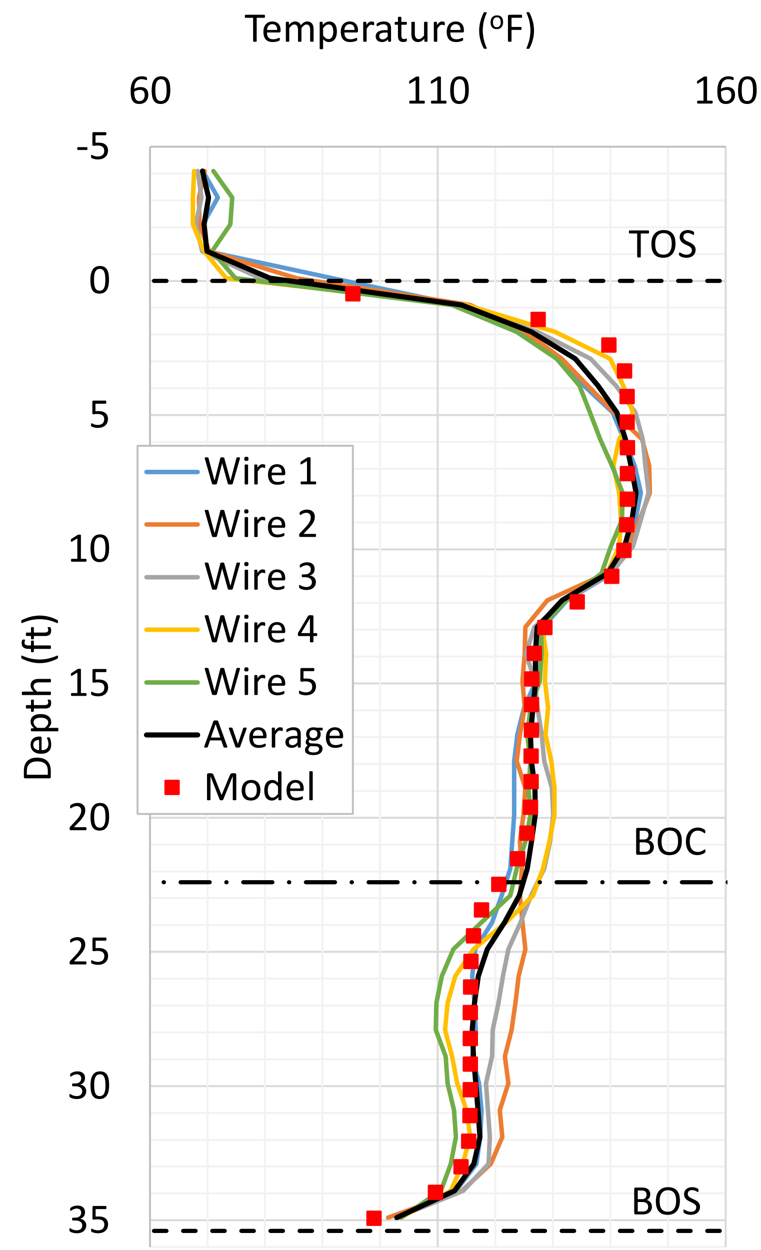
Change in soil strata (and construction procedure) at 12ft depth caused unexpected anomaly in thermal profile.



Case Study

Model data vs. Measured data





Conclusions

- The use of COMSOL® numerical modeling has been shown to be an effective tool in simulating concrete hydration behavior and an aid Thermal Integrity Profiling of drilled shafts.
    - Modeled parametric studies provide insight to general thermal relationships in foundations.
    - 3-D models used for advanced analysis of shafts with anomalies.
- The same governing equations and COMSOL® applications can used for analyses where excess temperature control to prevent thermal stress cracking is a concern.

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Questions?