STRUCTURAL CAPACITY EVALUATION OF DRILLED SHAFT FOUNDATIONS WITH DEFECTS

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Presentation Outline

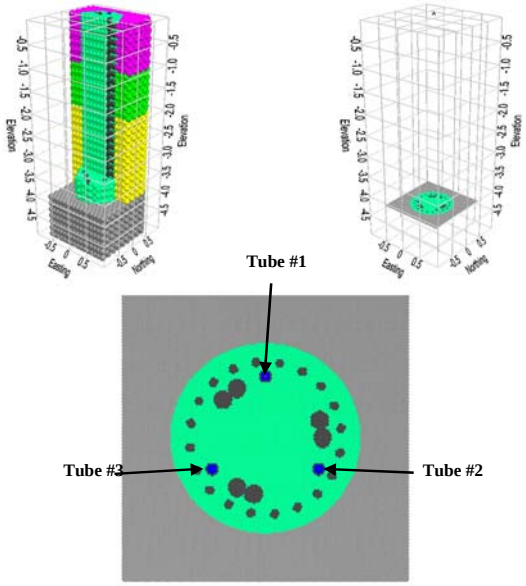
- **Background on Drilled Shafts and NDE Methods**
- **Field Testing and Tomography**
- **3-D Numerical Modeling of Drilled Shafts**
  - **Evaluating Factors Affecting CSL Results**
  - **Concrete Curing in Deep Foundations**
  - **Evaluating Drilled Shafts Performance with Anomalies**

Numerical Modeling Analysis of CSL in Drilled Shafts

The effect of the following factors on velocity propagation during testing of drilled shafts were examined:

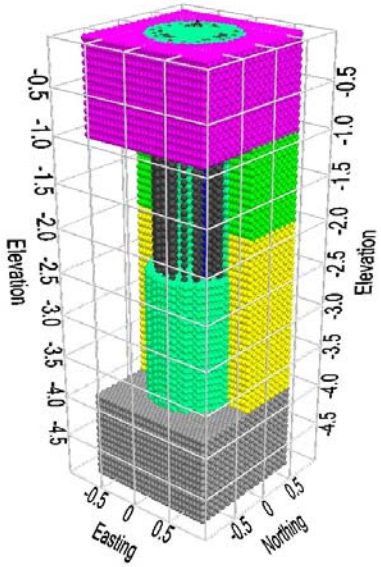
1. Surrounding geomaterials—soil vs. rock
2. Access Tubes—tube bending, sensor drift, steel vs. PVC tubes, and tube debonding
3. Rebar—CSL signal reflection and dispersion, thermal expansion, and rebar debonding
4. Common defects—honeycomb, soil intrusion, voids, and thermal cracking

3-D Numerical Modeling

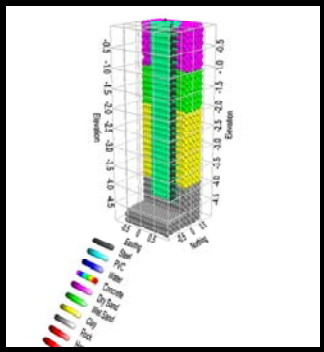


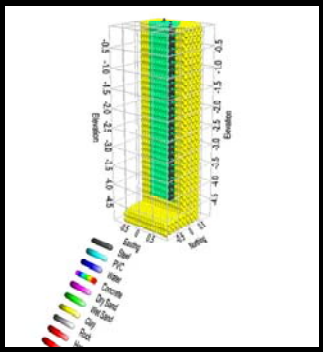
3-D Modeling Scale

- Steel
- PVC
- Water
- Concrete
- Dry Sand
- Wet Sand
- Clay
- Rock
- Defect

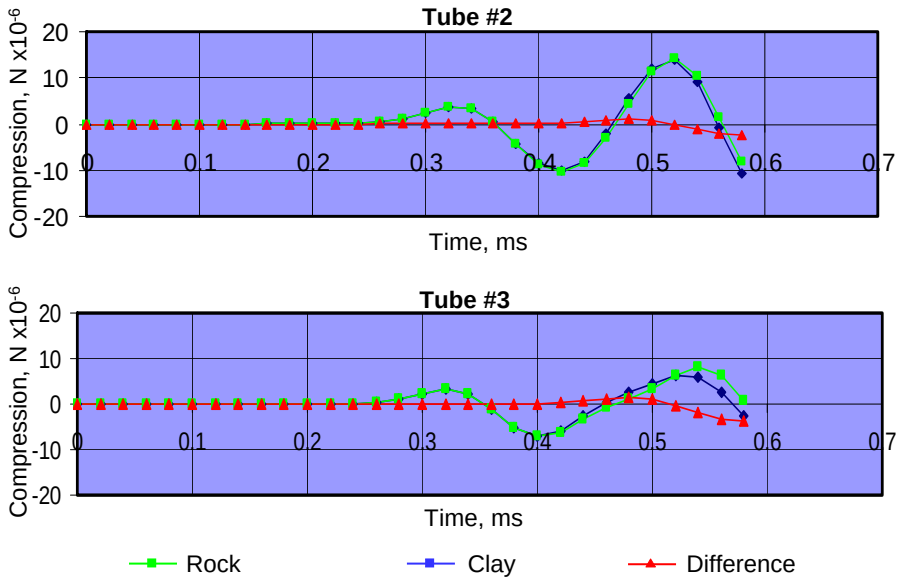


Surrounding Strata Effect

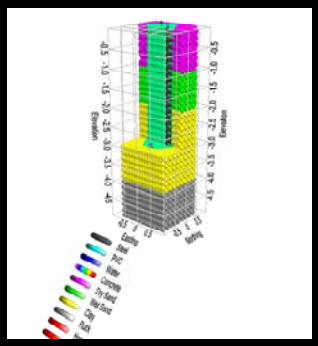


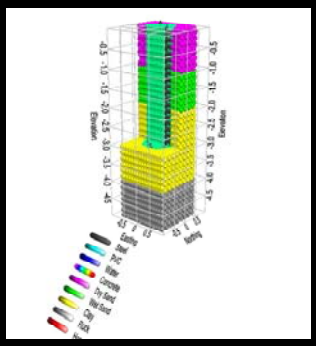


Rock Vs. Clay

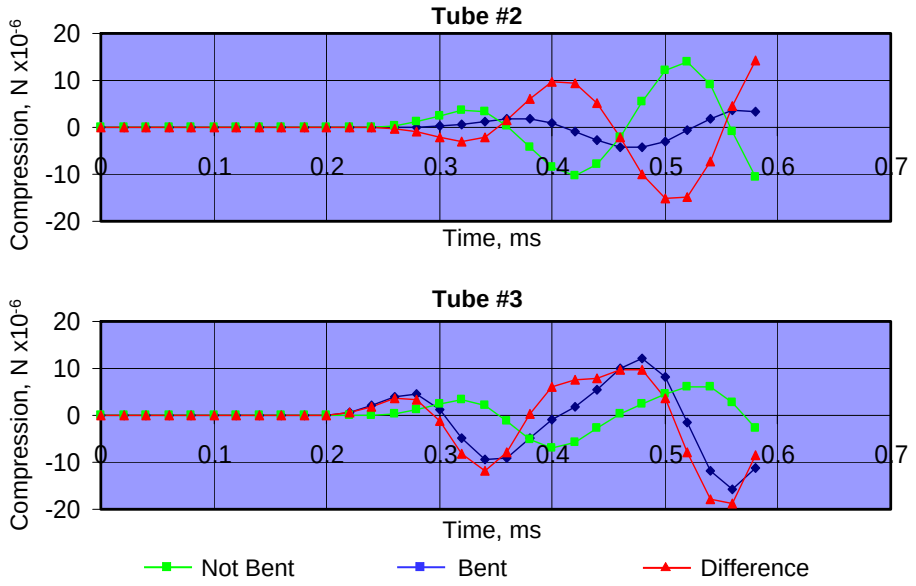


Tube Bending Effect

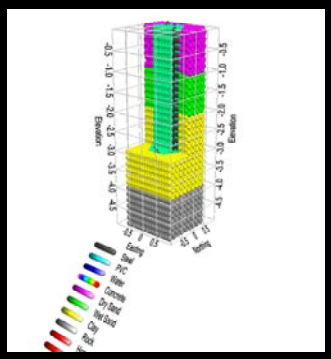


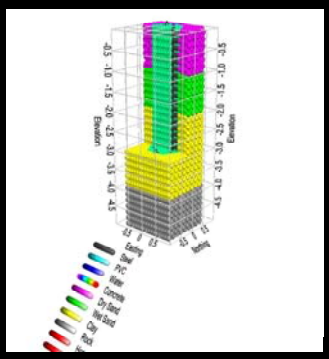


Bent Tube Effect

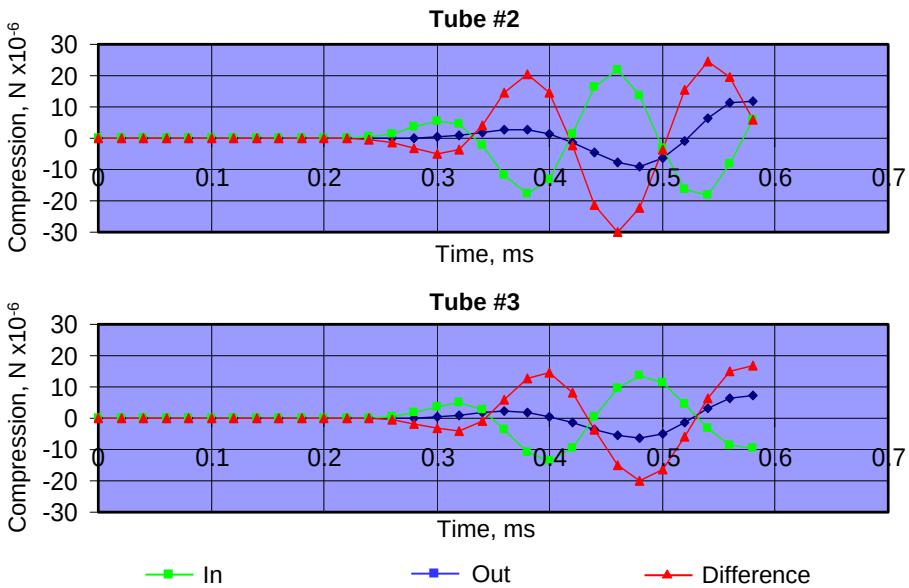


Sensor Drift Effect

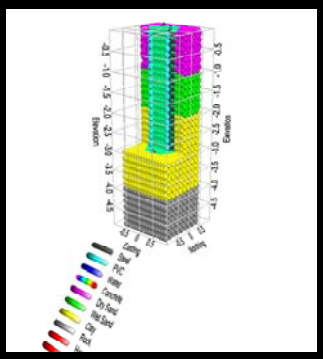


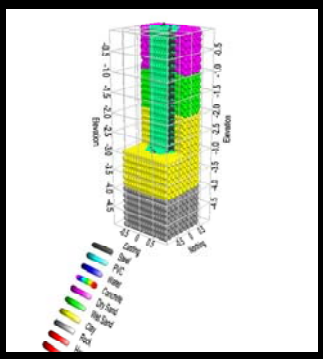


Sensor Drift Effect

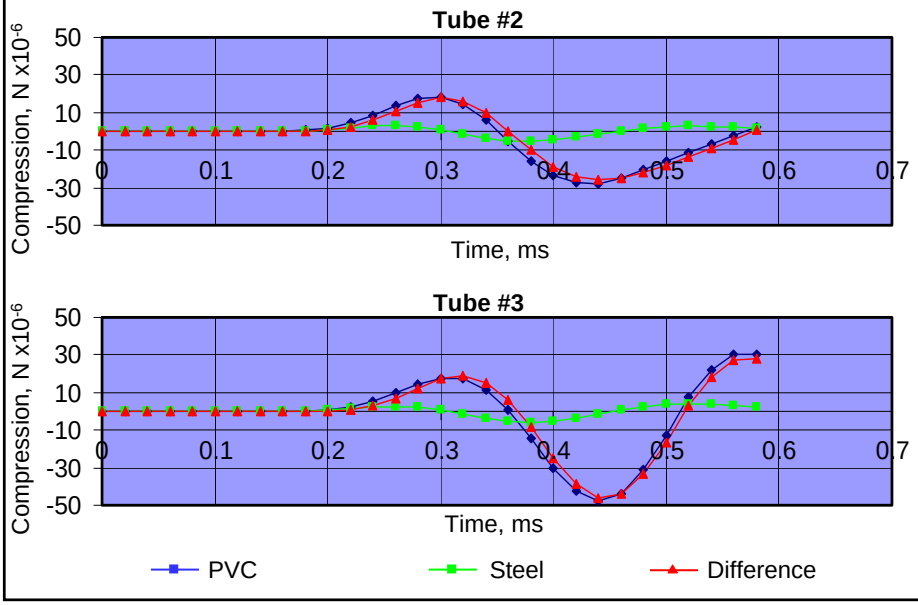


Tube Type Effect

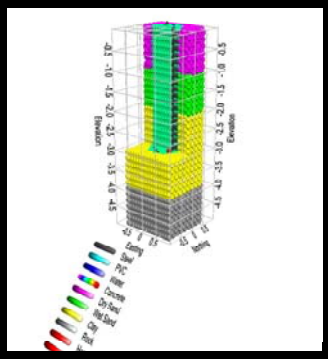


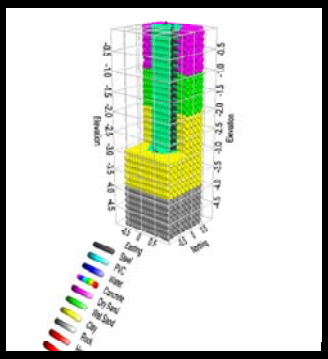


Effect of PVC vs. Steel Tubes

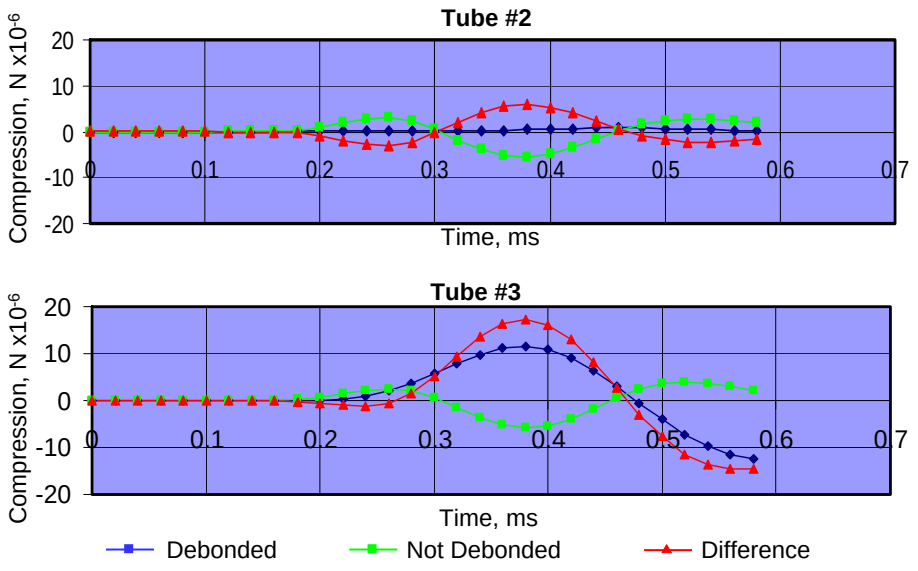


Tube Debonding Effect

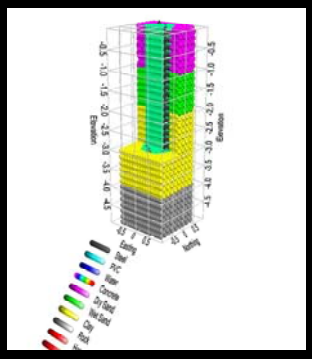


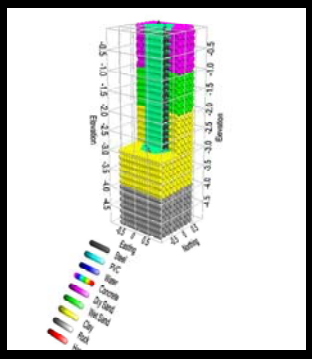


Tube Debonding Effect

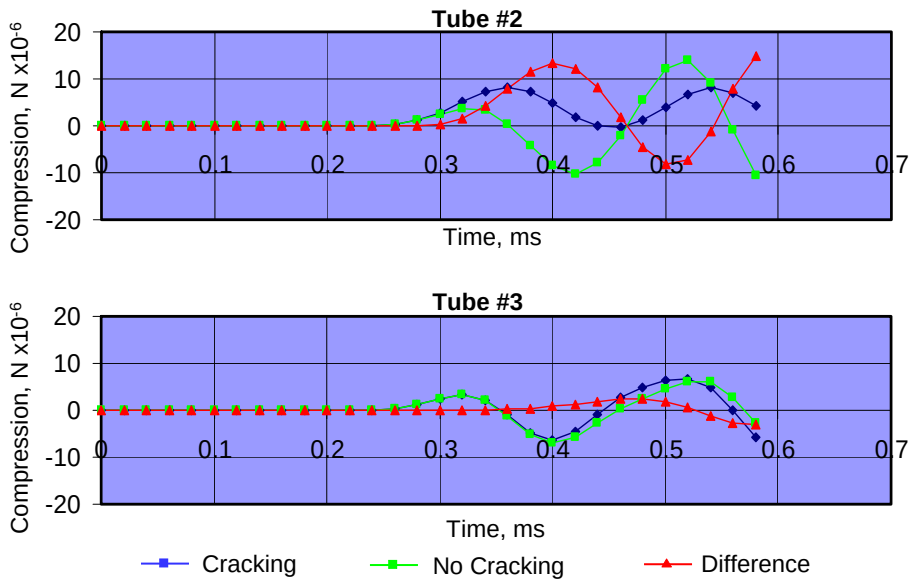


Concrete Cracking Effect

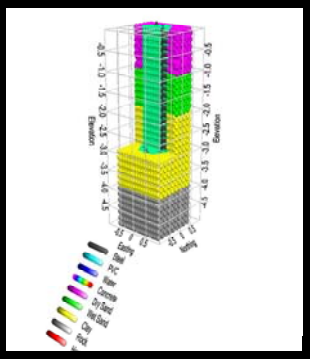


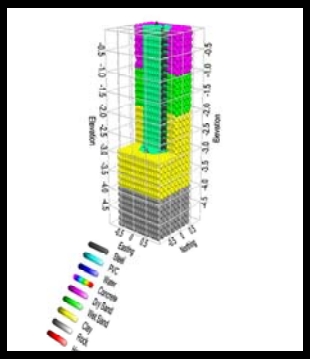


Concrete Cracking Effect

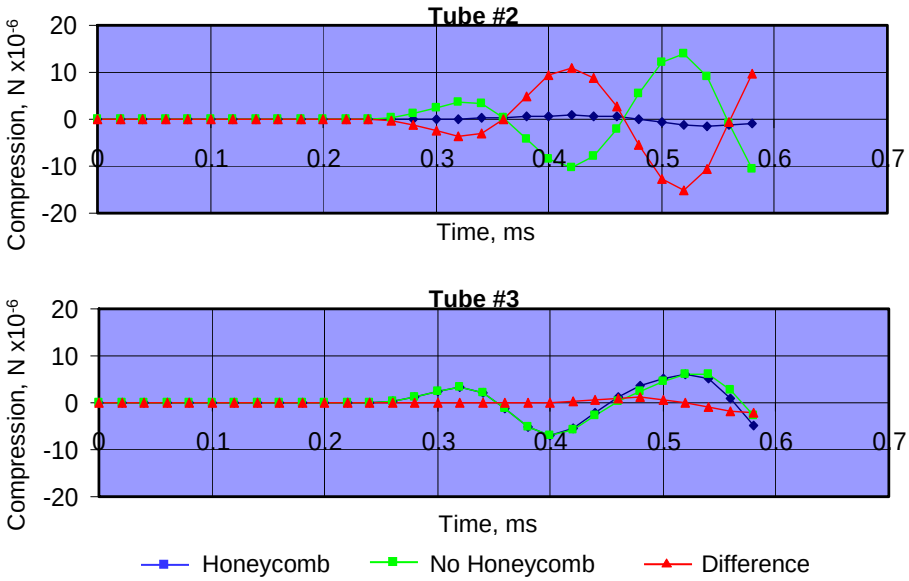


Honeycomb Effect

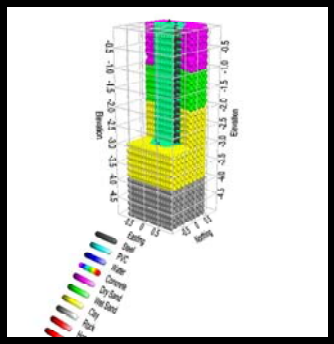


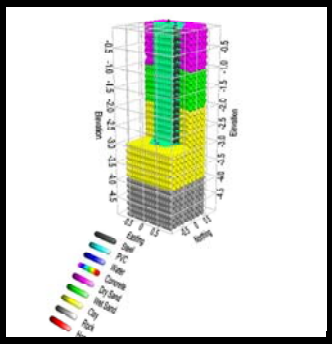


Honeycomb Effect

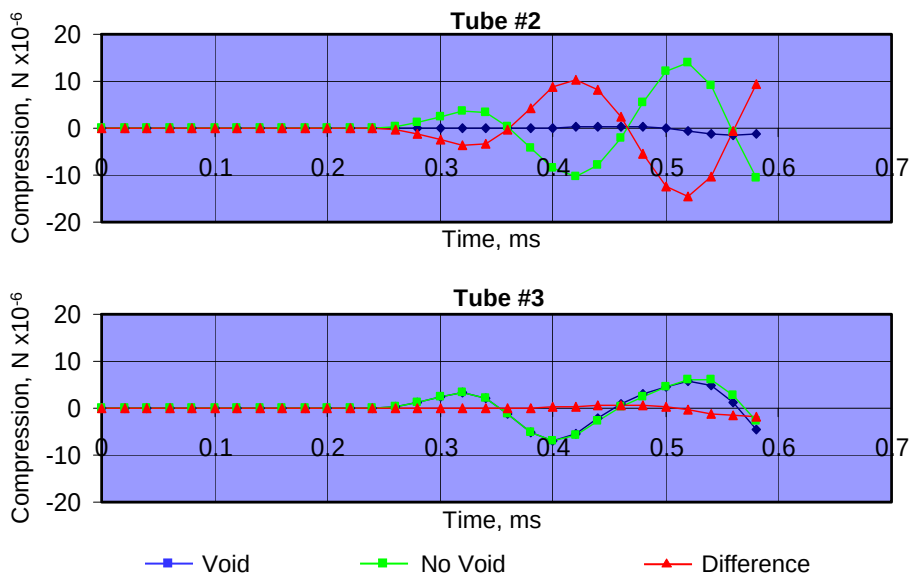


Void Effect

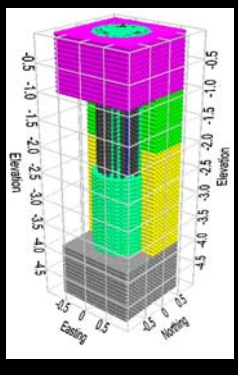




Void Effect

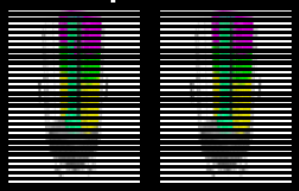


Numerical Modeling of the structural capacity of drilled shafts with defects

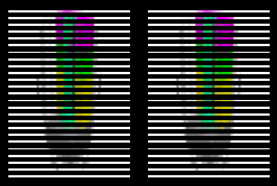


Drilled Shaft Loading

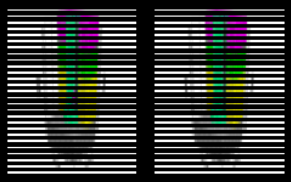
Compression-1



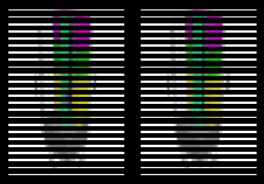
Cracking-1



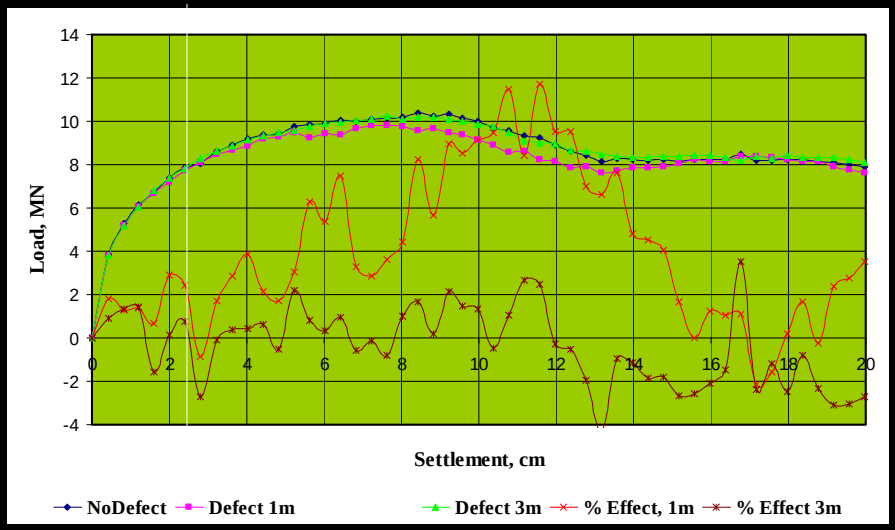
Compression-3



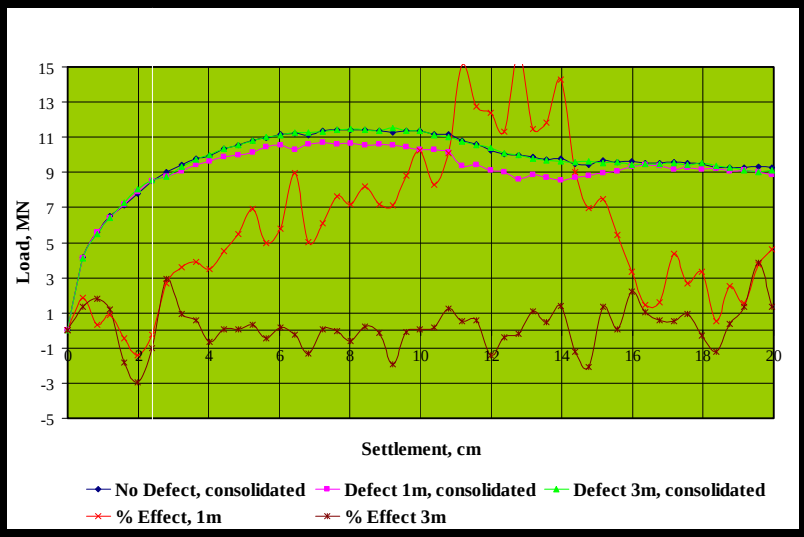
Cracking-3



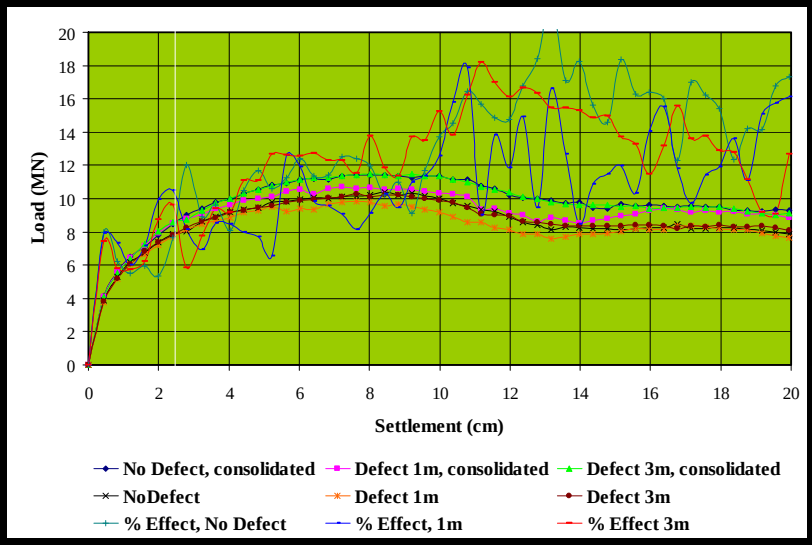
Effect of a Defect at Two Different Depths on Drilled Shaft Load Bearing Capacity



Effect of a Defect on Drilled Shaft Load Capacity with Shaft in Consolidated Soil



Effect of Soil Consolidation on Drilled Shaft Load bearing Capacity



Conclusion

- First, locate the defects.
  - Many variables influence the quality of CSL data.
  - Tomography can improve visualization of defects.
- Second, determine the structural capacity of the drilled shaft.
  - Based on experience, determine if the shaft can be accepted, rejected, or requires repair.
- Use 3D numerical modeling to both locate the defects and estimate structural capacity
  - Advancements in NDE (software/hardware)
  - 3D numerical model stress analysis

Modeling of Concrete Curing

Concrete curing involves complex Interaction of numerous variables:

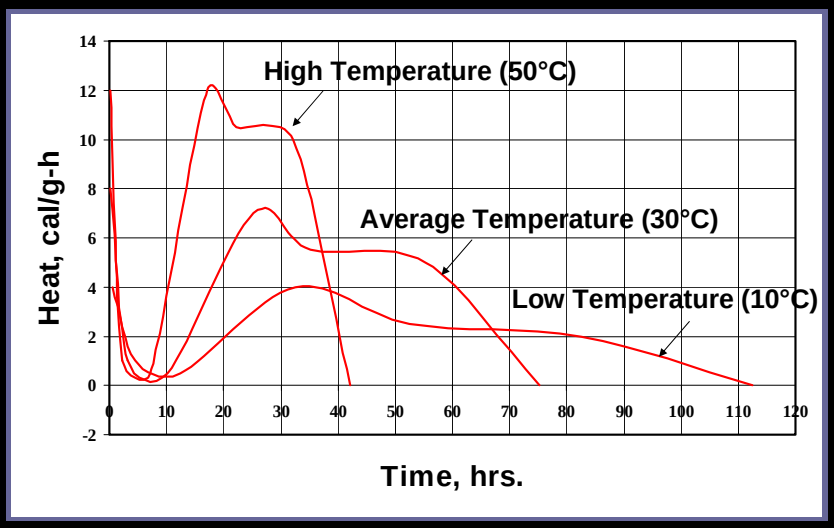
Variables

1. Thermal Conductivity
2. Tension Strength
3. Modulus
4. Heat Generation
5. Hydration Phases
6. Volume Expansion

Computed

1. Stress
2. Cracking
3. Temperature
4. Hydration Rate

Heat of Hydration Curves used in the Model

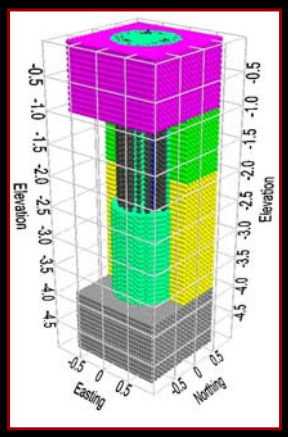


Empirically for a particular concrete mix by measuring heat generation under isothermal conditions

Actual Coefficients used in the Model

Temperature (C)	Hydration %	Heat	Time (hrs)	Thermal Conductivity	Strength	Stiffness	Radius
10	0	4	0.5	0.25	0.25	0.25	1
10	17	1	4	0.3	0.5	0.5	0.99
10	33	0.5	8	0.35	0.6	0.6	0.98
10	50	4	20	0.4	0.7	0.7	0.97
10	67	2.5	20	0.45	0.8	0.8	0.96
10	83	2	30	0.5	0.9	0.9	0.95
10	100	0	30	0.55	1	1	0.94
30	0	8	0.25	0.25	0.25	0.25	1
30	17	1	3	0.3	0.5	0.5	0.99
30	33	0.5	7	0.35	0.6	0.6	0.98
30	50	7	15	0.4	0.7	0.7	0.97
30	67	5.5	10	0.45	0.8	0.8	0.96
30	83	5	20	0.5	0.9	0.9	0.95
30	100	0	20	0.55	1	1	0.94
50	0	12	0.2	0.25	0.25	0.25	1
50	17	1	2	0.3	0.5	0.5	0.99
50	33	0.5	5	0.35	0.6	0.6	0.98
50	50	12	10	0.4	0.7	0.7	0.97
50	67	10.5	5	0.45	0.8	0.8	0.96
50	83	10	10	0.5	0.9	0.9	0.95
50	100	0	10	0.55	1	1	0.94

Concrete Curing in Drilled Shafts Surrounded by Rock vs. Clay

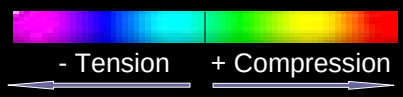


Different Thermal Conductivity For Rock and Clay

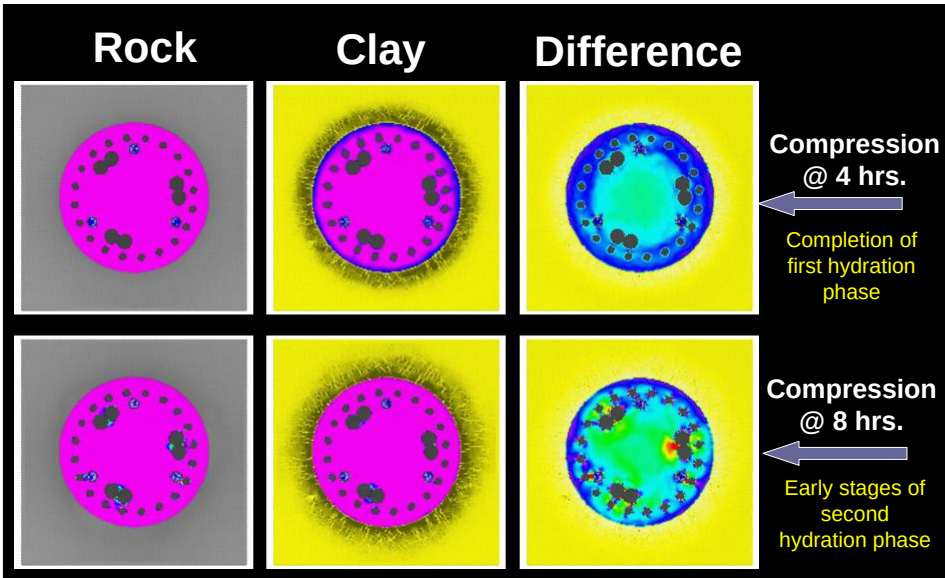
All Other Factors are Identical

- Ground Temperature = 10°C
- Pour temperature = 45°C
- Duration of Test = 5 days
  - (sufficient time due to high Initial concrete Temperature)

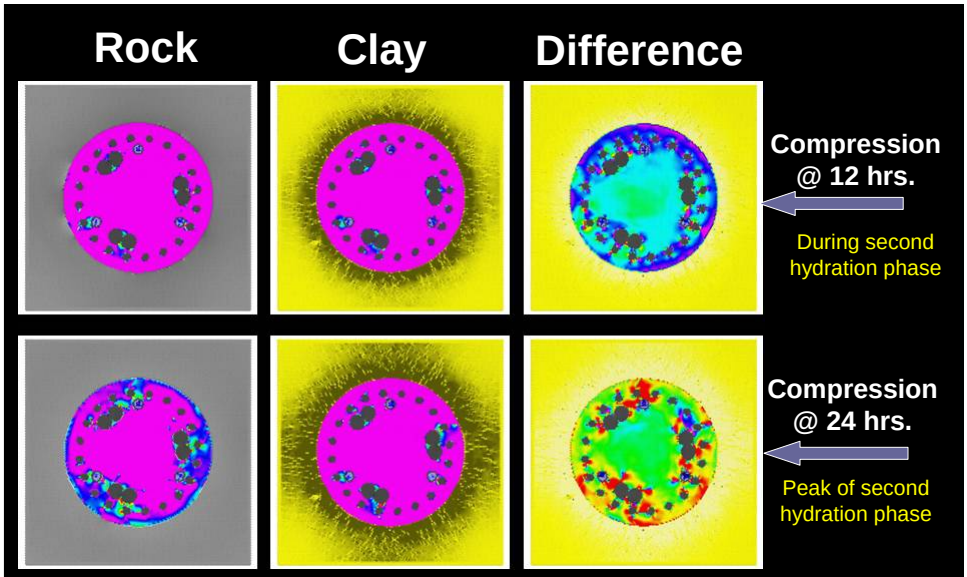
Compressional Stress Caused by Concrete Curing



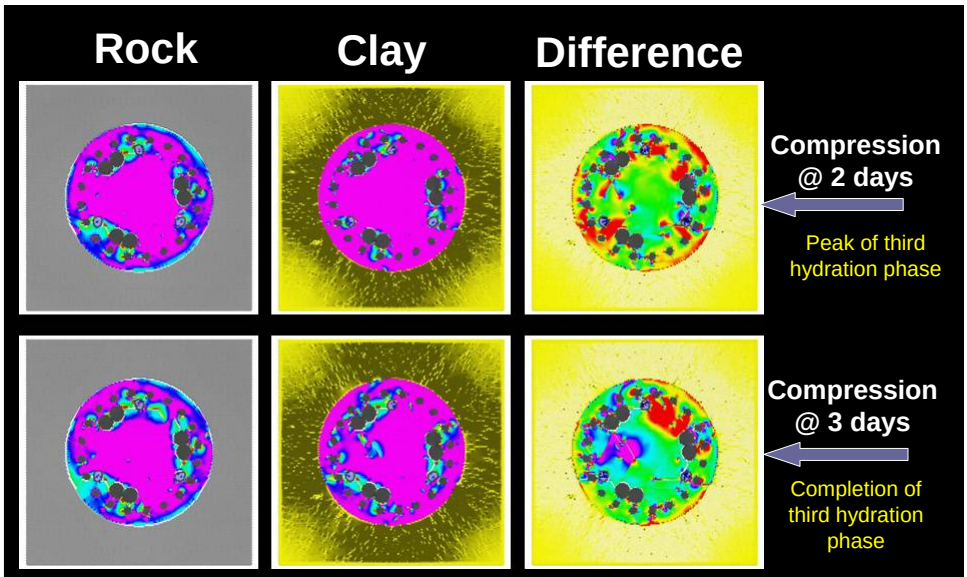
- Defined as the average force exerted on an element by attached springs.
- Zero compression means sum of all compression and tension forces are zero.
- Initial compression was set to zero since shaft excavation relieves lateral compression



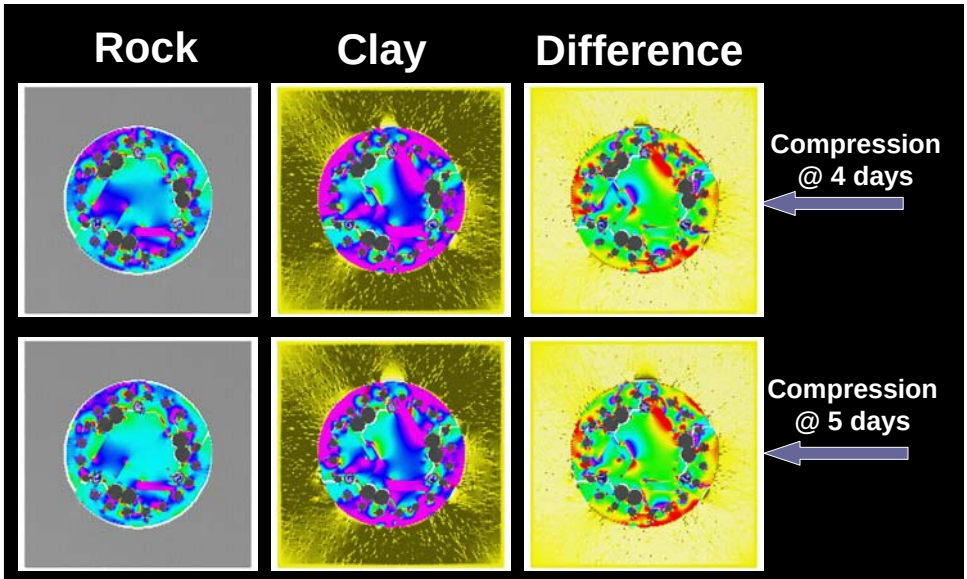
Concrete under high tension due to shrinkage in clay, and not rock.
Clay starts to deconsolidate, crack, and deform as the concrete shrinks.
Less tension around perimeter of shaft near the rebar cage in clay.



Release of tension forces are indicated in the shaft due to separation from the rock. Slight debonding begins to occur between rebar/tubes and concrete because of higher tension forces in the shaft



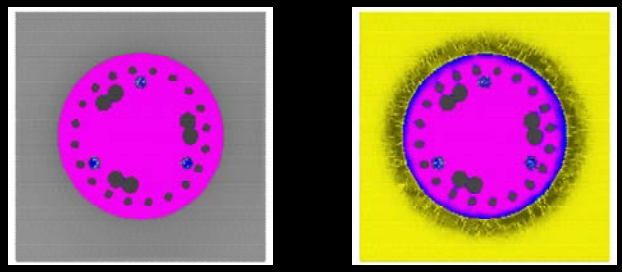
Release of tension forces continue to spread in the shaft due to radial cracking near the cage. Deconsolidation of the clay continues to expand farther away from the shaft.



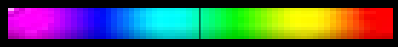
After 4 days, stress has stabilized. The rock is not under stress, but the clay is under tension due to concrete shrinkage.

The concrete is left in a final state of internal tension stresses, which can result in loss of strength during both lateral and axial loading

Stress Animation

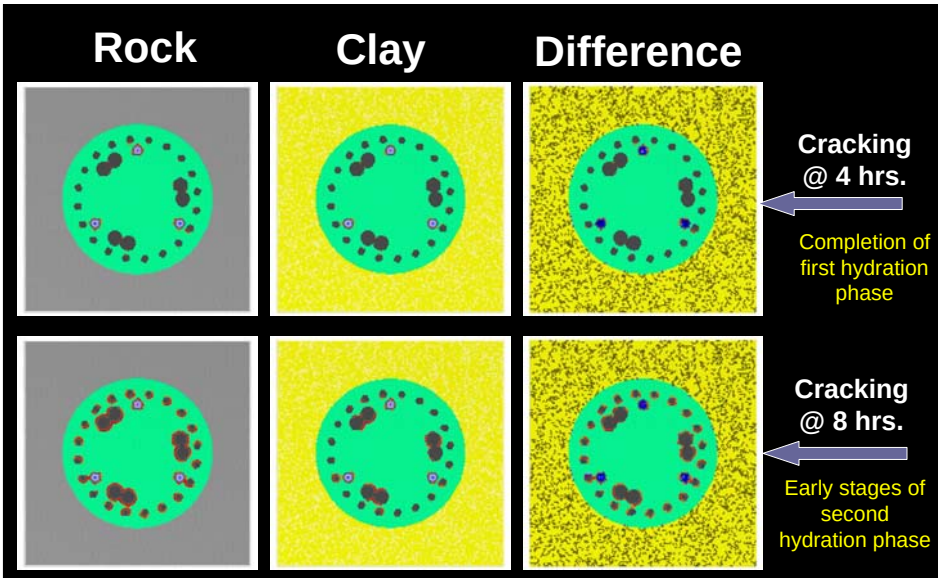


Cracking During Concrete Curing

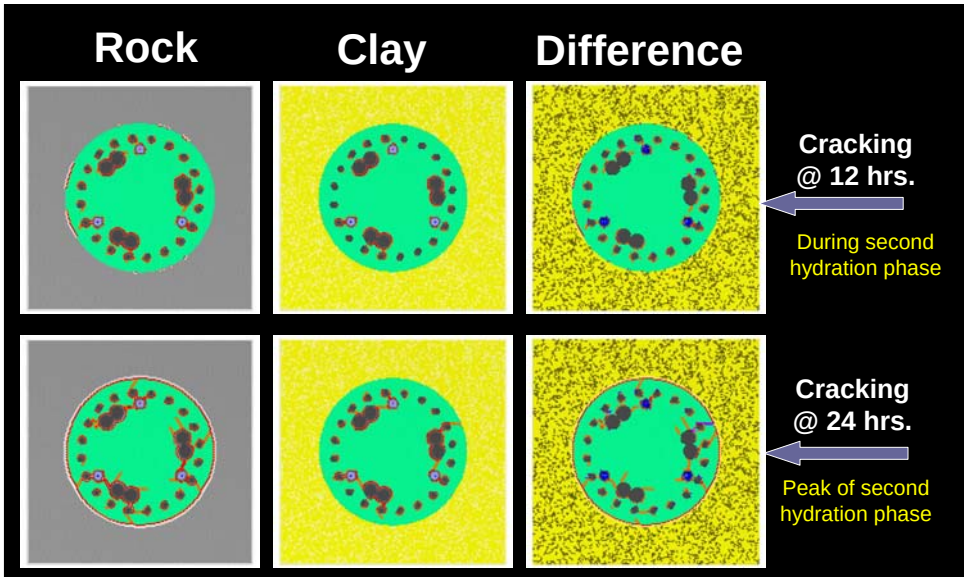


Number of Broken springs between elements

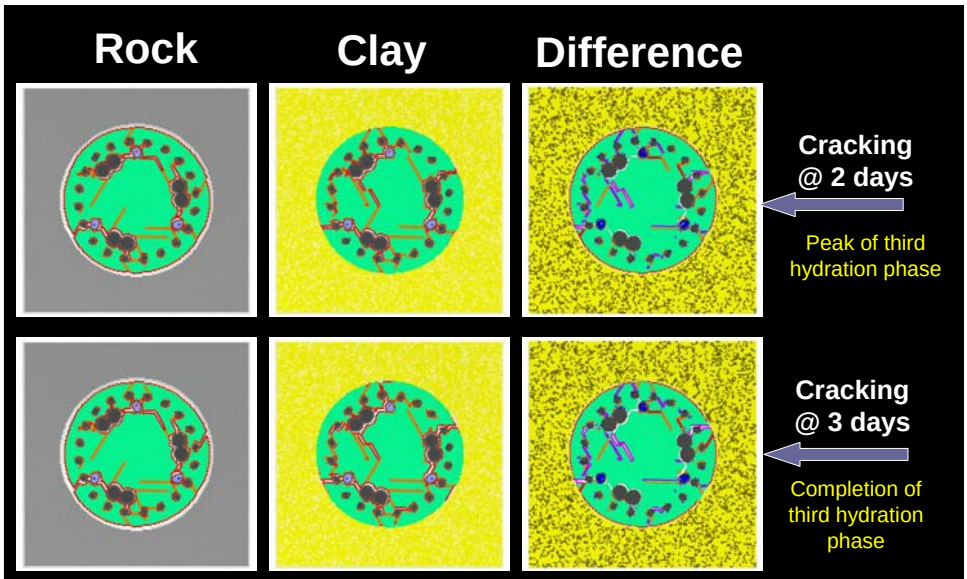
- Defined as the number of broken springs on each element.
- Zero indicates that the forces created by concrete curing did not exceed the spring stiffness between any two elements.
- No cracks are initially introduced in the concrete – concrete slowly changes from liquid to solid state



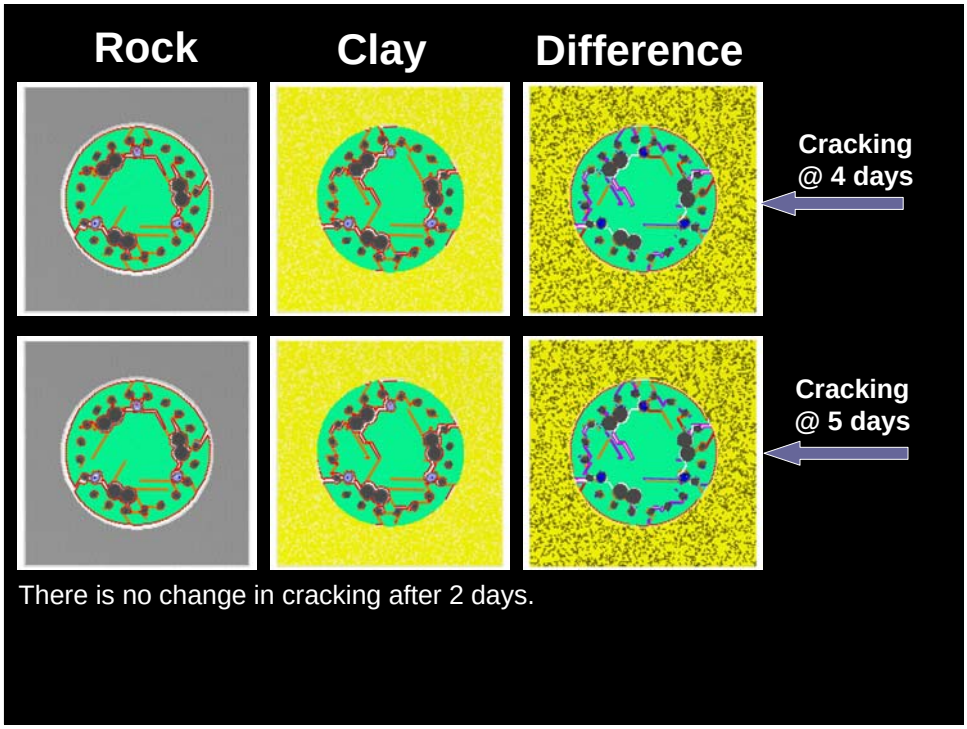
After 4 hours, cracking begins around the rebar and access tubes due to tension. The cracking almost doubles after 8 hours.
The difference plot shows that there are more cracks in the clay than in the rock.



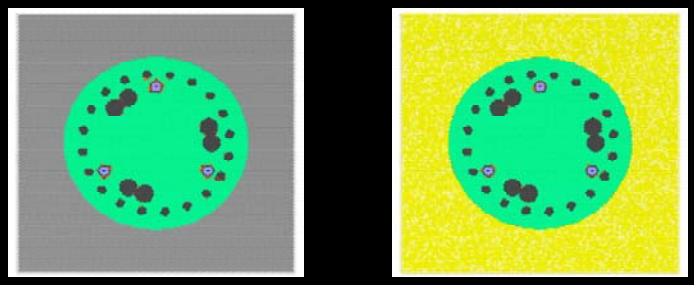
After 12 hours, cracking begins at the rock/concrete interface. By 24 hours, the concrete has completely debonded from the rock, and cracks begin to propagate between rebar and connect.
The difference plot shows that there are more cracks in the concrete surrounded by rock.



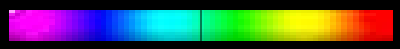
After 2 days, most of the cracks have already formed. The difference in cracking is minimal.
In this case, the controlling factor was the initial placement temperature, not the surrounding ground conditions.



Cracking Animation

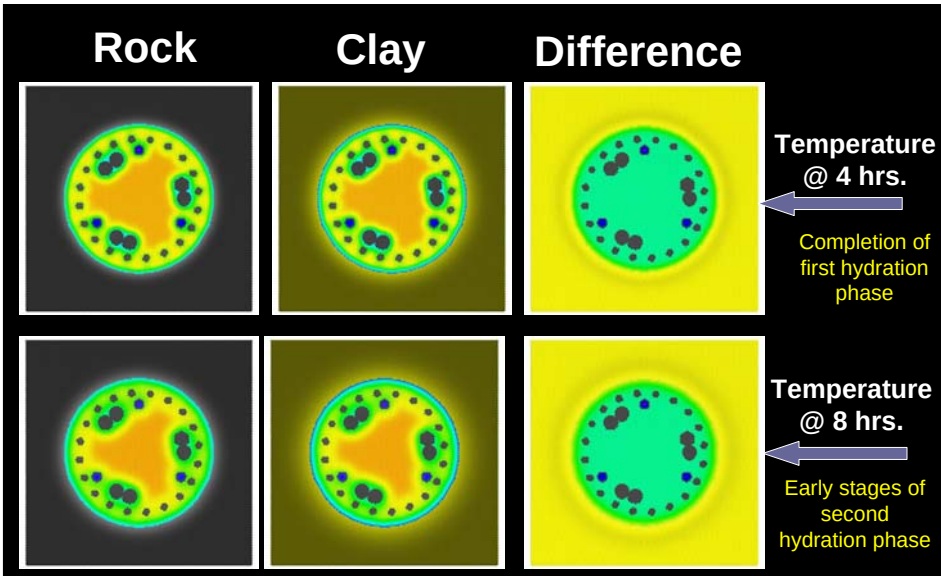


Temperature Due to Chemical Reaction and Transfer to Surroundings

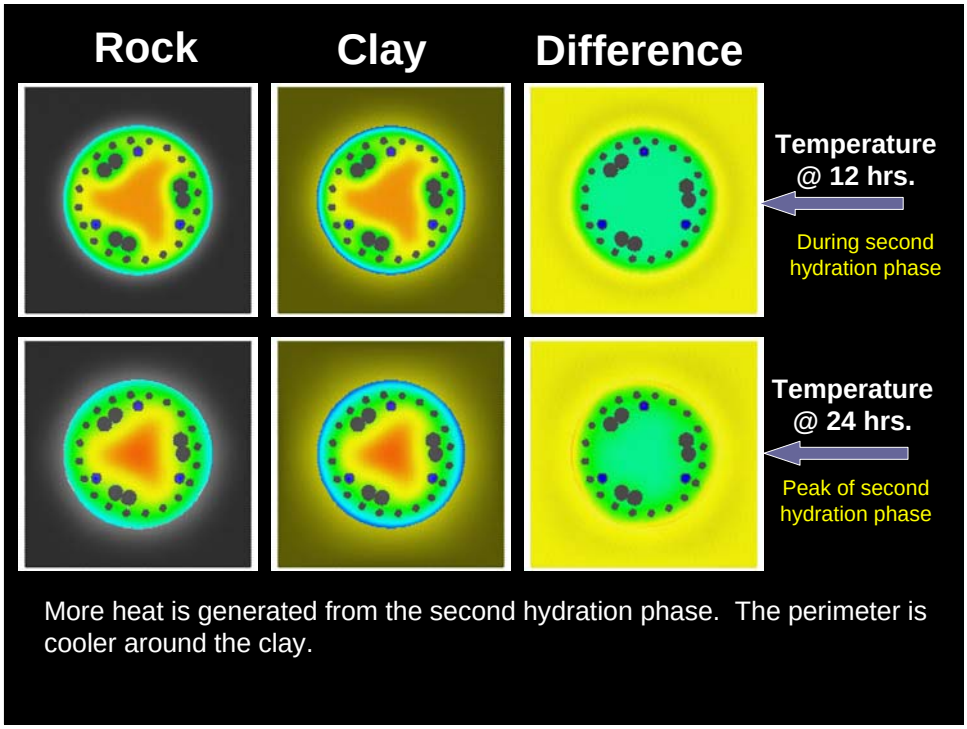


Temperature

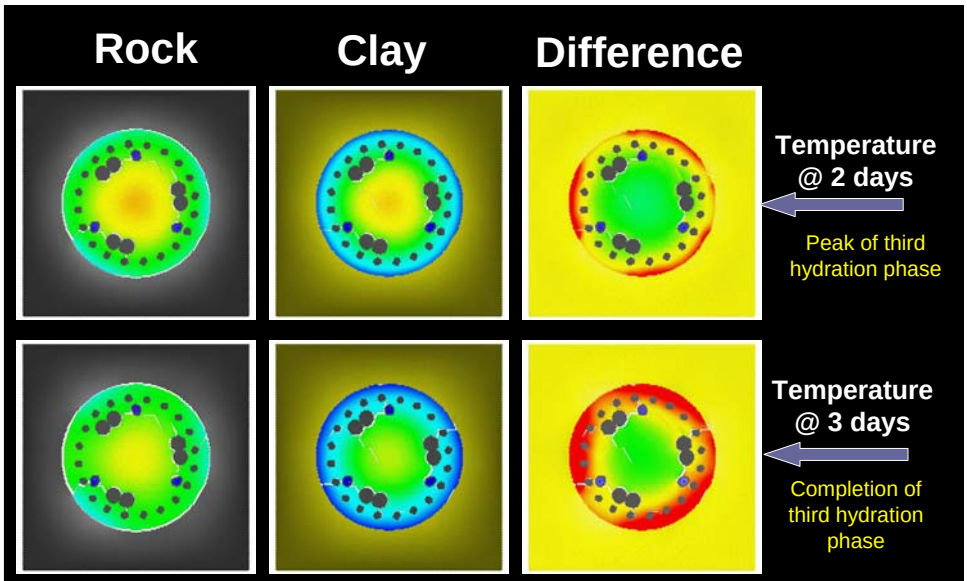
- Heat is allowed to transfer across springs that are broken at a reduced rate, depending on the separation
- Spring connections that are >2 times the element radius are eliminated so convection is not allowed across large cracks



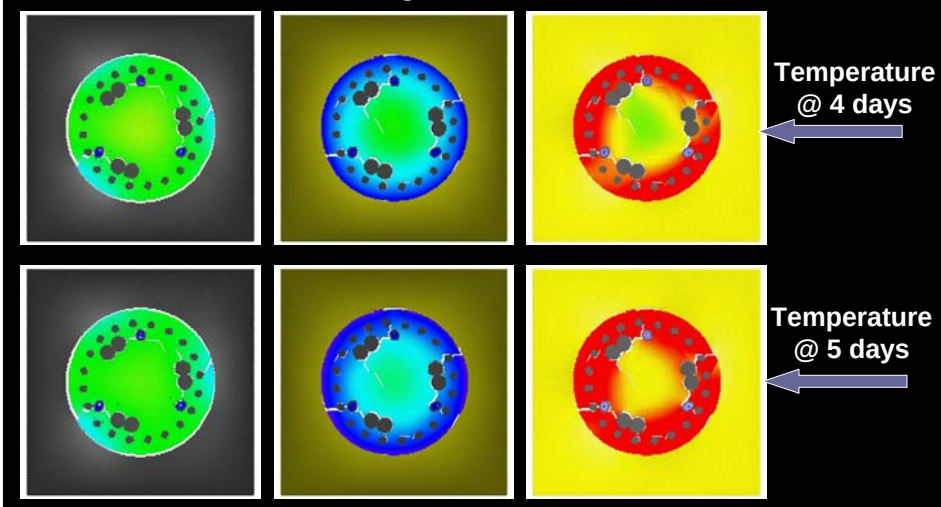
Temperature of shaft stays high due to high placement temperature. Temperature is lower in region around rebar and access tubes. Temperature of rock adjacent to shaft is higher as shown in the difference. More heat is transferred into the clay



More heat is generated from the second hydration phase. The perimeter is cooler around the clay.

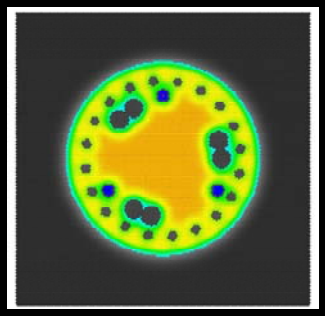


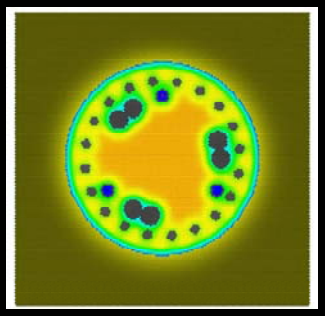
After 2 days, the shaft in rock is at a higher temperature.
After 3 days, The shaft surrounded by rock remains hot but has lower temperature gradient, due to convection across the concrete/rock interface.



After 4 days the shaft temperature continues to decrease. Much less heat is transferred out of the shaft surrounded by rock. The perimeter of the shaft in the clay is cooler than in rock.

Temperature Animation





Concrete Curing Conclusion

- Internal cracking between rebar is very likely in drilled shafts.
- The outside perimeter of the shaft is generally cooler than the core.
- Attributed to these factors, CSL velocity is almost always lower on the top of the shaft and along the perimeter of the shaft than through the center.

Drilled Shaft Foundations

Larger, deeper, non-redundant shafts are becoming more popular in the US

Drilled Shaft Anomalies

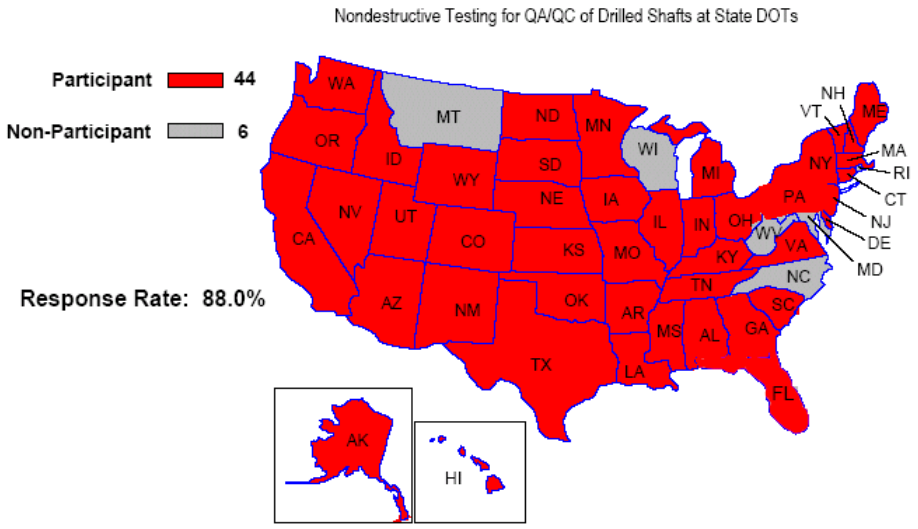
- Honeycomb
- Concrete Cracking
- Soil Intrusion
- Settlement of Sand
- Trapped Mud/Voids

NDE Methods for Drilled Shafts

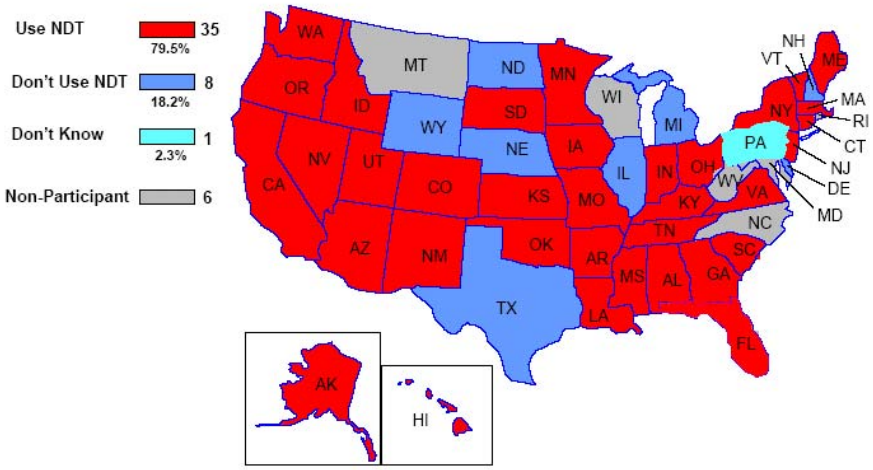
1. CSL
Crosshole Sonic Logging
2. GGDL
Gamma-Gamma Density Logging
3. IR/SE
Impulse Response/Sonic Echo

Detailed description of each method is included in the Report

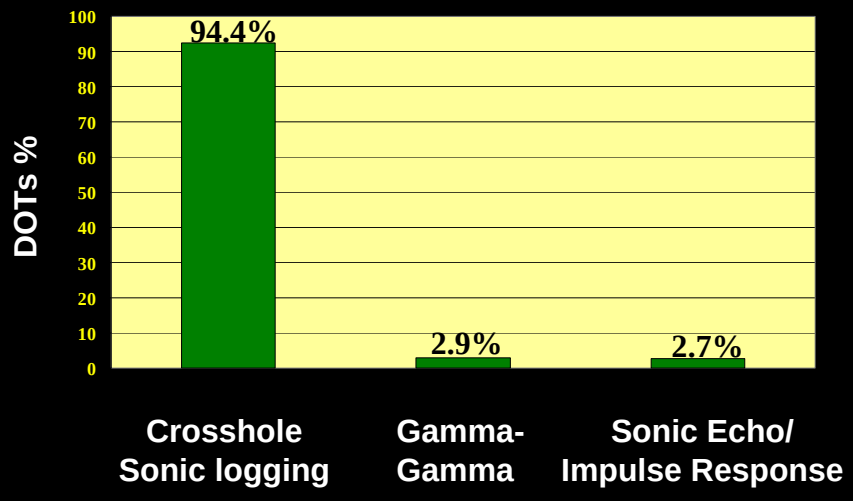
State DOT Participants



Use of NDE for Drilled Shafts



Which is the primary NDE method used for drilled shafts?



GGDL

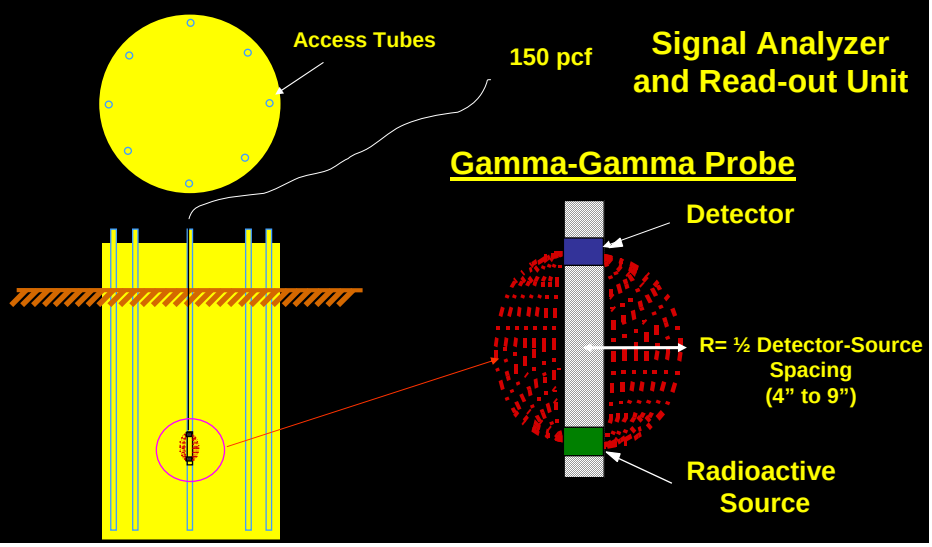
Gamma-Gamma Density Logging

The 4 pi (omni directional) GGDL uses a weak Cesium-137 Source to emit gamma rays *photons* into the surrounding material.

GGDL Principles

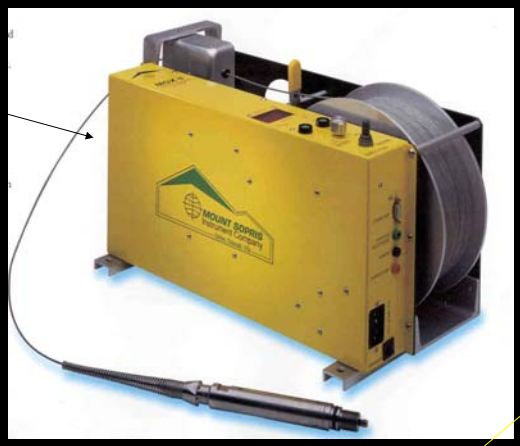
- ✓ **A small fraction of the emitted gamma rays *photons* are reflected back to the probe and their intensity are recorded as counts per second (cps).**
- ✓ **The measured count rate (cps) is dependent on the density of the surrounding medium.**
- ✓ **Anomalous zones (soil intrusions, poor concrete, or voids) are characterized by high count rate.**
- ✓ **The tool is calibrated in a material of known density.**

GGDL Schematic

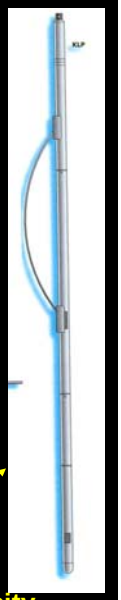


GGDL System

Portable Digital Logger Model5MGB-1000 with a single probe winch



PC for Data Analysis and Display



Probe Model KLP2780
4 PI Omni-Directional Density

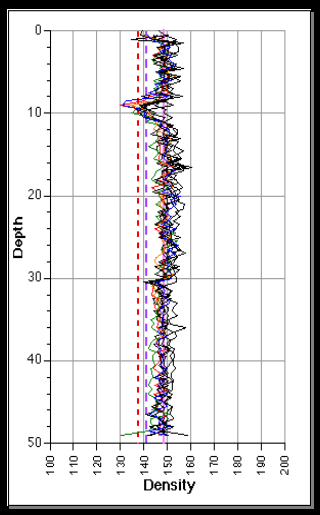
GGDL Advantages

- ✓ Air or water filled PVC or steel, 2-in dia. access tubes.
- ✓ Test fresh concrete while restoration is still feasible (minimal changes in concrete density as it sets).
- ✓ Not affected by tube debonding.
- ✓ Images the soil-concrete contact.
- ✓ Results are converted into concrete unit density (pcf).

GGDL Disadvantages

- ✓Images small areas (up to 9-in radius) around each tube.
- ✓Does not image the interior of the drilled shaft.
- ✓Requires specialized training and a "State Certification"to operate the system.
- ✓If the probe is lost in the hole, the drilled shaft must be removed.

GGDL Data

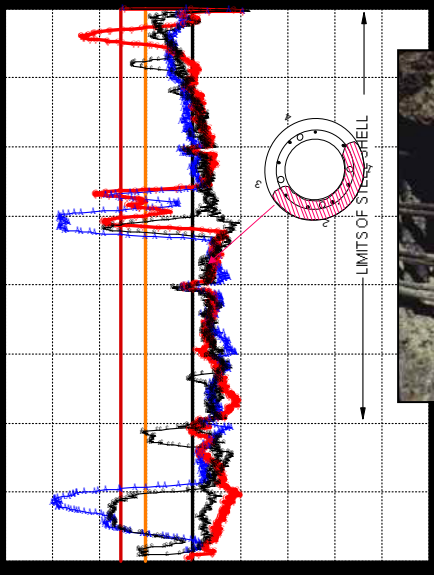


A STATISTICAL MEASURMENT

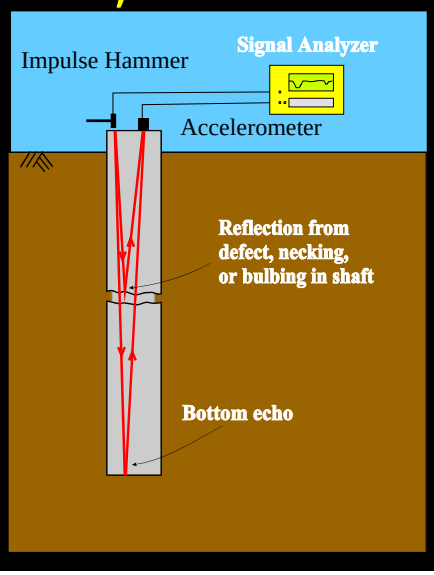
TWO
standard deviations below the mean of gamma-gamma test data represents *QUESTIONABLE ZONE*.

THREE
standard deviations below the mean of gamma-gamma test data represents *POOR QUALITY CONCRETE ZONE*.

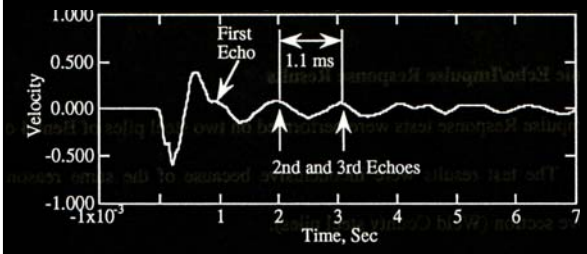
GGDL Example



Sonic and Impulse Echo Response (SE-IR) Test Method



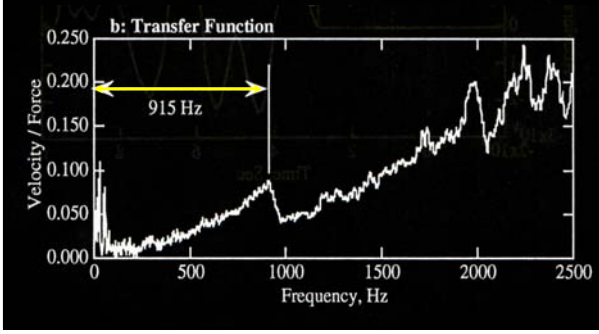
Sonic and Impulse Echo Datasets



Sonic Echo

(Time Domain, t)

Depth = V x Δt /2 =
11,980 x 1.1 x 10^{-3} /2 =
6.6 ft



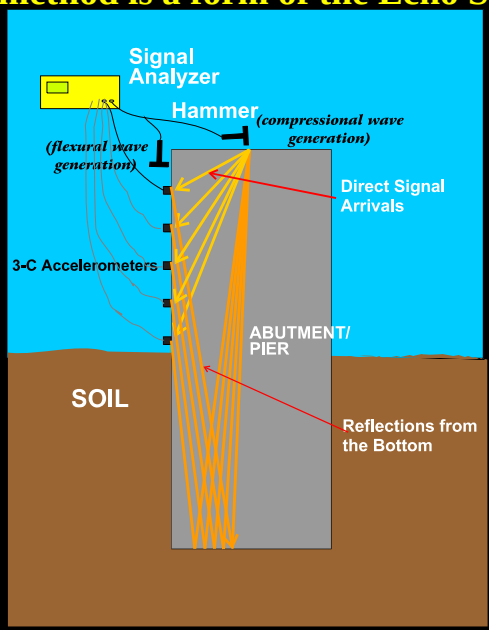
Impulse Response

(Frequency Domain, f)

Depth = V / (2 x Δf) =
11,980 / (2 x 915) =
6.5 ft

UltraSeismic Method: Vertical Profiling

This method is a form of the Echo Sonic



Cross Hole Sonic Logging

ASTM D 6760-02

Designation: D 6760 – 02

Standard Test Method for Integrity Testing of Concrete Deep Foundations by Ultrasonic Crosshole Testing[1]

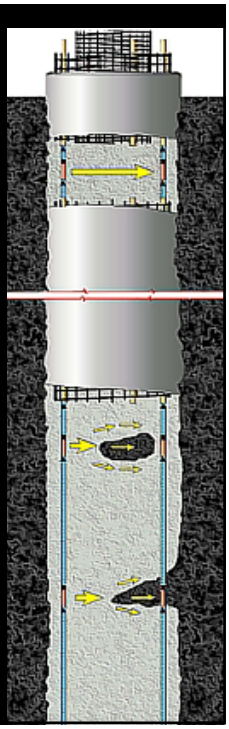
This standard is issued under the fixed designation D 6760; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

Drilled Shaft Preparation

- Install 50-mm-diam. steel access tubes.
- Number and spacing of tubes is determined by shaft diameter.
- Tubes extended at least 1- m above the top of the shaft.
- Care should be taken to assure that tubes are vertical.
- Tubes must be free of obstacles and must retain water throughout the testing period.
- Tube joints should be water tight and non shrinking.

Crosshole Sonic Logging

A direct, low strain, non-destructive method for detecting defects inside the rebar cage of a drilled shaft.

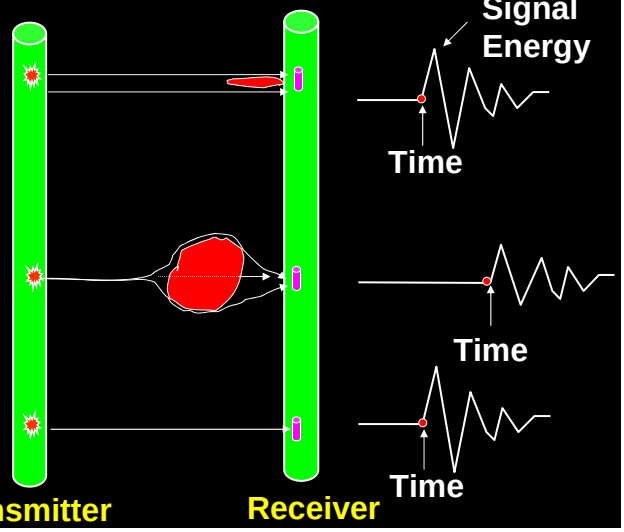


Basic CSL Theory

The basic principal of the CSL test is that ultrasonic pulse velocity varies proportionally with concrete density and elastic modulus.

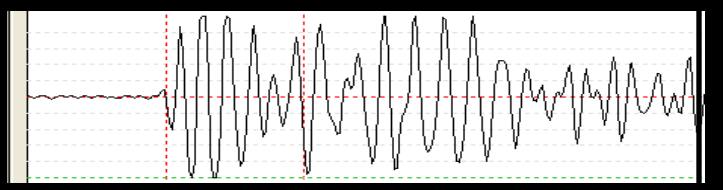
Pulse Velocity = Path Length/Transit Time

CSL Testing

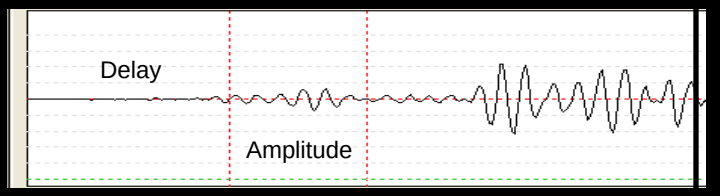


Actual CSL Data

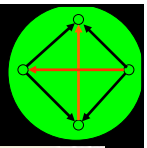
Normal

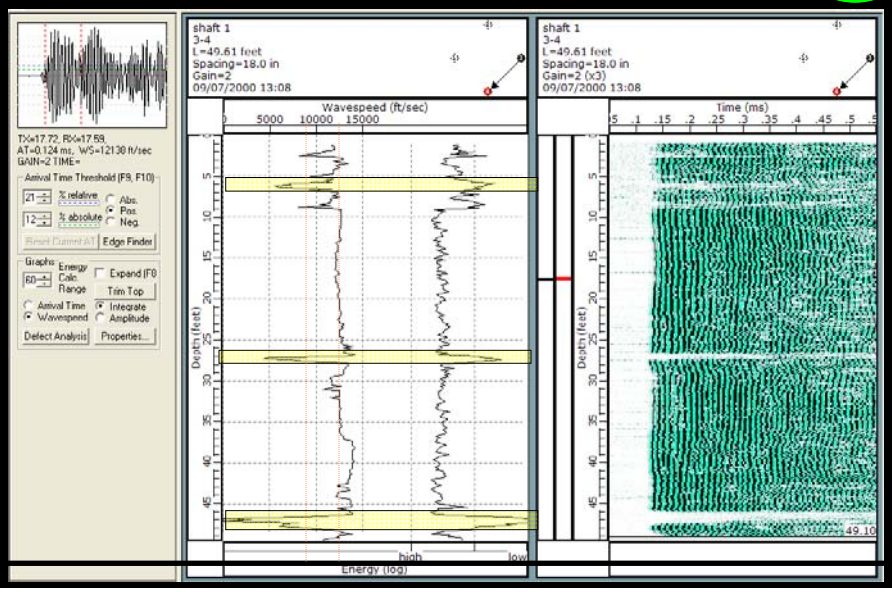


Not Normal

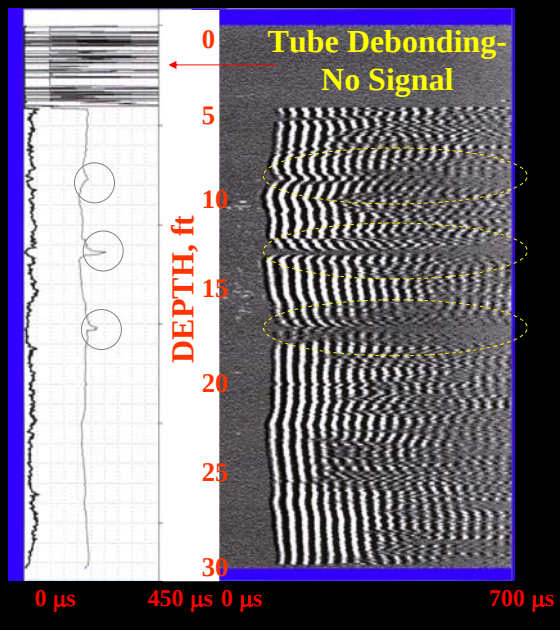


Normal Concrete =12,000 ft/s
25% Reduction = 9,000 ft/s





CSL Results



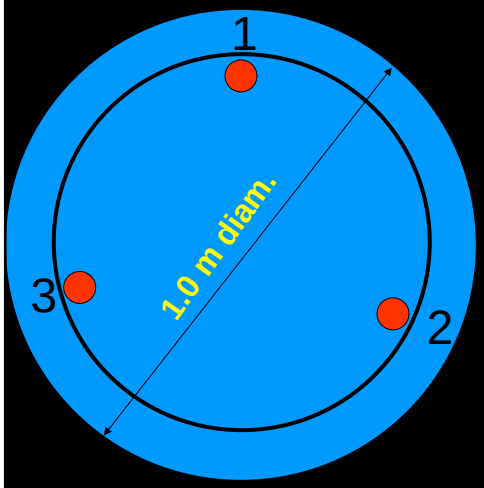
Concrete Condition Rating Criteria

CCRC Rating	Rating Symbol	Velocity Reduction	Indicative Results
Good	G	0 to 10%	Acceptable concrete
Questionable	Q	10 % to 25 %	Minor concrete contamination or intrusion. Questionable quality concrete.
Poor	P/D	≥ 25 %	Defects exist, possible water slurry contamination, soil intrusion, and or poor quality concrete.
Water	W	V= 1,450 m/s to 1525 m/s	Water intrusion, or water filled gravel intrusion with few or no fines present.
No signal	NS	No signal received	Soil intrusion or other severe defect absorbed the signal, tube debonding if near top.

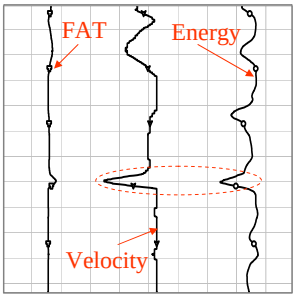
Field Tests and 3-D Tomographic Imaging Application For CSL Data Presentation

"Two Case Studies"

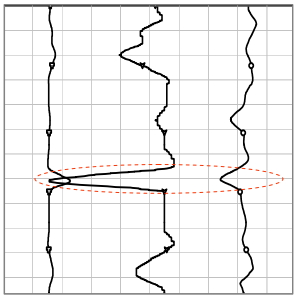
Case Study #1



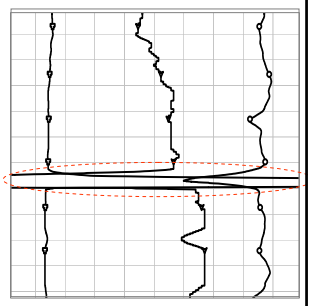
CSL Plots Pre-Grouting Tests #1 and #2



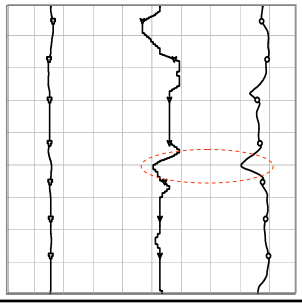
Tubes 1-2

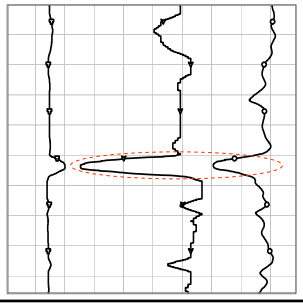


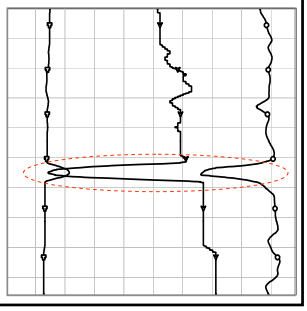
Tubes 1-3



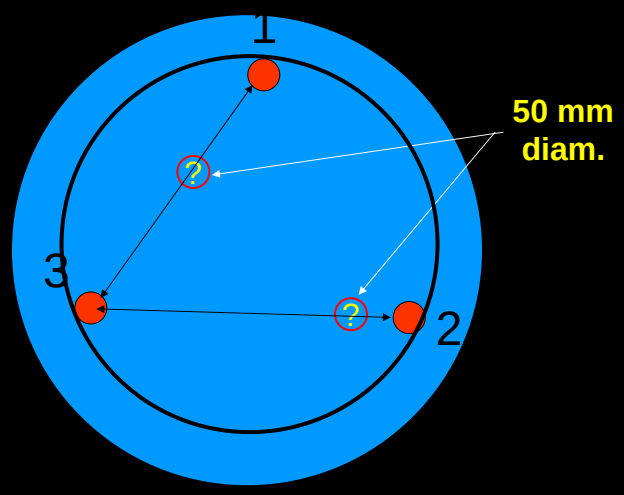
Tubes 2-3

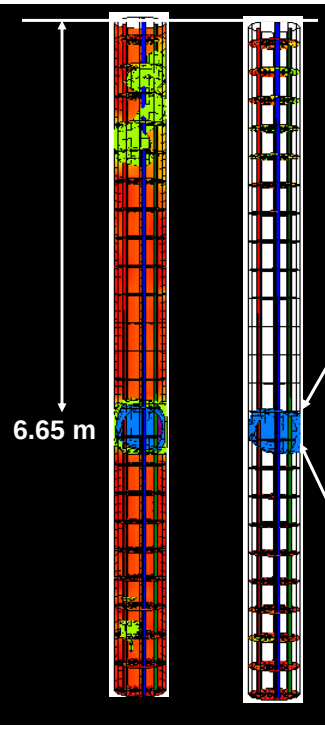






Anomaly Location

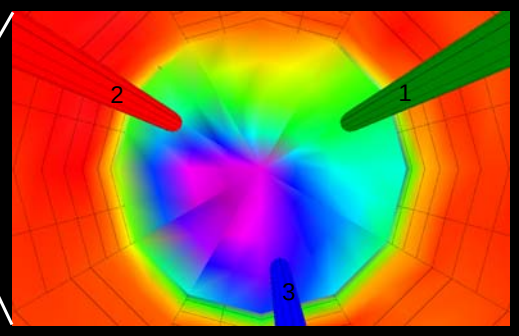




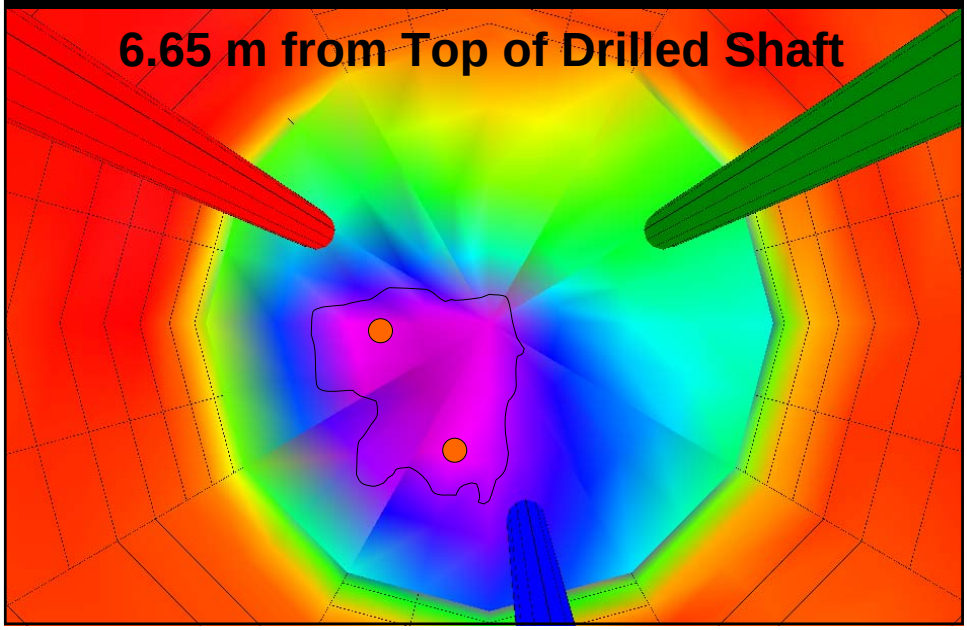
Average Shaft Velocity is 3,660 m/s

10% Green (3,294 m/s),

20% Blue (2,928 m/s)

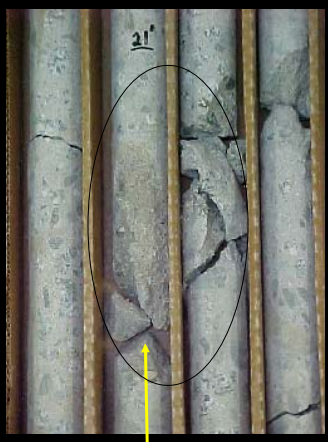


Anomaly Location

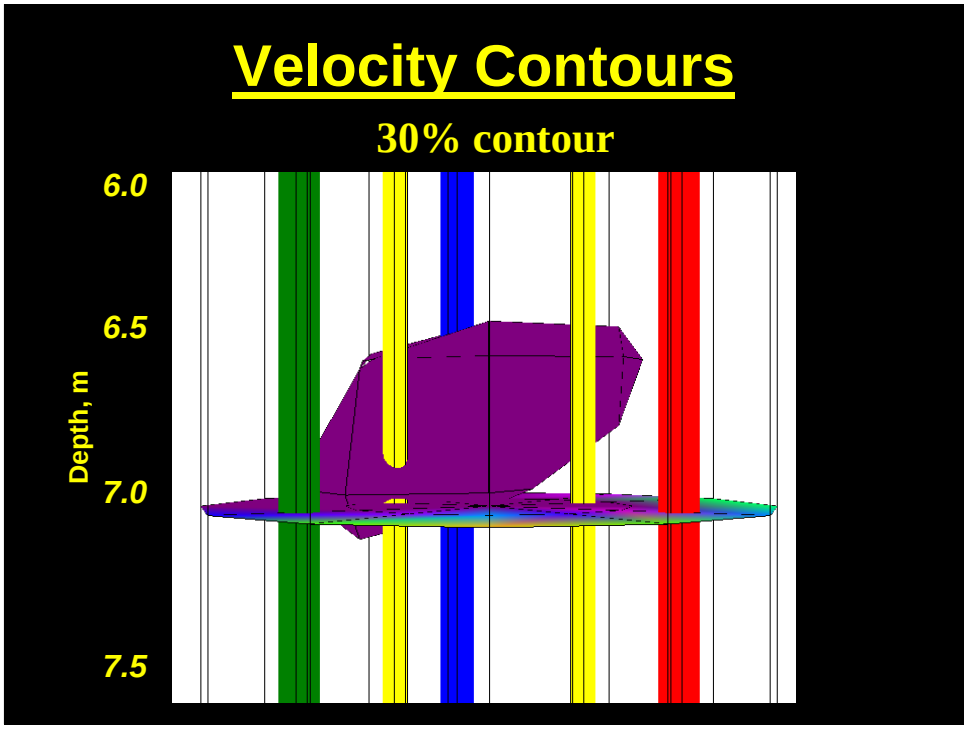


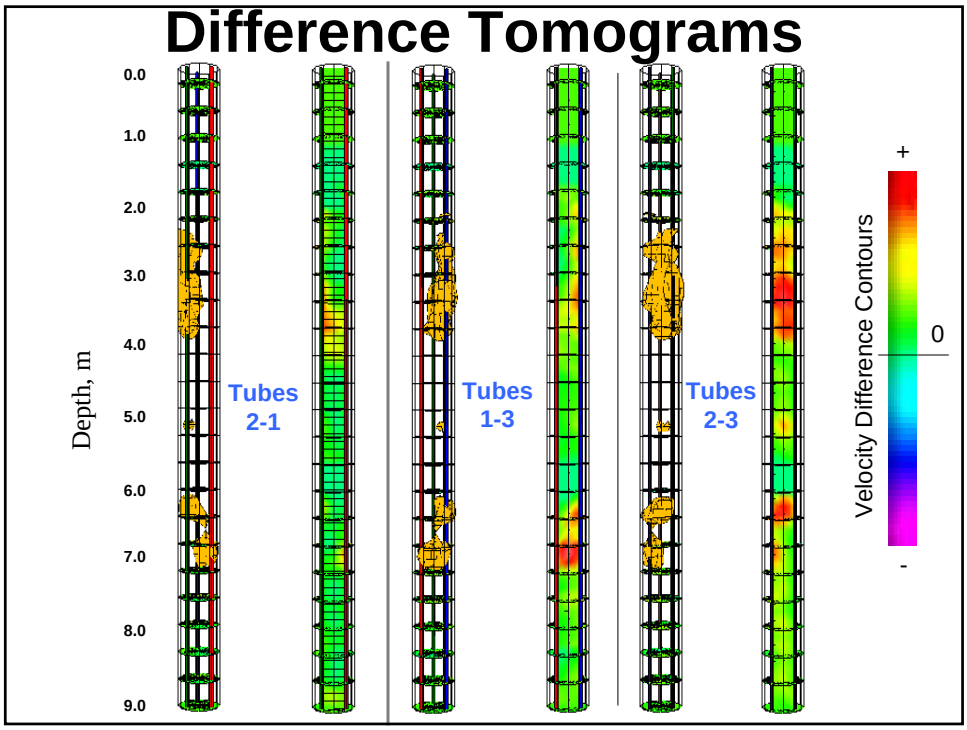
Location of Coreholes

Core From Shaft with Defect

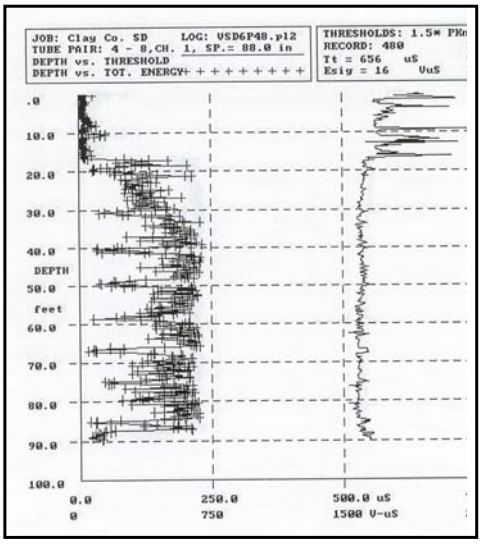


Weak Zone

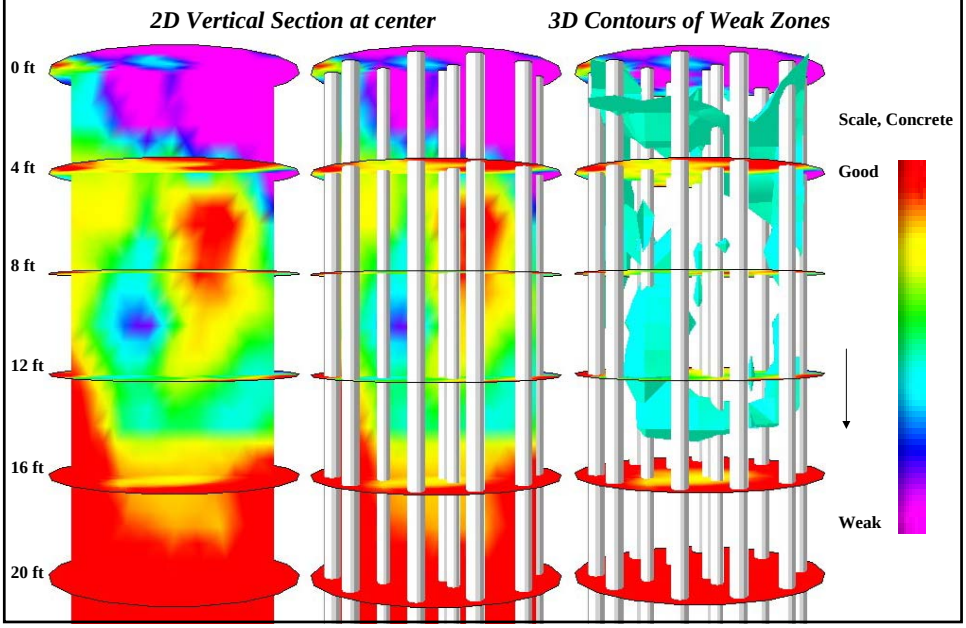

Velocity Contours
30% contour
6.0
6.5
7.0
7.5
Depth, m


Difference Tomograms
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
Depth, m
Tubes 2-1
Tubes 1-3
Tubes 2-3
+
0
-
Velocity Difference Contours

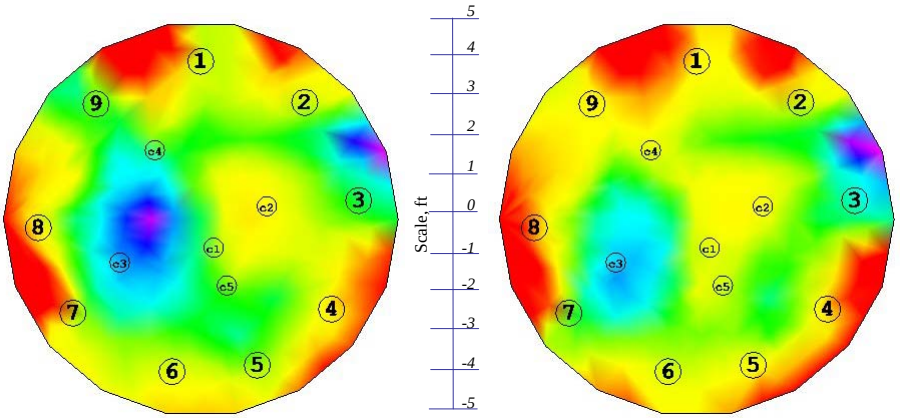
CSL Data



CSL Tomographic Images



CSL Tomographic Images



Horizontal Image @ 10 ft

From top of Shaft

Relative Concrete Scale

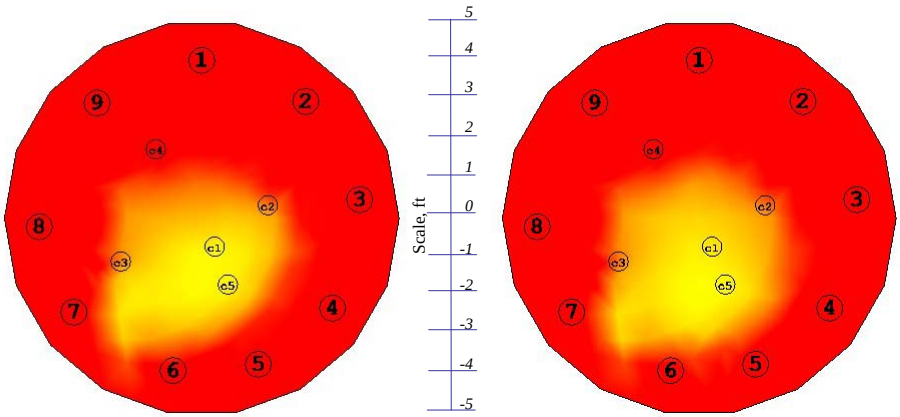
Good

Weak

Horizontal Image @ 11 ft

From top of Shaft

CSL Tomographic Images



Horizontal Image @ 16 ft

From top of Shaft

Relative Concrete Scale

Good

Weak

Horizontal Image @ 17 ft

From top of Shaft

Tomographic Imaging Conclusion

- 3-D color-coded tomographic images adds advantage to the CSL system output by imaging the location, size, and geometry with high accuracy
- If the CSL data is not accurate, tomography exaggerates the problem

"Although 3-D tomographic data analyses are applied, CSL data analysis is still hampered by uncertainty with respect to what constitutes flaws"

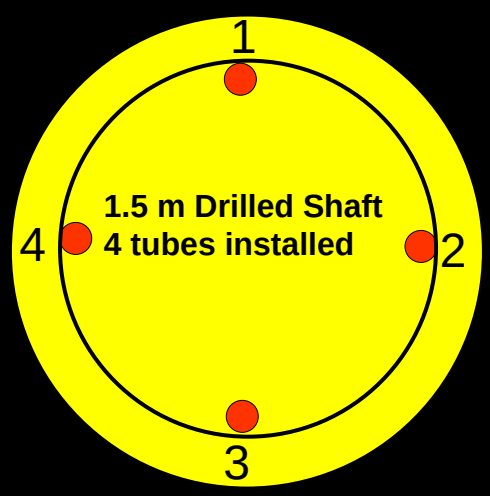
Concrete Rating Criteria—reduction from *"shaft average velocity"*

- ***Good/Acceptable:*** 0-10%
- ***Questionable:*** 10-25%
- ***Poor/Not Acceptable:*** >25%

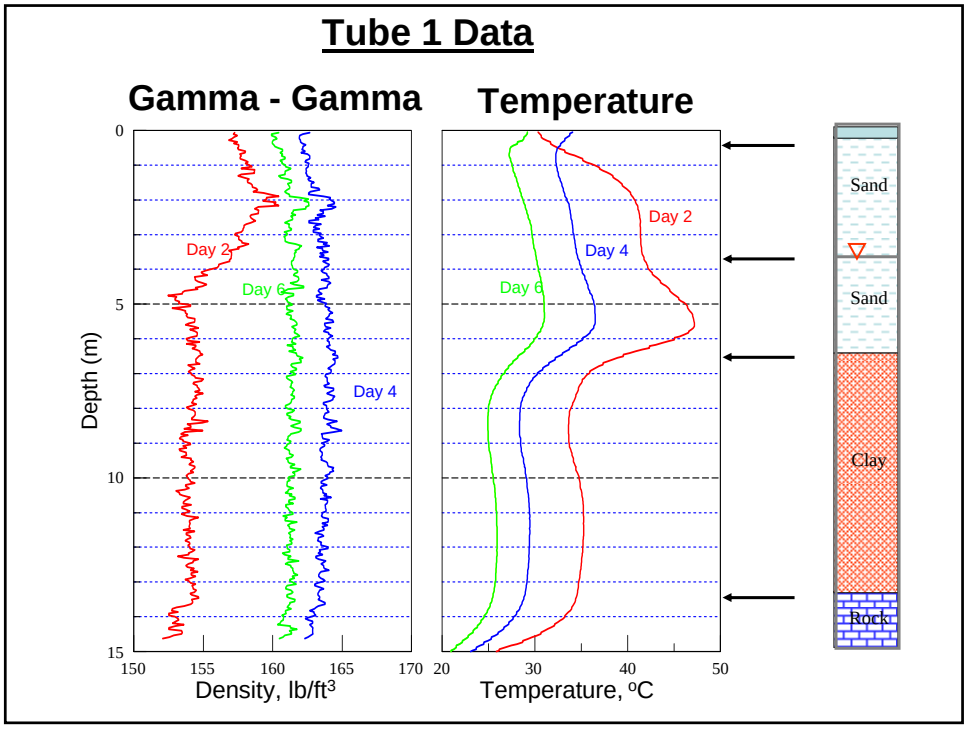
CSL Data Evaluation

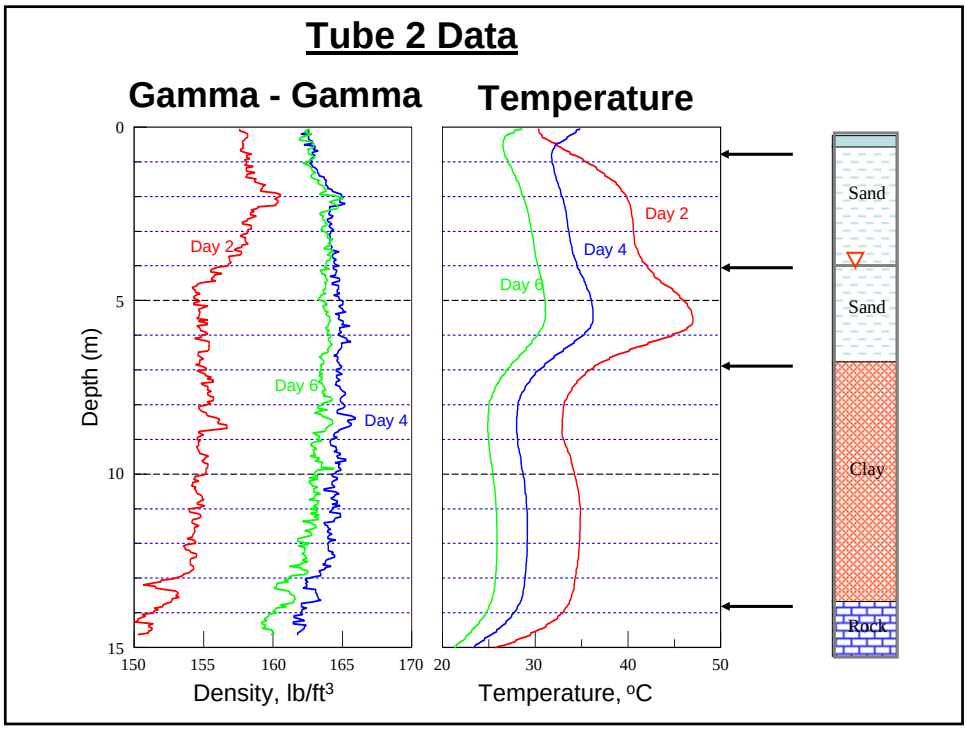
- Many variables affect CSL data
  - Curing time, aging
  - Shaft geometry, bulging, steel cage effects
  - Tube bending, tube debonding, sensor drift
  - Concrete hydration rate, cracking
  - Groundwater table elevation
  - Concrete defects during construction
  - Lithology, cohesion, surface contact

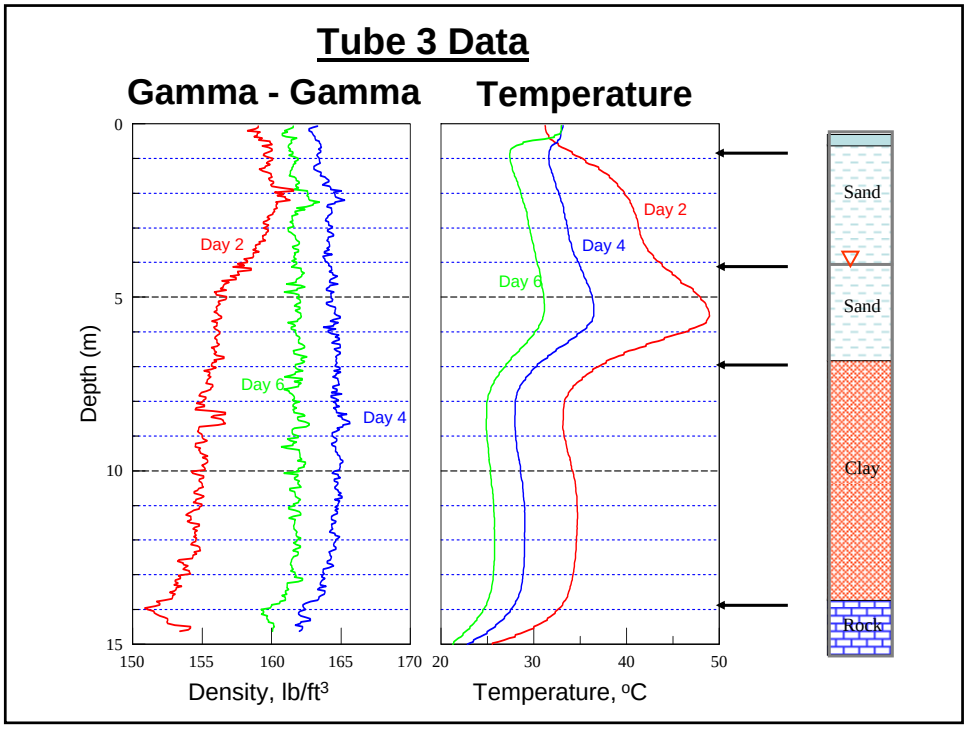
Case Study #2

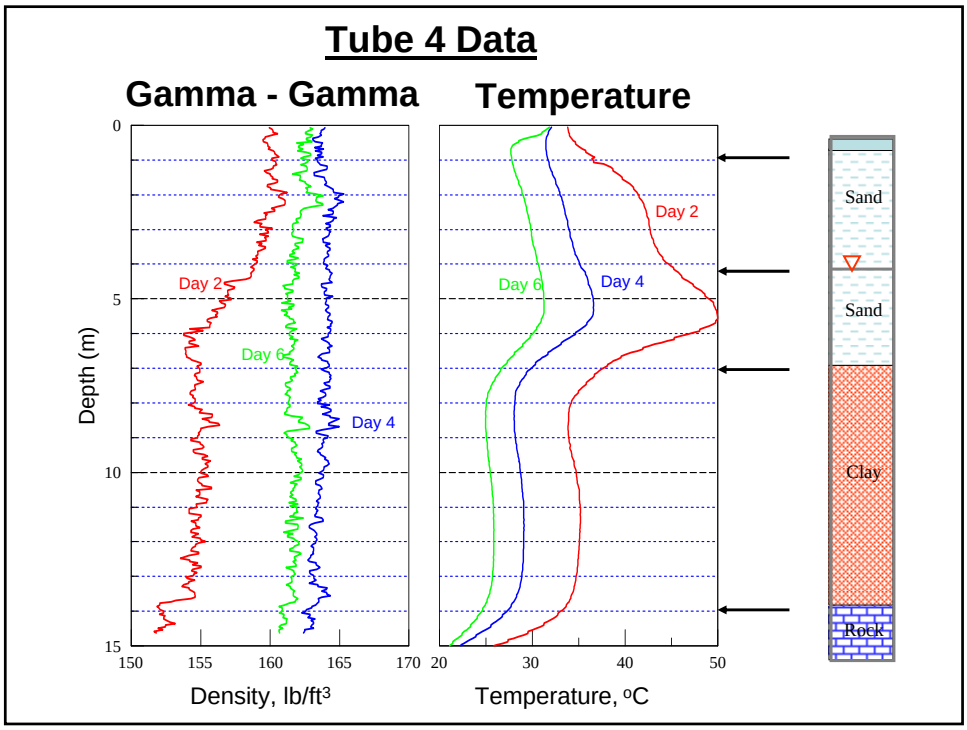


2 Drilled Shafts Monitored for 7 days
Temperature, Density, Moisture, and Velocity

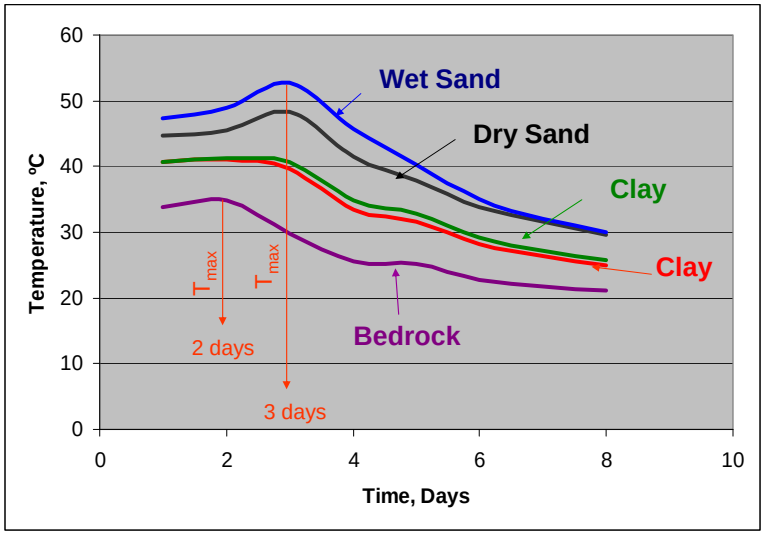

Tube 1 Data
Gamma - Gamma
Temperature
Depth (m)
0
5
10
15
Day 2
Day 6
Day 4
150
155
160
165
170
Density, lb/ft3
20
30
40
50
Temperature, oC
Sand
Sand
Clay
Rock

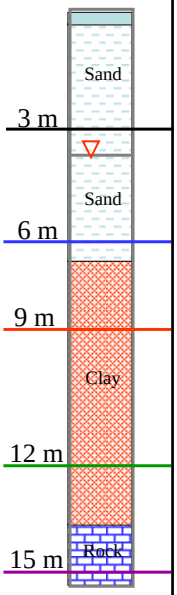

Tube 2 Data
Gamma - Gamma
Temperature
Depth (m)
0
5
10
15
Day 2
Day 6
Day 4
150
155
160
165
170
Density, lb/ft3
20
30
40
50
Temperature, oC
Sand
Sand
Clay
Rock


Tube 3 Data
Gamma - Gamma
Temperature
Depth (m)
0
5
10
15
150
155
160
165
170
20
30
40
50
Day 2
Day 4
Day 6
Density, lb/ft3
Temperature, oC
Sand
Sand
Clay
Rock


Tube 4 Data
Gamma - Gamma
Temperature
Depth (m)
0
5
10
15
150
155
160
165
170
20
30
40
50
Day 2
Day 4
Day 6
Density, lb/ft3
Temperature, oC
Sand
Sand
Clay
Rock

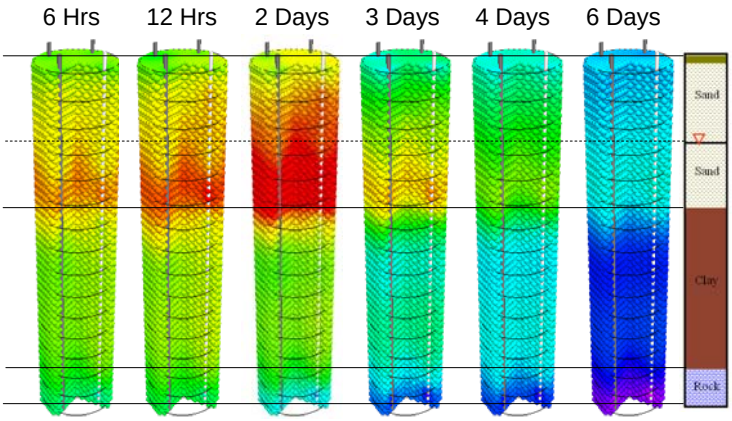
Temperature

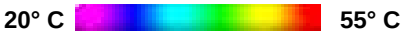




Controlling Variable: Soil/Rock Thermal Conductivity

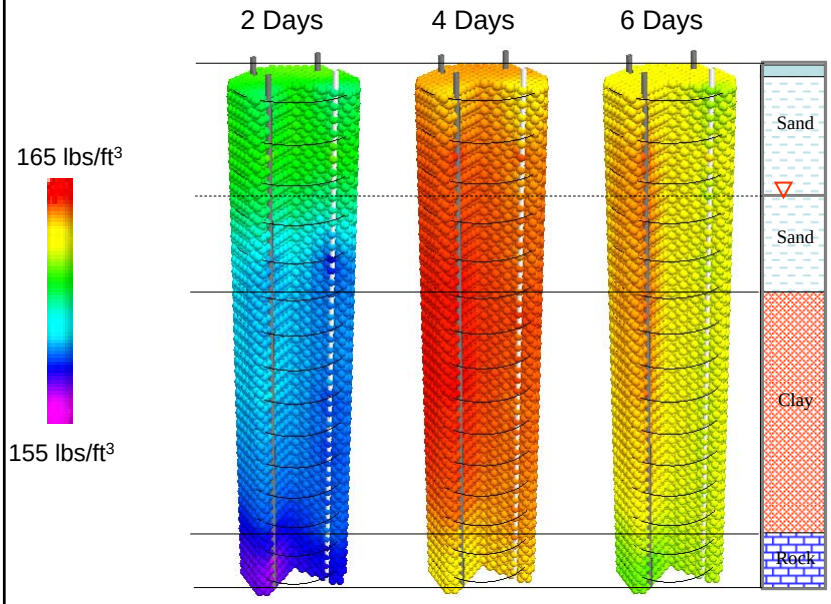
Temperature



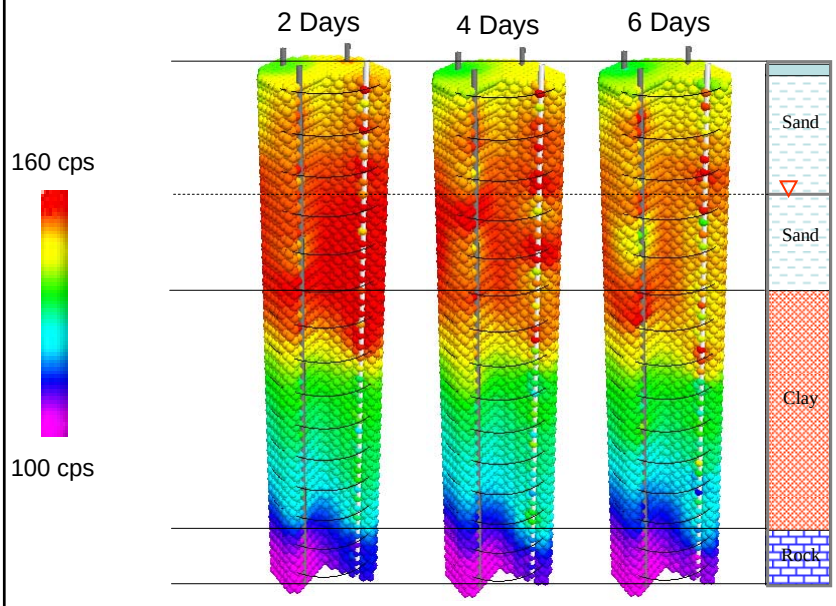


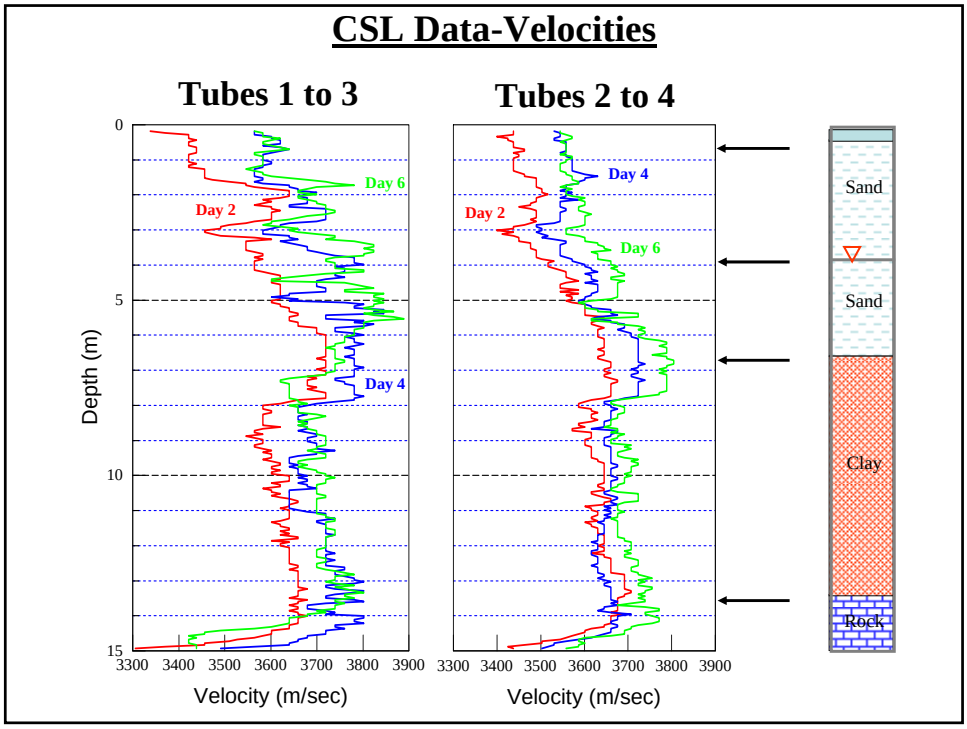
Temperature scale

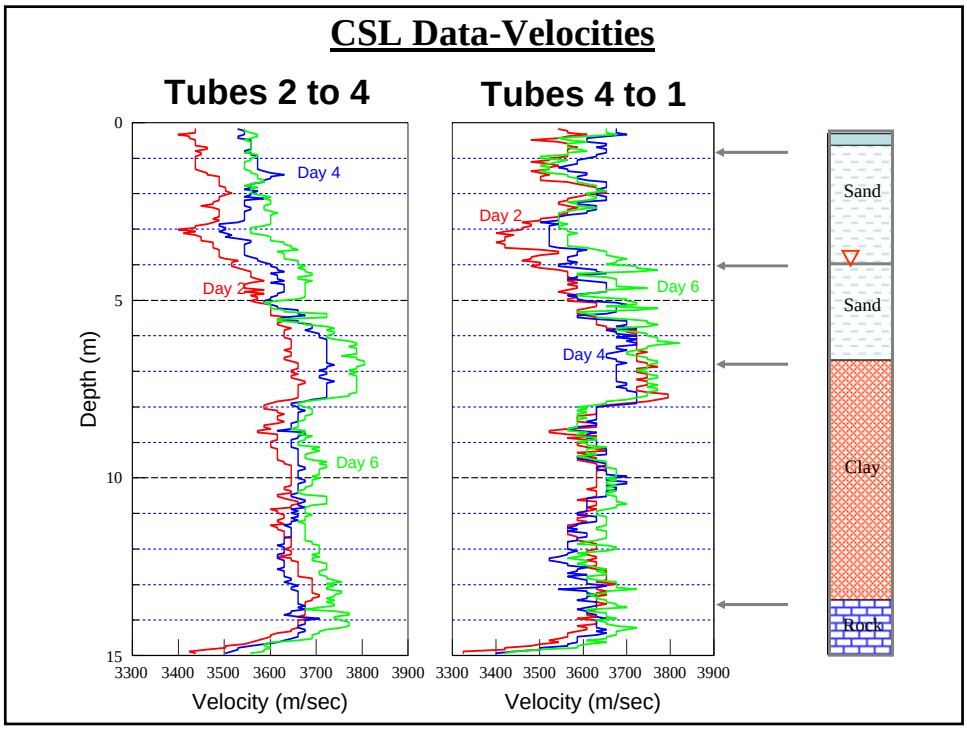
Density



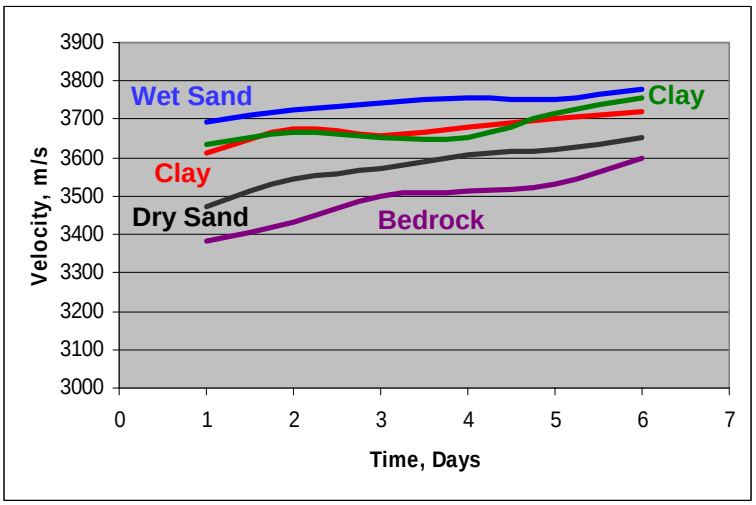
Moisture

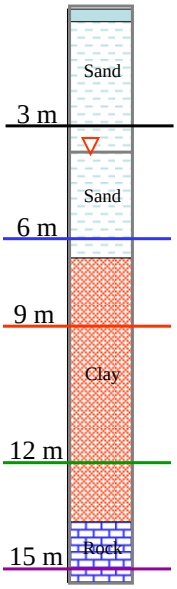



CSL Data-Velocities
Tubes 1 to 3
Tubes 2 to 4
Day 6
Day 2
Day 4
Day 4
Day 2
Day 6
Depth (m)
0
5
10
15
3300 3400 3500 3600 3700 3800 3900
Velocity (m/sec)
Sand
Sand
Clay
Rock


CSL Data-Velocities
Tubes 2 to 4
Tubes 4 to 1
Day 4
Day 2
Day 6
Day 2
Day 6
Day 4
Depth (m)
0
5
10
15
3300 3400 3500 3600 3700 3800 3900
Velocity (m/sec)
Sand
Sand
Clay
Rock

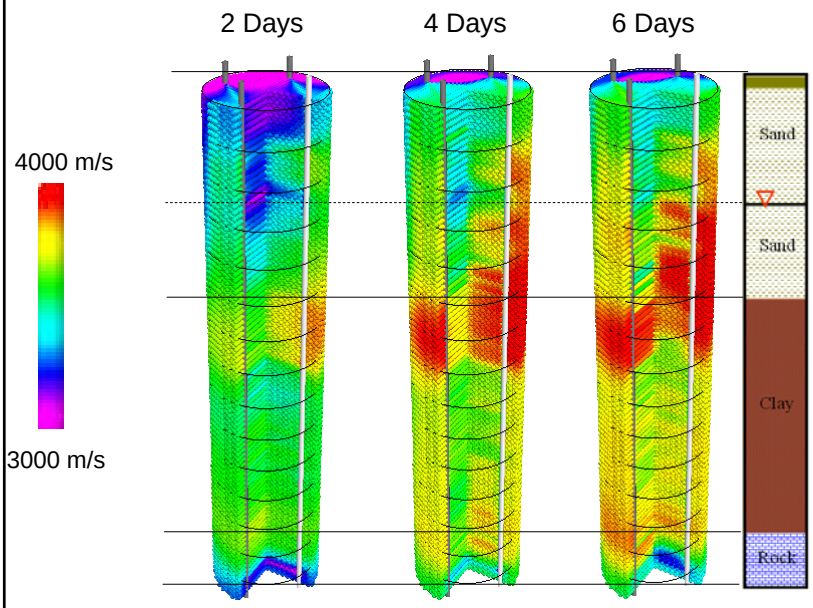
Velocity



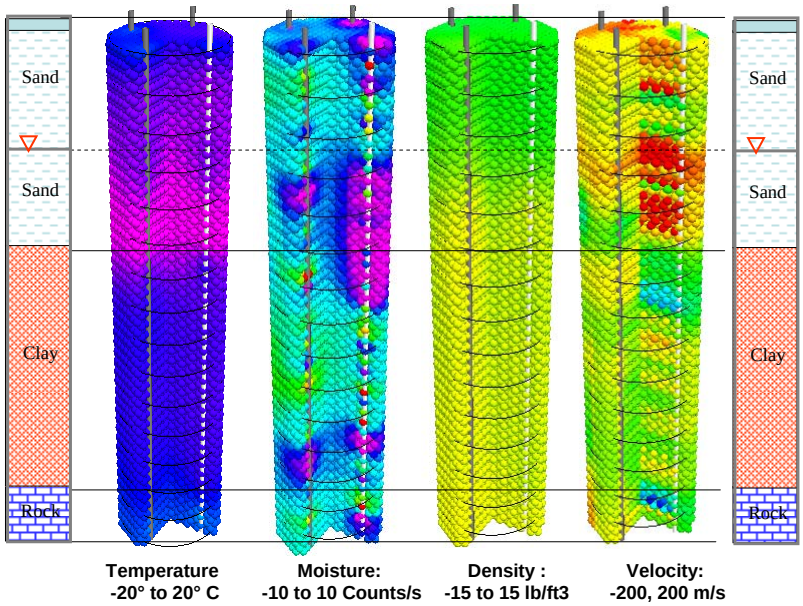


Controlling Variable: Soil/Rock Thermal Conductivity as it Relates to Strength

CSL Velocity



Difference Tomograms Day 6 - 2



Field Study Conclusions

Concrete strength in a drilled shaft is not only a function of time but also a function of the physical properties of the surrounding soil/rock and the depth of the water table.

Specifically, two noteworthy parameters:

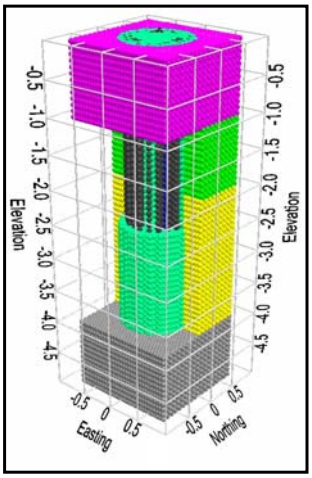
Field Study Conclusions

- Thermal conductivity of geomaterials: controls relative changes in temperature.
- Permeability of geomaterials: controls small relative changes in the moisture content.

These parameters in turn control concrete curing and concrete strength—as it relates to incremental changes in velocity and density.

3D Numerical Modeling

- Account for variables
- Isolate parameters
- Determine serviceability
- Determine failure mode

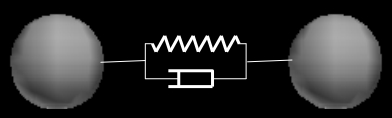


Geostructural Analysis Package (GAP)

High Resolution Dynamic Model that Combines Well-Developed Techniques from:

1. Distinct Element Method (DEM)
2. Practical Flow Code (PFC)
3. Material Point Method (MPM)
4. Finite Difference (FD)

GAP
Visco-Elastic Contact Model



- Geotechnical Materials
  - Rock, soil, clay, dry or wet sand, etc.
- Construction Materials
  - Wood, steel, concrete, PVC, etc.
- Fluids
  - Water and air
- Material Interactions
  - Solids / fluids, friction, interlocking