The Not So Hidden Cost in Deep Foundation Design

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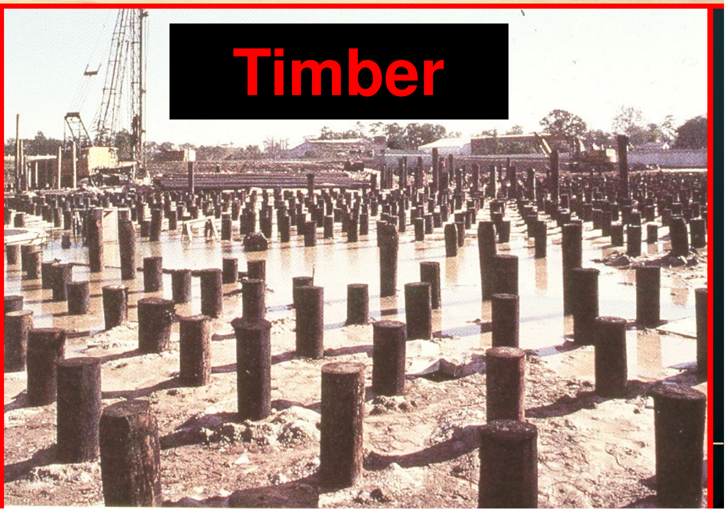
Deep Foundations


Cast-in-Place


H-pile


Pipe


Precast Concrete


Timber

Deep Foundation Choice?

- Type of Load
  (axial, lateral, torsion)
- Magnitude of Load
- Project Size & Complexity
- Site Conditions
- Environmental Conditions

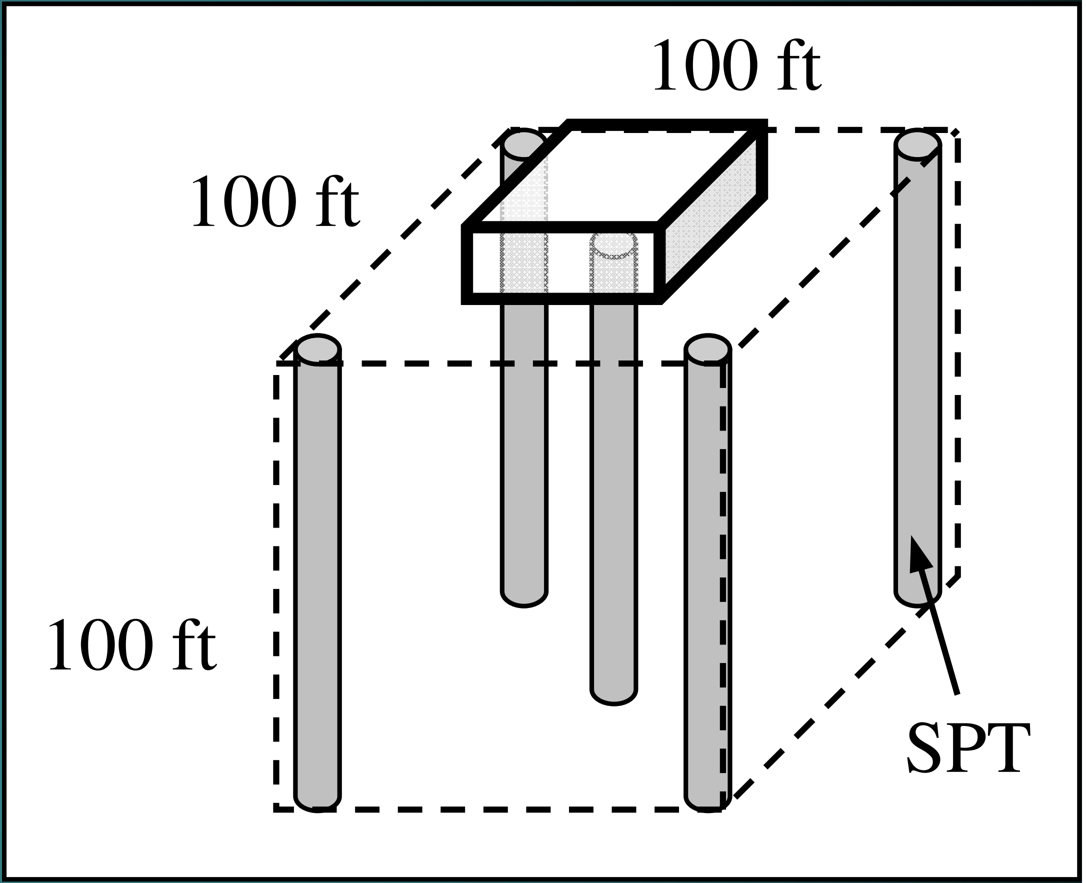
Engineering Decisions

- Local Availability & COST
- Familiarity (engineer, client) & complacency
- Foundation Cost Controlled by Design Uncertainty (conservatism & safety factor)

Deep Foundation Design Uncertainty

- **Site Variability**
  - Axial, lateral, depth to bearing stratum
  - Strength, stiffness, test quality
  - Typically test < 0.01% of site
- **Design Method:** $R_N = R_{side} + R_{base}$
  - Calibration, empiricism, codes, resistance or safety factors based on uncertainty
- **Construction Quality**
  - Contractor experience
  - Quality of supervision

Deep Foundation Uncertainty



- **Site Variability**
- 50 ft x 50 ft Footing
- SPT Sampler
- 18 in x 2 in dia
- Sampling every 2.5 ft (60% of soil column)
- Assume each boring represents 8 in dia soil column
- Five borings sample ~0.01% of 1 million cf
- Concrete testing typically samples about 0.2%

Deep Foundation Uncertainty

- LRFD = Load & Resistance Factor Design
- Probabilistic Limit State Design
- $\sum (\gamma_i Q_i) \leq \sum (\varphi_i R_{Ni})$
- γ_i = Load Factors (>1) (service, strength, extreme)
- Q_i = Nominal Loads (live, dead, wind, earthquake)
- φ_i = Resistance Factor (<1), depends on R_{Ni} (reduced by 0.10 for non-redundant foundations)
- R_{Ni} = Nominal Resistance (theoretical or msd.)
- Target Probability of Failure = 1 in 1000

Deep Foundation Uncertainty

Pile Type	Method for R_N	AASHTO LRFD φ
Driven	Side & Base, Clay	0.25 - 0.40
Driven	Side & Base, Sand	0.40
Driven	ENR / Gates Formula	0.10 / 0.40
Driven	Wave Equation	0.40
Drilled Shaft	Side, Clay (α)	0.55
Drilled Shaft	Side, Sand (β)	0.45
Drilled Shaft	Base, Bearing Eqn.	0.40
Driven	Dynamic Test (5%+)	0.65
Drilled Shaft	Dynamic Test (5%+)	0.60
Driven / Shaft	Static Test, med. COV	0.70 (0.50 - 0.90)

Reduce Cost by Reducing Uncertainty:

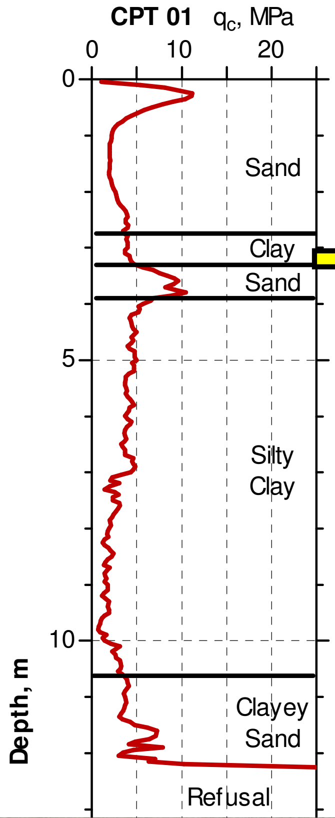
- **Informed design (integrated investigation: geophysics + insitu testing + sampling)**
- **Design verification (testing)**
- **Optimization (redesign)**
  - **reduce length, size, number**
  - **change type (driven, drilled, anchor)**
  - **reduce cost and construction time ($$)**
  - **FLT's experience - savings 5X test cost**
- **Quality control testing to assure performance & reduce remediation cost**

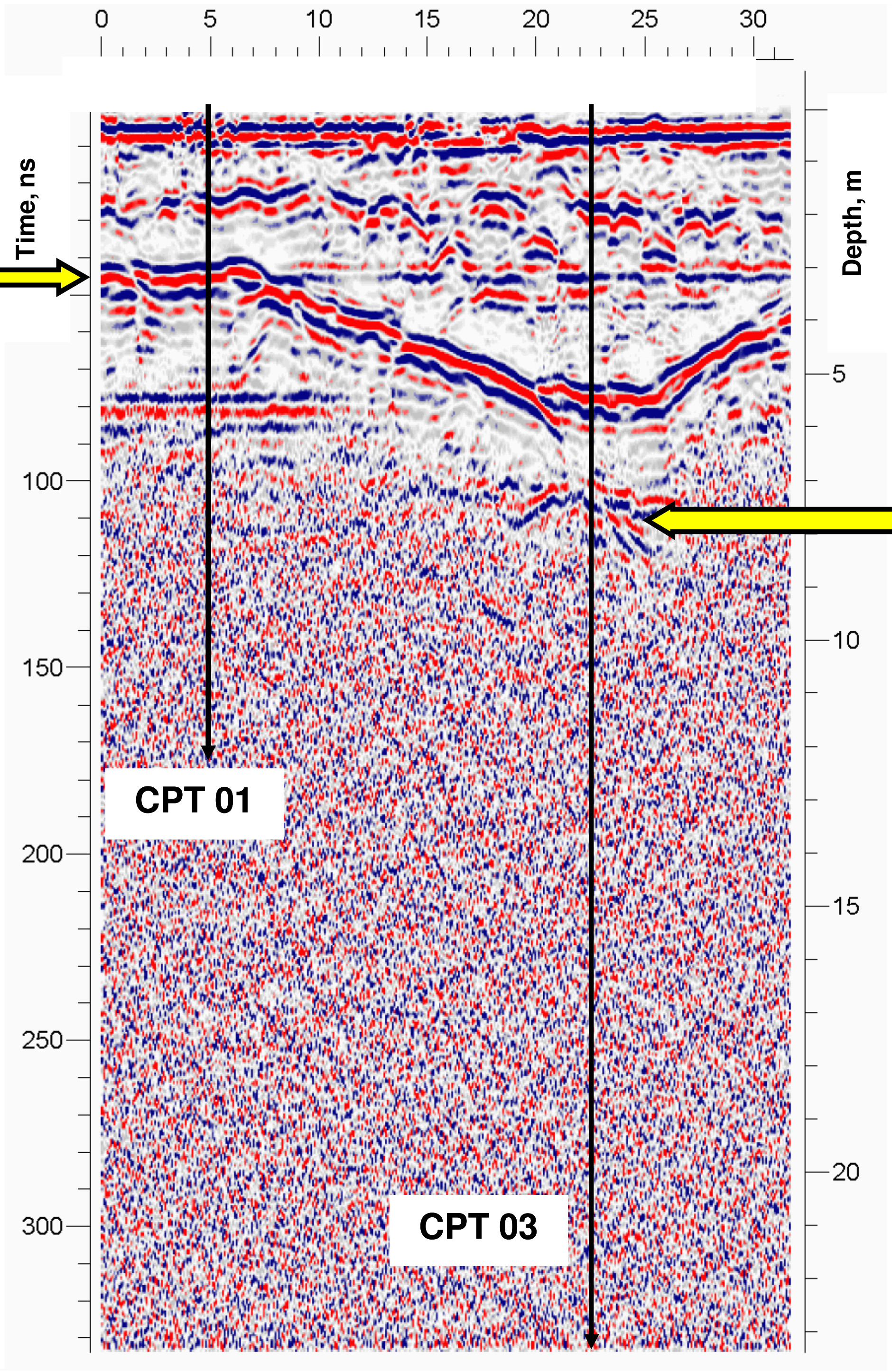
Integrated Ground Investigation

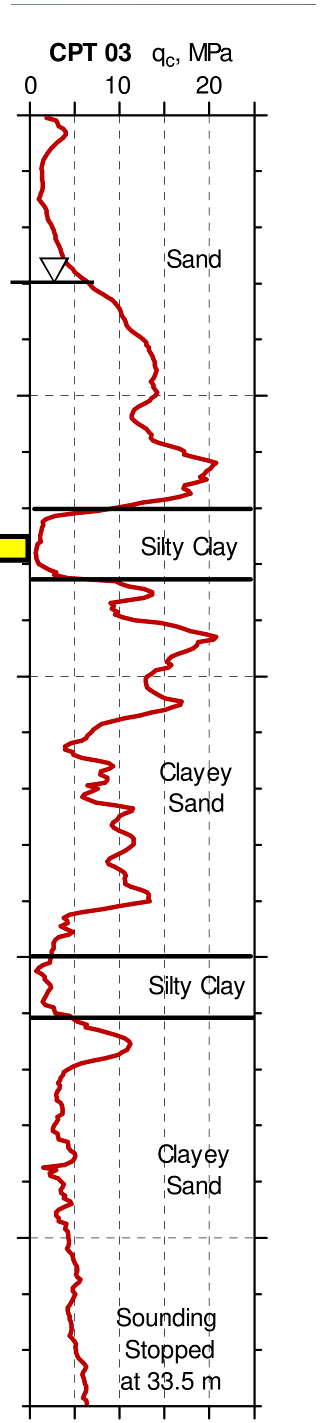
- Measure (not guess) ground properties for foundation design
- More time characterizing site → more reliable design
- Staged approach - progressively more targeted techniques
- Geophysical techniques provide overview of geological conditions
- Intrusive investigation calibrates geophysical information
- Insitu testing (CPT/DMT) reduces uncertainties associated with sampling disturbance and laboratory testing
- Insitu profiling (CPT) identifies thin layers missed by drilling and sampling program
- SPT not so great ("standard", drilling disturbance, energy)
- Sampling and testing to characterize specific problem zones
- Does not have to cost more, and can cost less
- Full scale tests to calibrate design methods for a site?
- Preliminary pile tests included to prepare better plans?

GPR Example

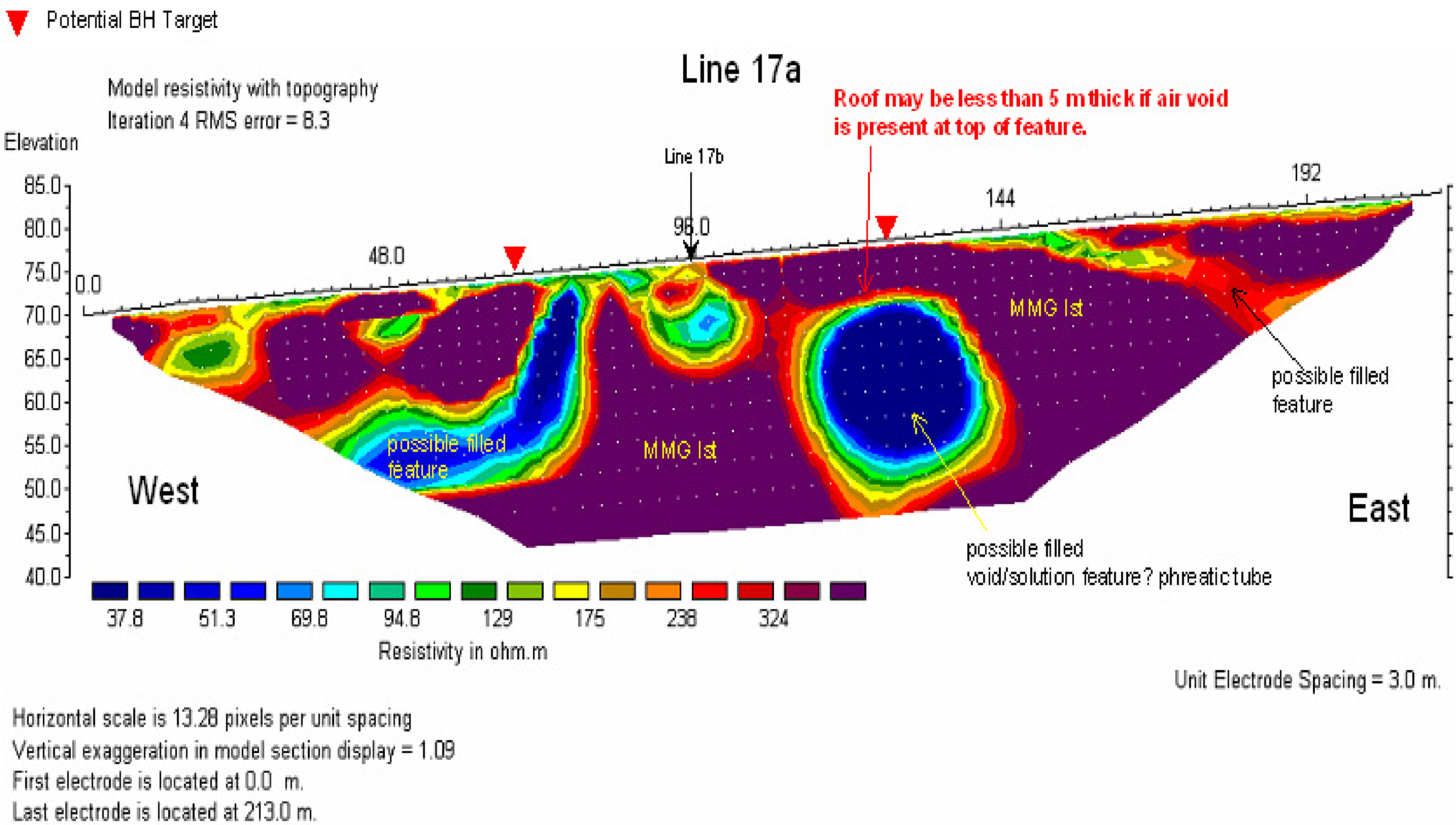
UF Insitu Test Site







Electroresistivity



Roof may be less than 5 m thick if air void is present at top of feature.

possible filled feature

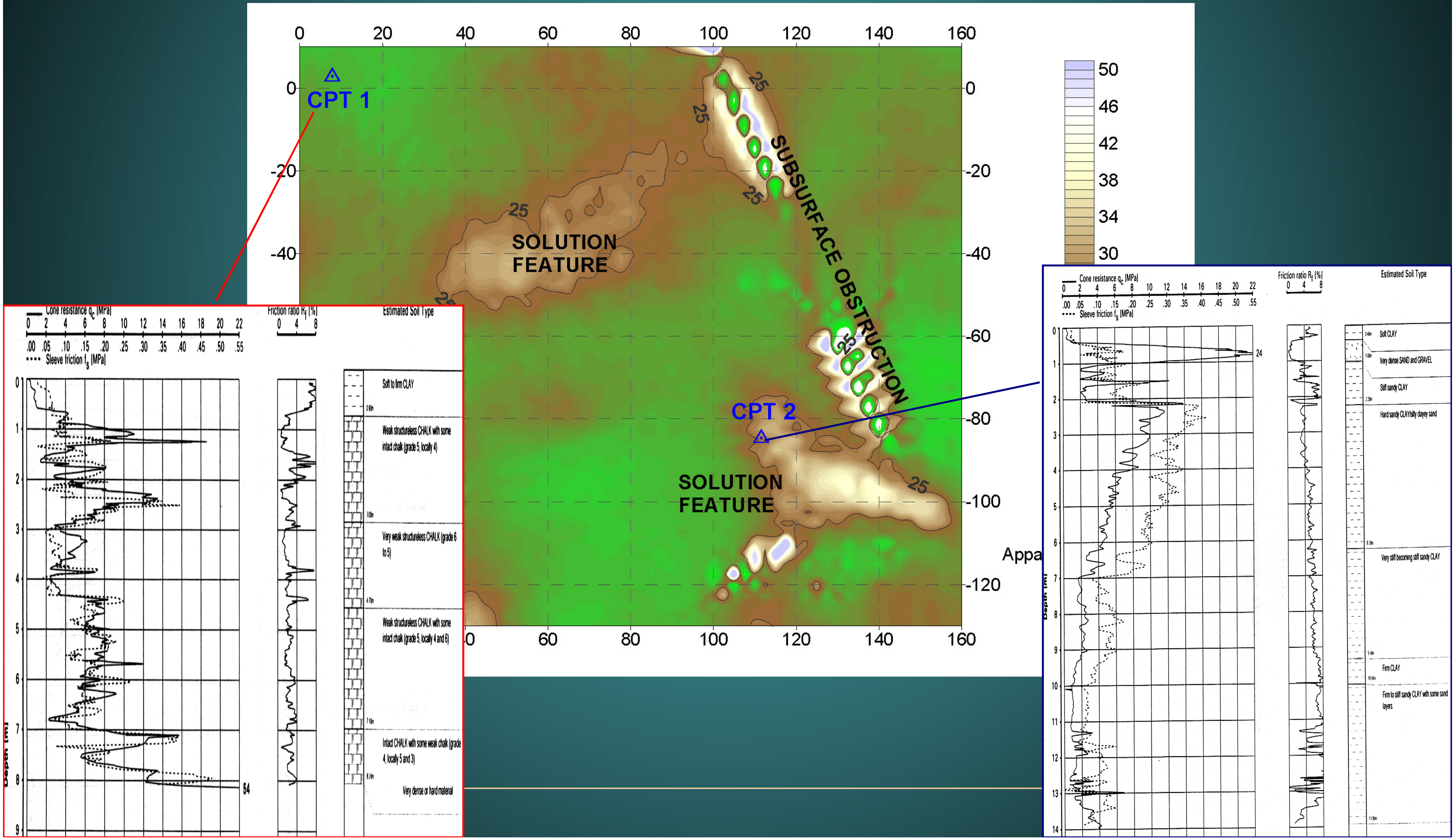
possible filled void/solution feature? phreatic tube

Unit Electrode Spacing = 3.0 m.

Horizontal scale is 13.28 pixels per unit spacing
Vertical exaggeration in model section display = 1.09
First electrode is located at 0.0 m.
Last electrode is located at 213.0 m.

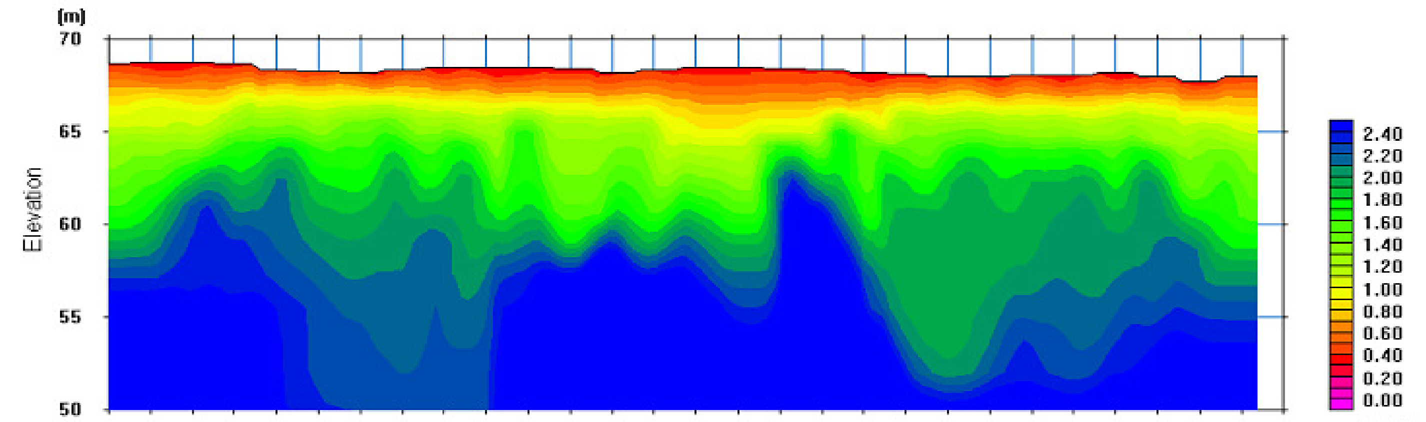
Electromagnetic Conductivity

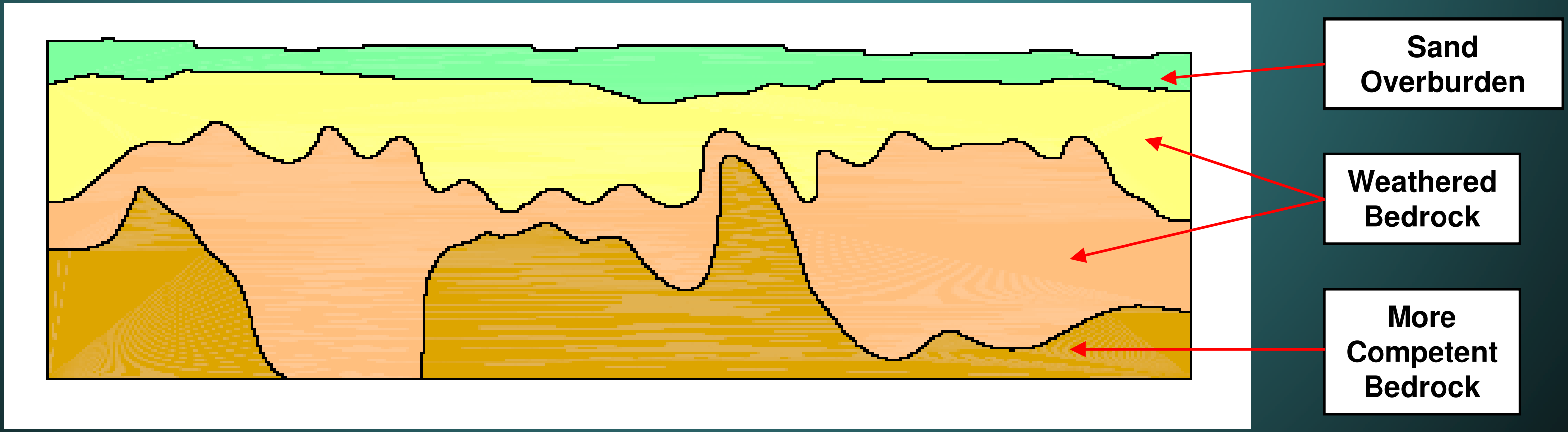
Electromagnetic Conductivity Profile



Seismic Refraction Tomography

Bedrock Mapping





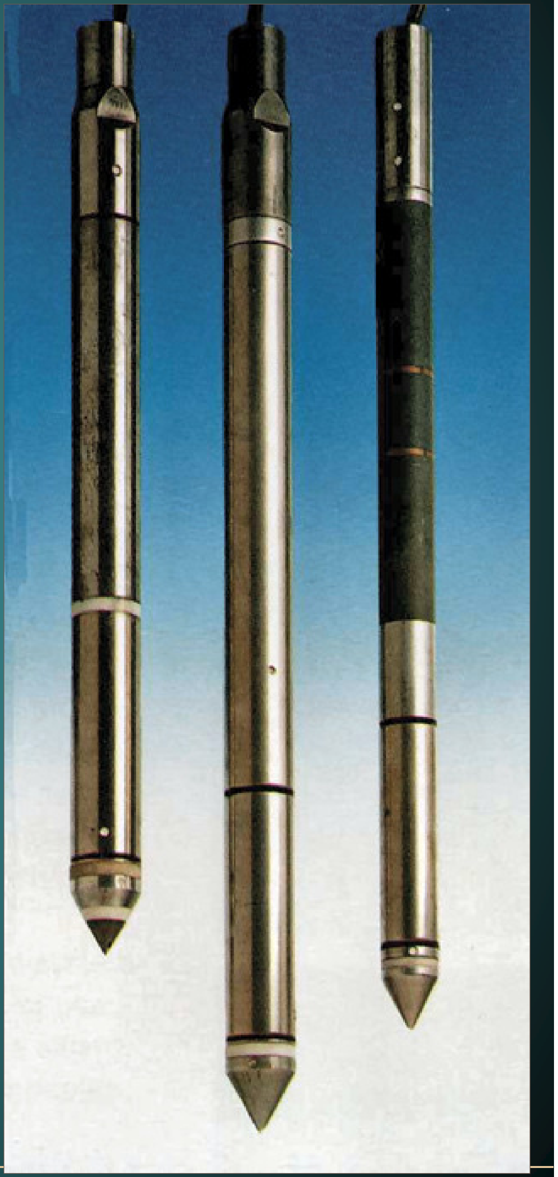
Sand Overburden

Weathered Bedrock

More Competent Bedrock

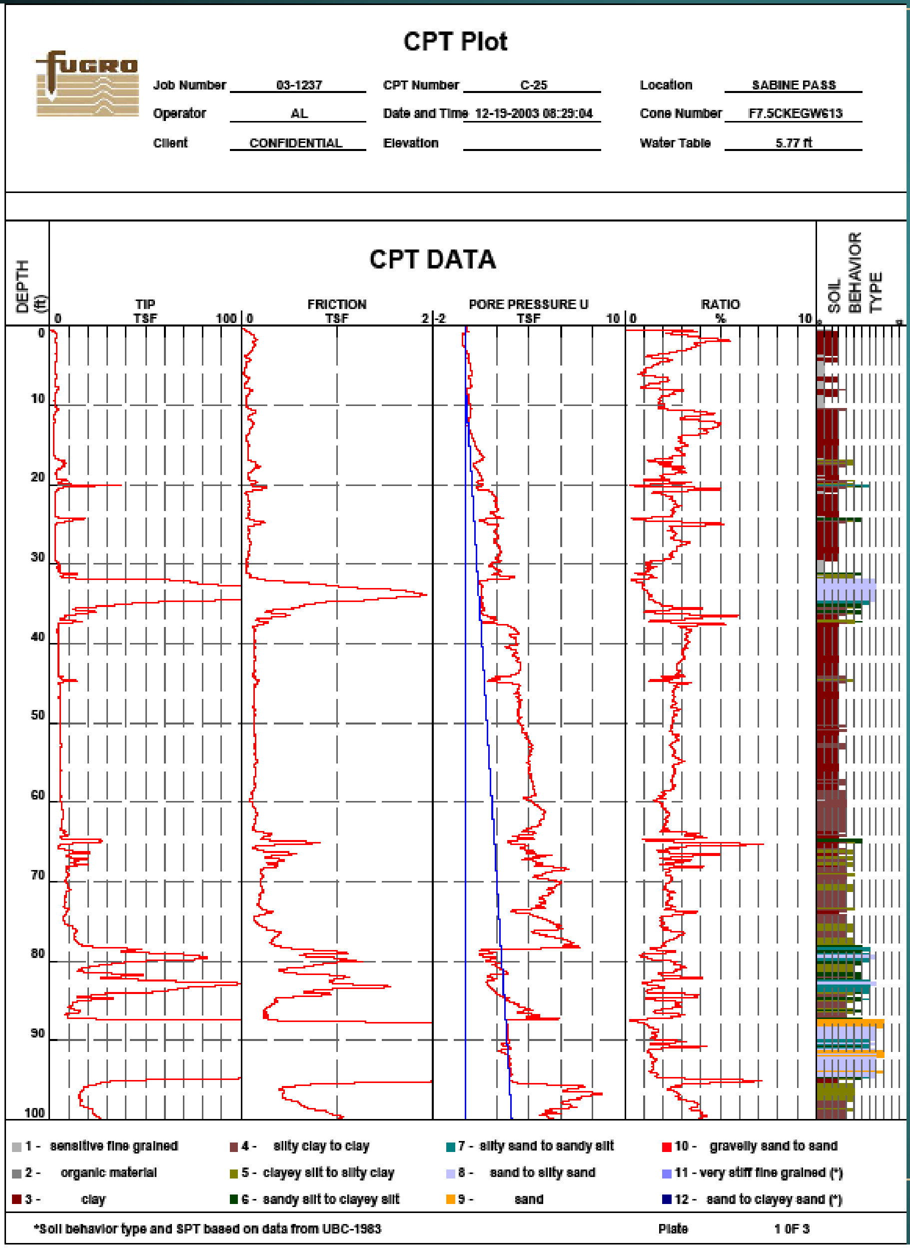
Insitu Cone Penetrometer Test (CPT)

- Robust push-in tool (ASTM D5778)
- Profiles penetration resistance
- Estimates soil type
- Undrained shear strength (clay)
- Friction angle (granular soils)
- Footing settlement, bearing pressure, pile capacity
- Compaction quality control
- Depth to cavities or bearing stratum
- Optimize borehole program



CPT Platforms

CPT Measurements / Soil Type



CPT Plot

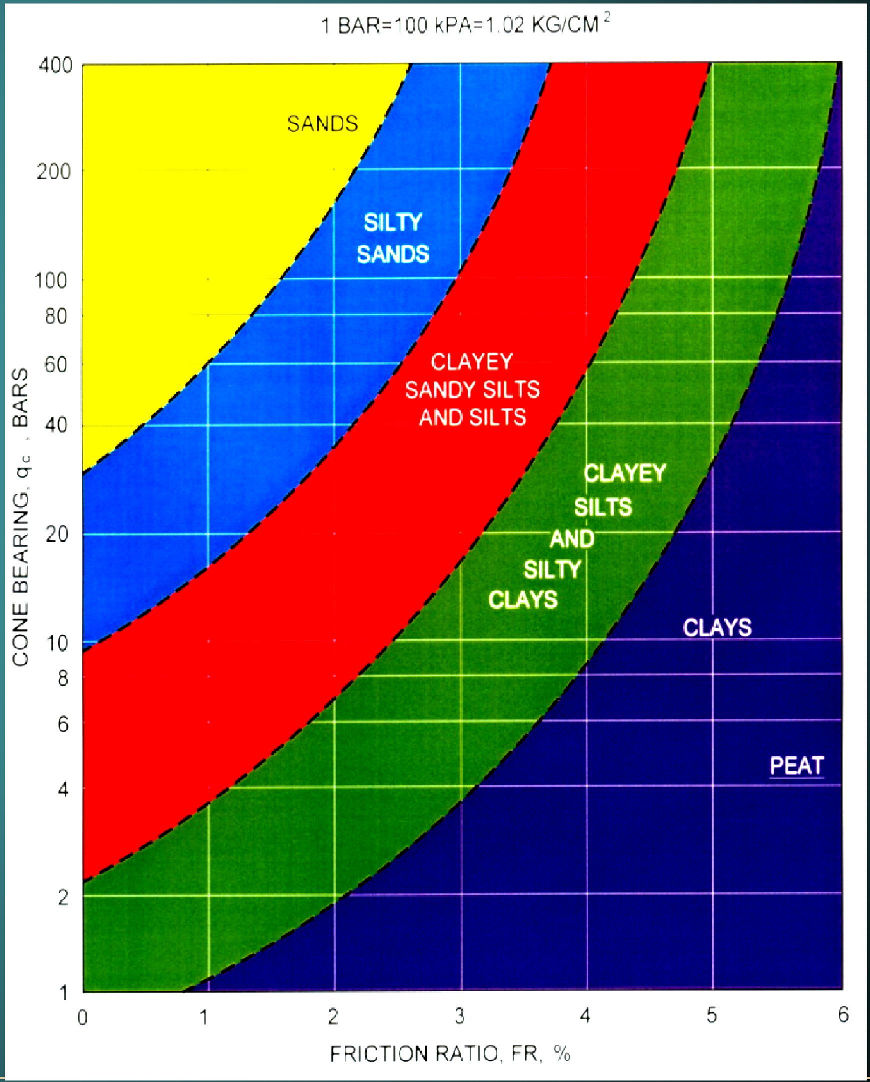
Job Number	03-1237	CPT Number	C-25	Location	SABINE PASS
Operator	AL	Date and Time	12-19-2003 08:29:04	Cone Number	F7.5CKEGW613
Client	CONFIDENTIAL	Elevation		Water Table	5.77 ft

CPT DATA

■ 1 - sensitive fine grained	■ 4 - silty clay to clay	■ 7 - silty sand to sandy silt	■ 10 - gravelly sand to sand
■ 2 - organic material	■ 5 - clayey silt to silty clay	■ 8 - sand to silty sand	■ 11 - very stiff fine grained (*)
■ 3 - clay	■ 6 - sandy silt to clayey silt	■ 9 - sand	■ 12 - sand to clayey sand (*)

*Soil behavior type and SPT based on data from UBC-1983

Plate 1 0F 3

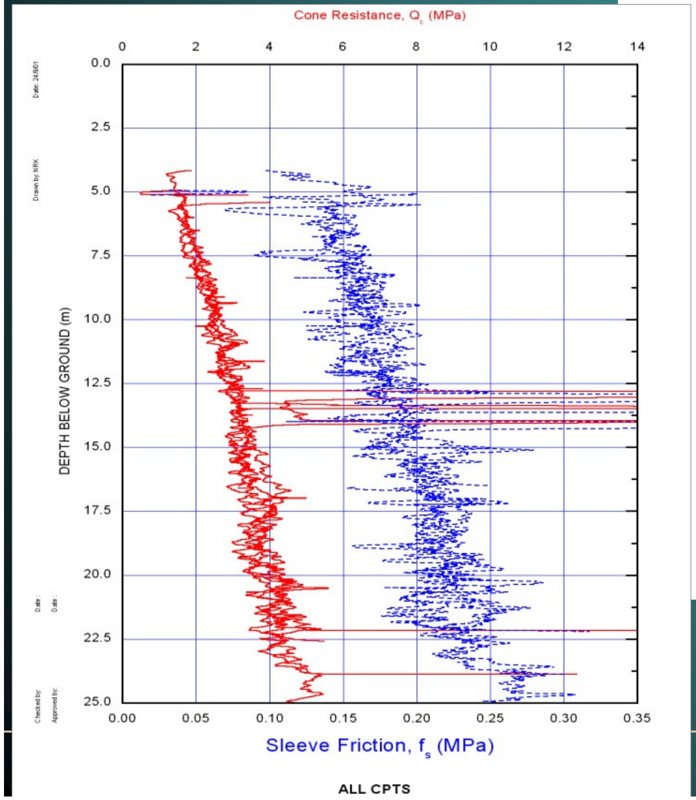


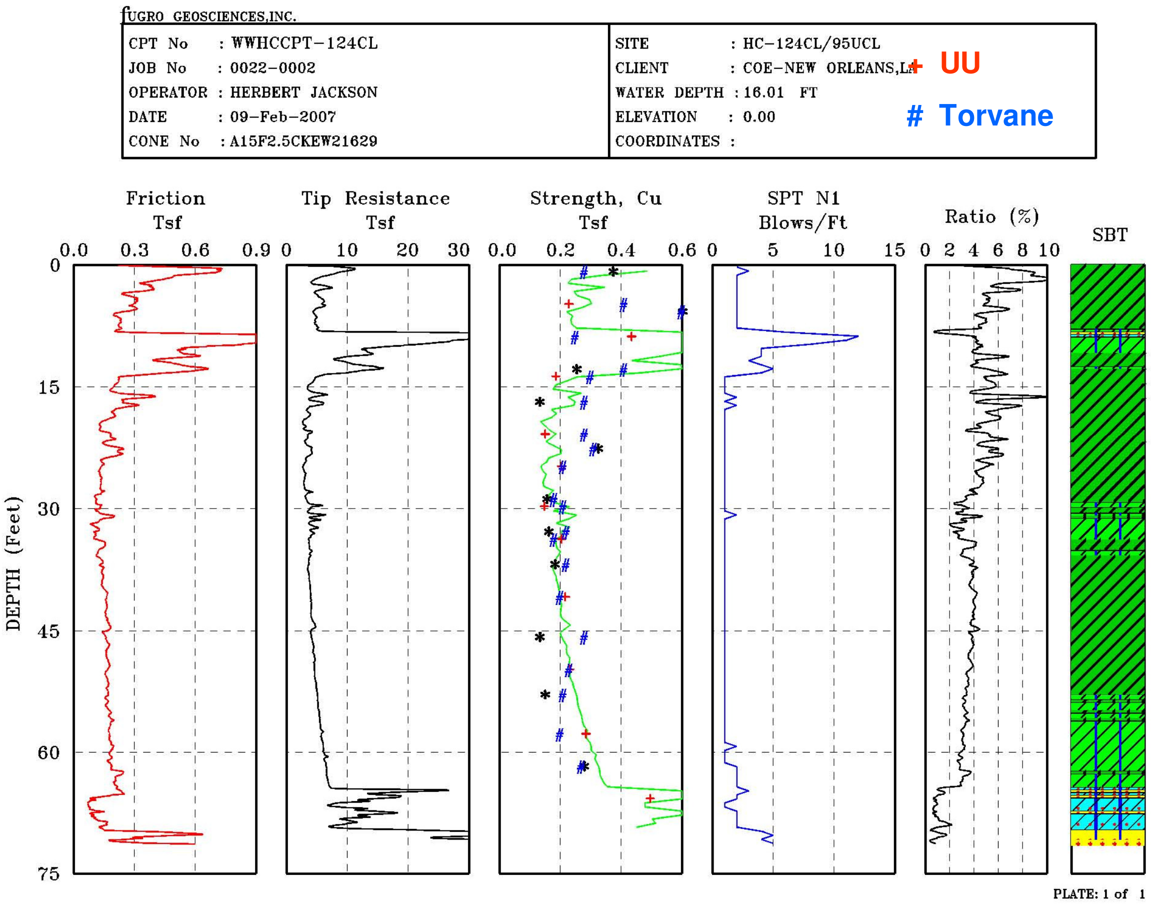
CPT Engineering Properties Cohesive Soils

Shear Strength

$S_u = q_c / N_k$

$15 < N_k < 20$




FUGRO GEOSCIENCES,INC.

CPT No : WWHCCPT−124CL
JOB No : 0022−0002
OPERATOR : HERBERT JACKSON
DATE : 09−Feb−2007
CONE No : A15F2.5CKEW21629

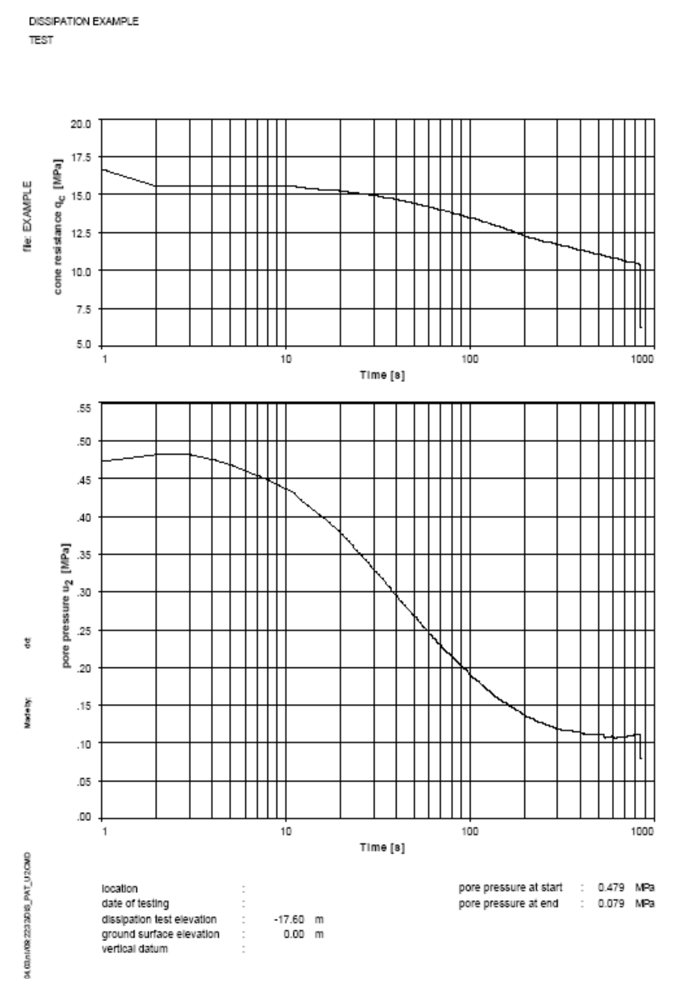
SITE : HC−124CL/95UCL
CLIENT : COE−NEW ORLEANS,LA
WATER DEPTH : 16.01 FT
ELEVATION : 0.00
COORDINATES :

+ UU
# Torvane

CPT Pore Pressure Dissipation Tests

Coefficient of Horizontal Consolidation – c_h

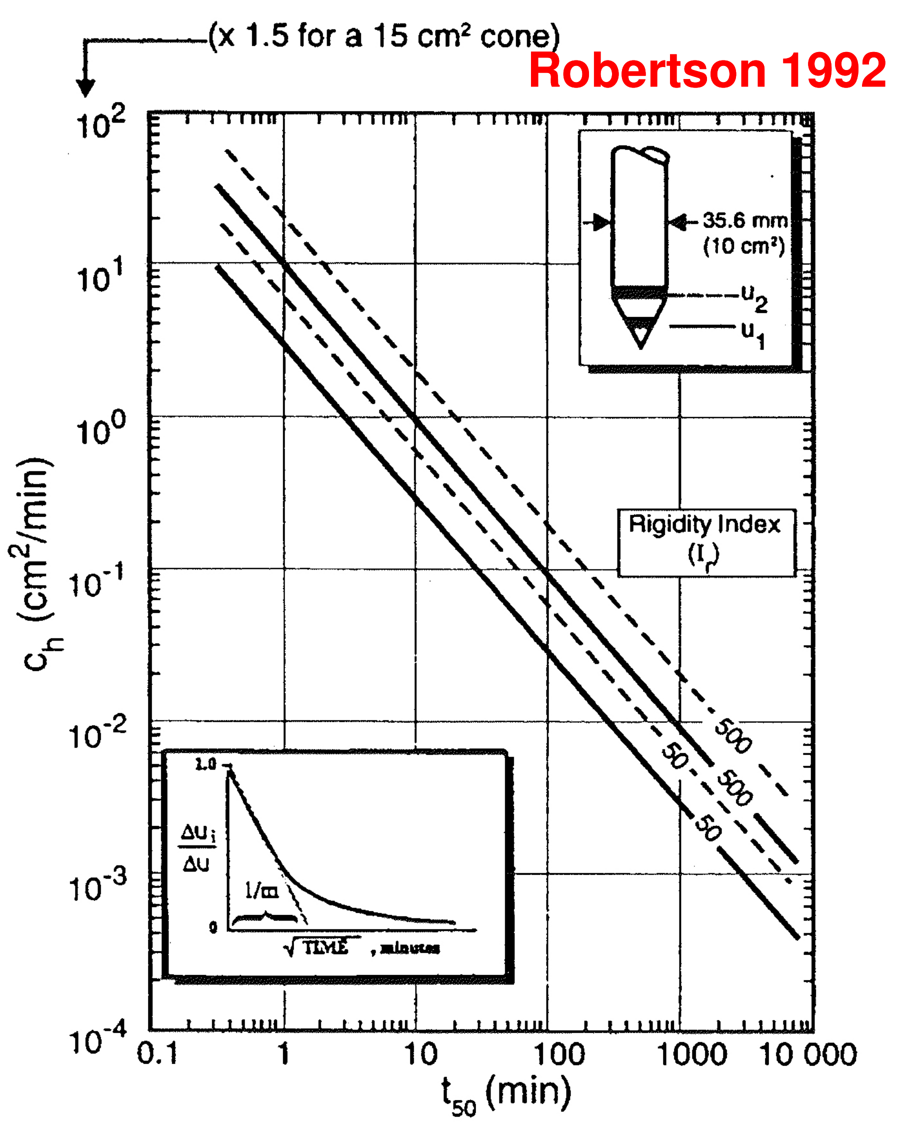
Design of Wick Drains, Embankment Settlement Rates



DISSIPATION EXAMPLE
TEST

location :
date of testing :
dissipation test elevation : -17.60 m
ground surface elevation : 0.00 m
vertical datum :

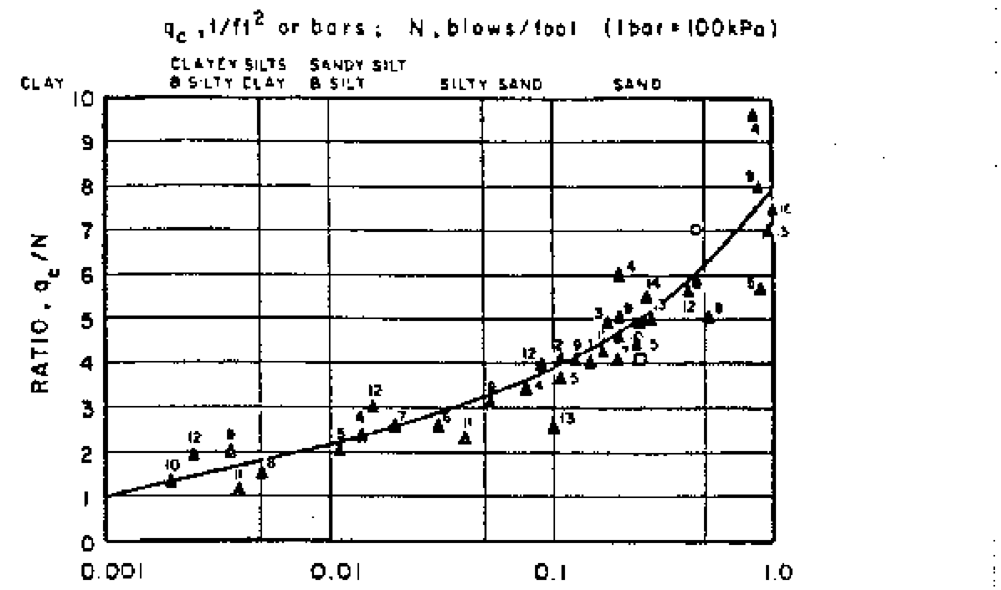
pore pressure at start : 0.479 MPa
pore pressure at end : 0.079 MPa



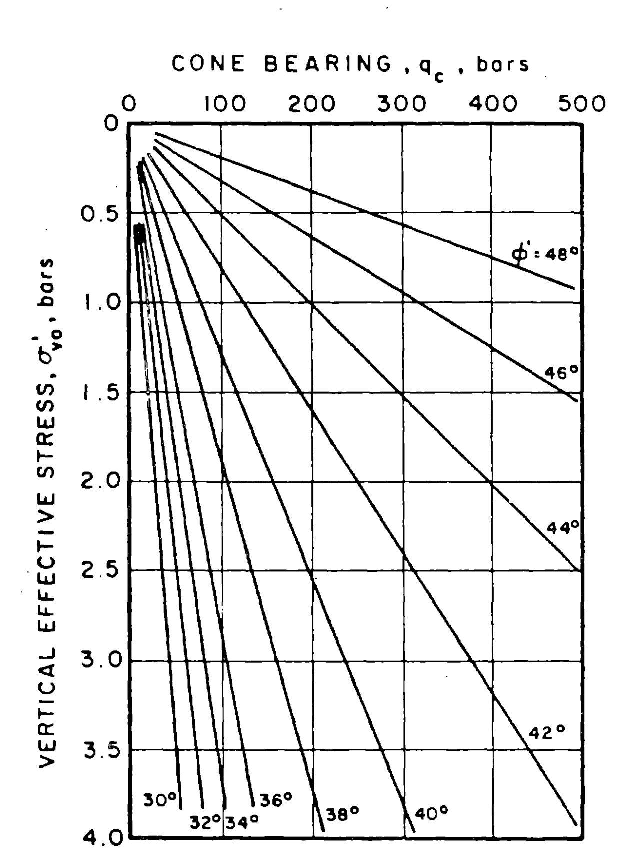
Robertson 1992

CPT Engineering Properties Cohesionless Soils

- **Density description**
- **Relative Density (Dr)**
- **Angle of Internal Friction (φ)**
- **SPT equivalent (N)**
- **Young's Modulus (E)**
- **Constrained Modulus (M)**



Variation of q_c/N with Mean Grain Size (Robertson et al, 1983)

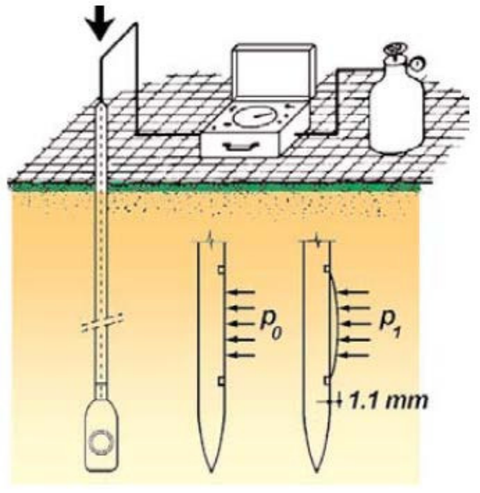


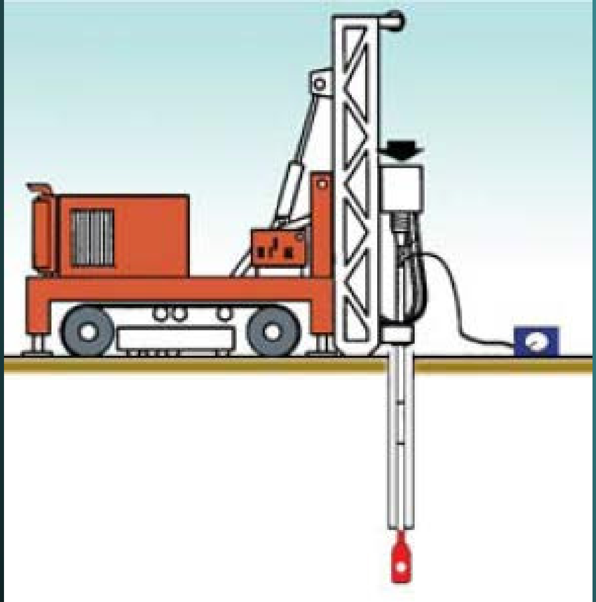
Proposed Correlation of Tip Resistance to Peak Friction Angle for Uncemented Quartz Sands (Robertson and Campanella, 1983)

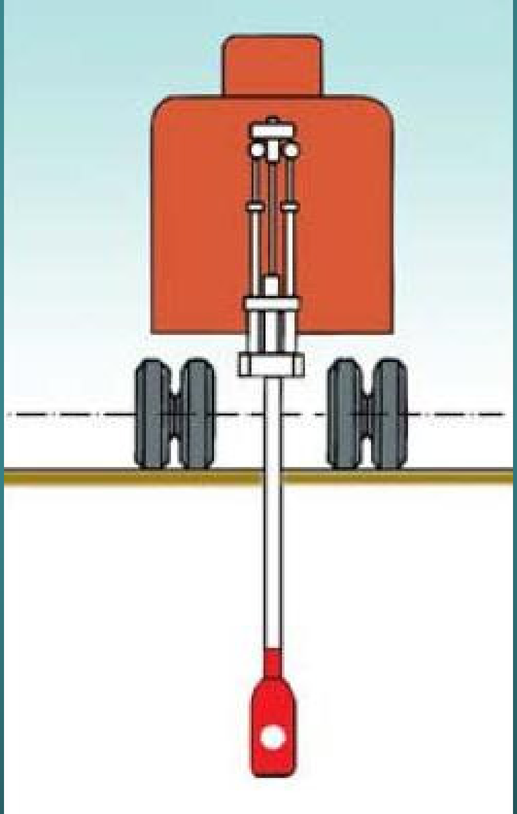
Marchetti Dilatometer

Push-in Flat Blade Minimizes Penetration Disturbance

(ASTM D6635)







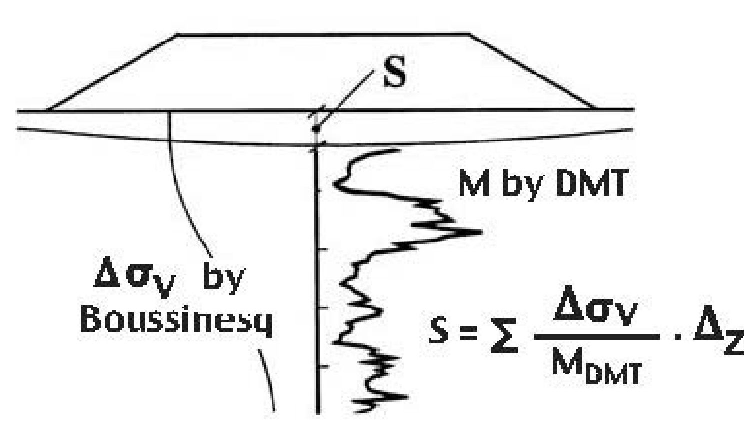
Measurements:

- Insitu Lateral Stress
- Modulus
- Shear Strength
- Depth Profile (every 20 to 30 cm)

Marchetti Dilatometer

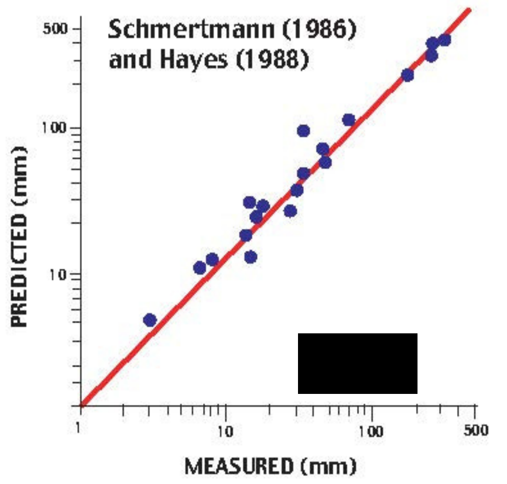
Uses:

- Settlement
- Slope Stability
- Lateral Stress (walls, tunnels, excavations)
- Compaction Control
- Dissipation Testing, c_H



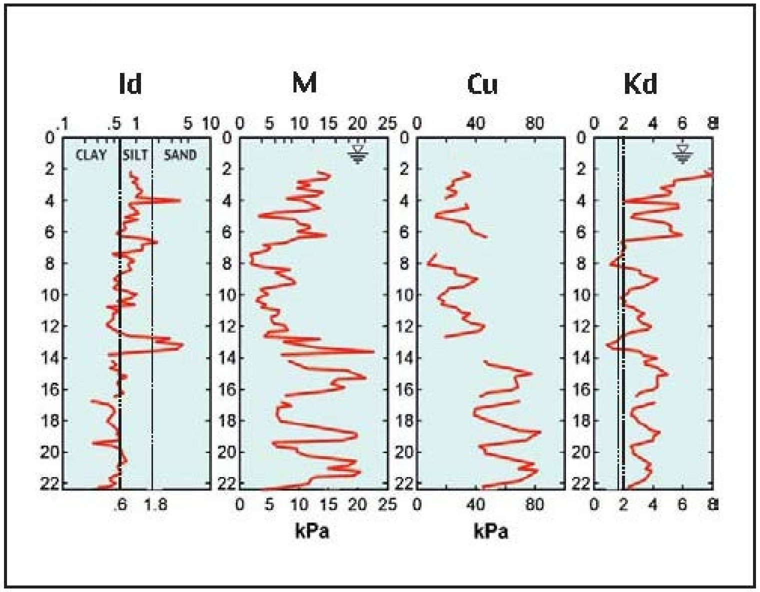
$$S = \sum \frac{\Delta\sigma_V}{M_{DMT}} \cdot \Delta_Z$$

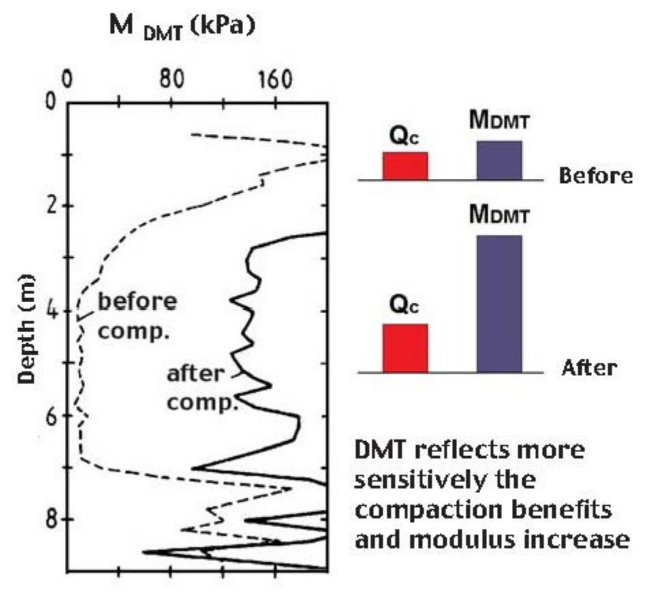
DMT predicted Settlements



[redacted]

Soil parameters





DMT reflects more sensitively the compaction benefits and modulus increase

Reduce Cost by Reducing Uncertainty:

- Informed design (integrated investigation: geophysics + insitu testing + sampling)
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  - reduce length, size, number
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Top-down Static Load Tests (ASTM D1143)

Design Optimization requires load to failure <u>plus instrumentation</u>

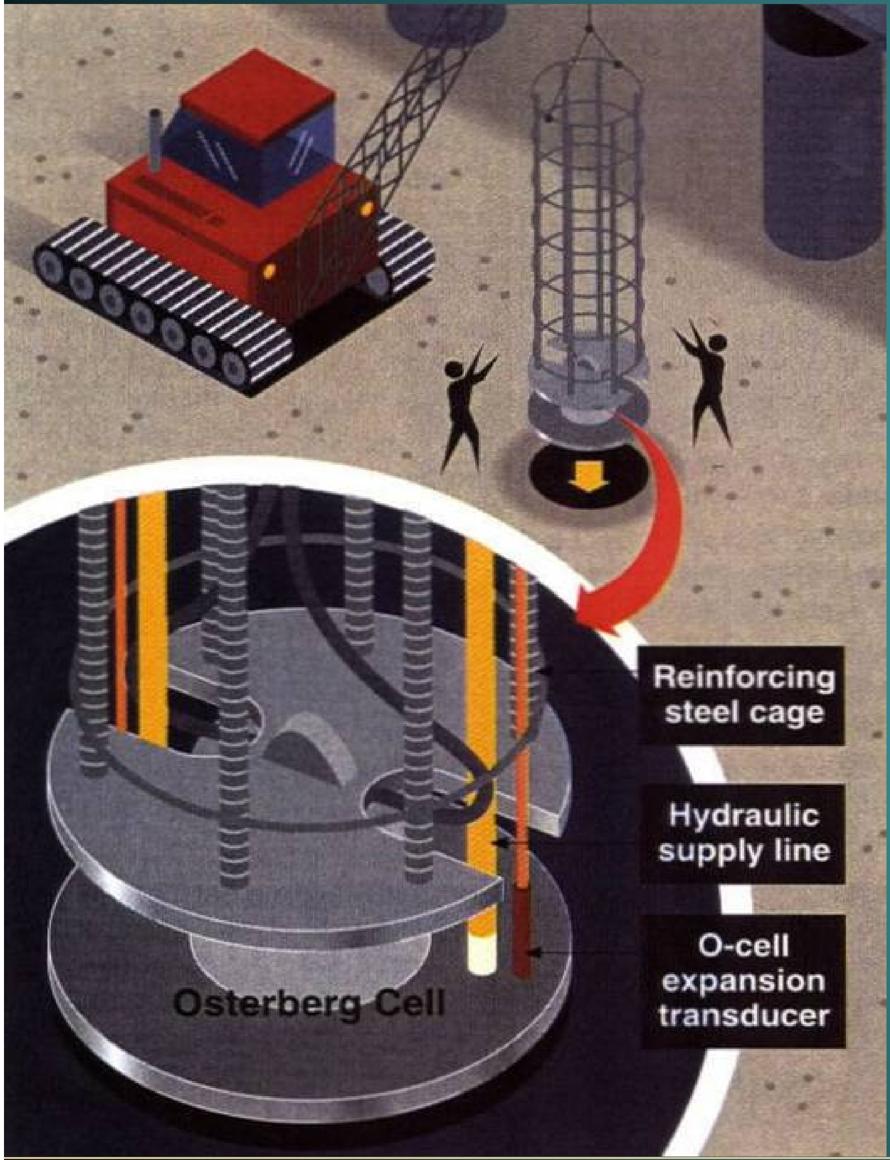
Static Test Instrumentation

- Quick Test: ~20 loads to failure, 5 min load increments
- Redundant load and deflection measurements, reference beams
- Shade / weather protection
- Plot Creep 1-4 min Creep vs. Load to find Creep Limit
- Strain gauges and telltales to develop load transfer diagram

Automated Uni-Directional Testing

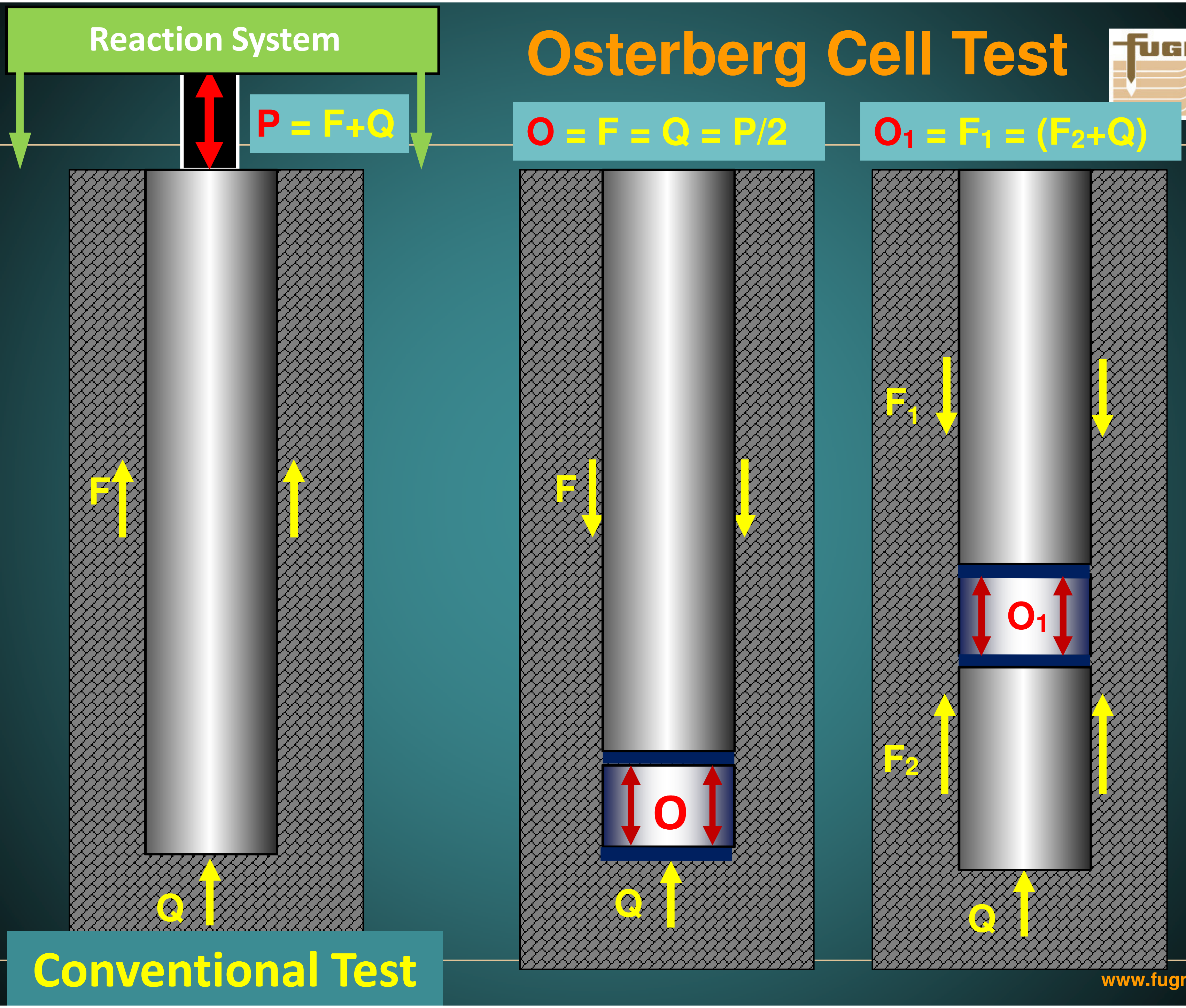
- Load control
- Real-time results
- Creep data
- Reduced analysis

Bi-Directional Osterberg Cell Testing



- Specialized jack cast into pile uses bearing beneath it to mobilize side shear above it
- Developed by Dr. Jorj Osterberg and American Equipment
- First commercial test in drilled shaft / bored pile in 1989
- LOADTEST Inc. founded 1991, (purchased by Fugro in 2008)
- Test performed following ASTM D1143 (writing new Standard)

Osterberg Cell Test



$P = F+Q$

$O = F = Q = P/2$

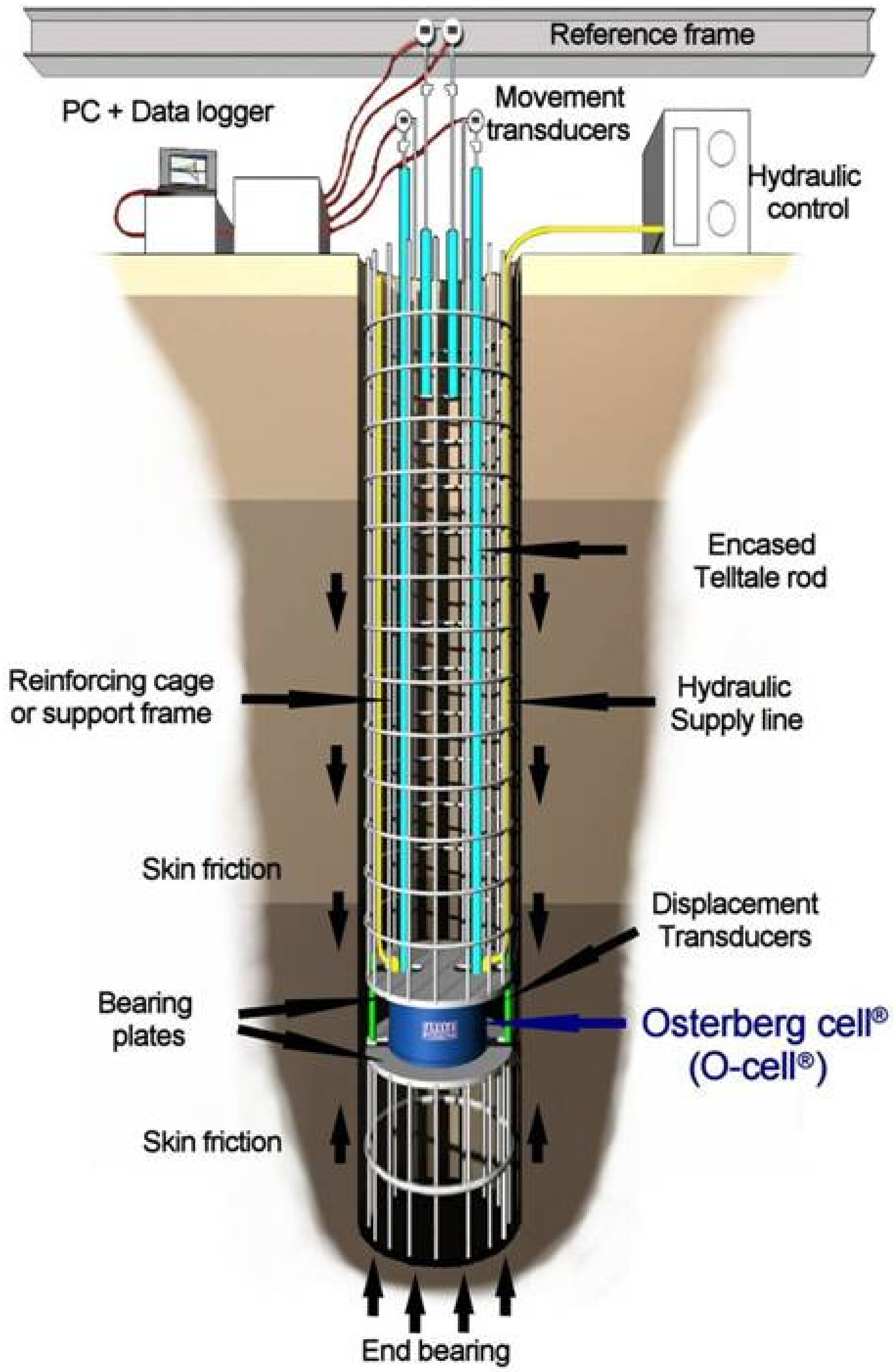
$O_1 = F_1 = (F_2+Q)$

Conventional Test

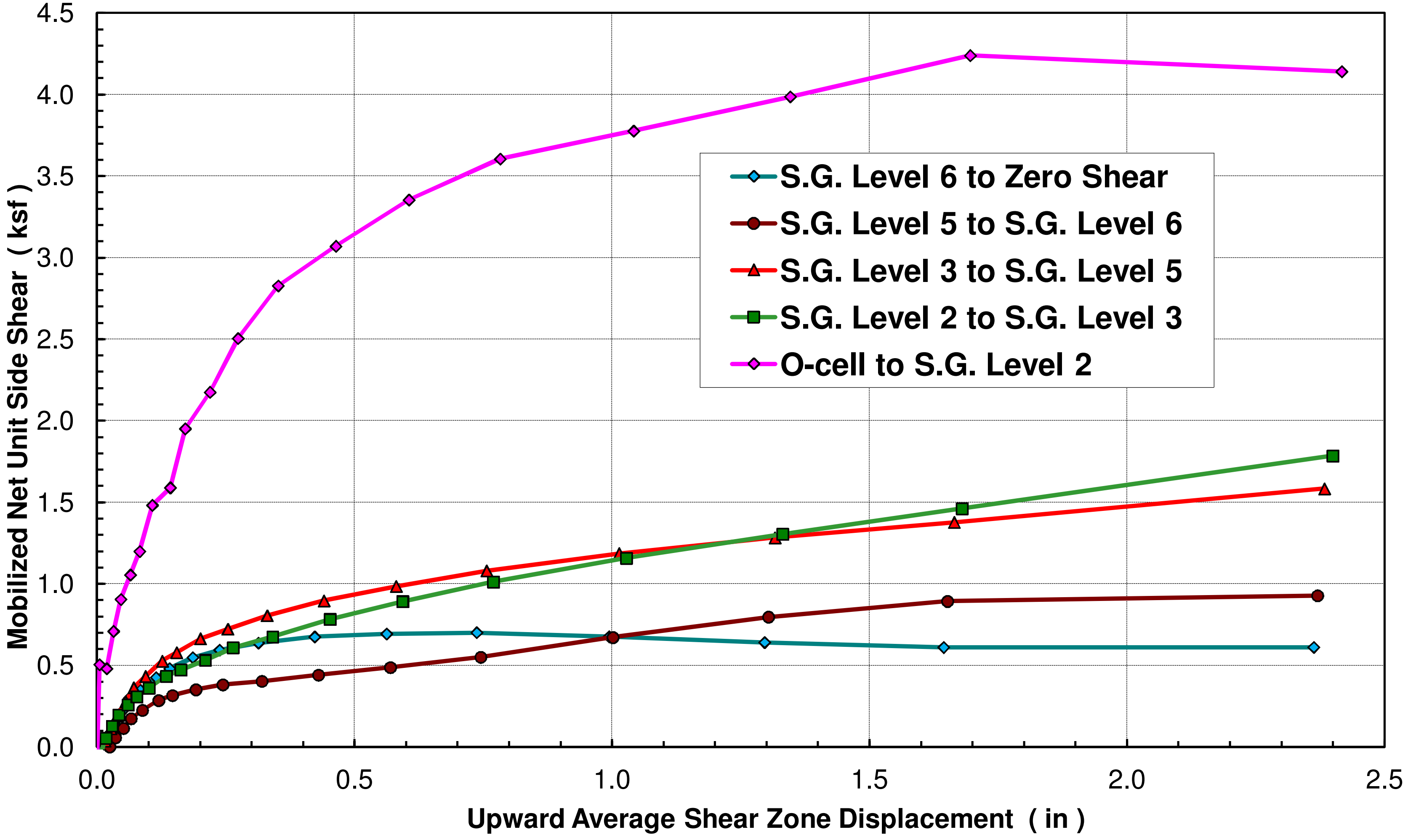
www.fugro.com

O-cell Instrumentation

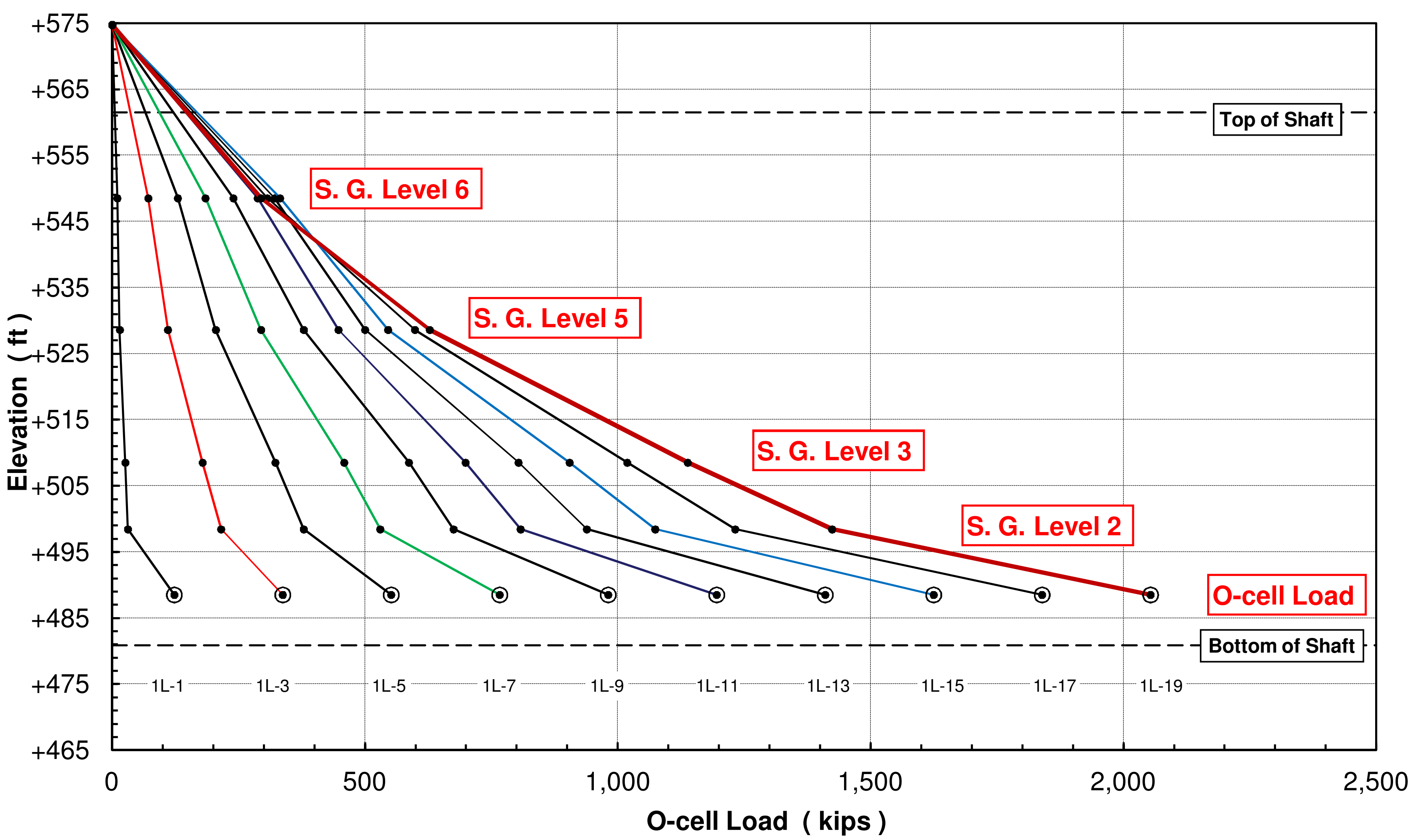
- O-cell Expansion Transducers
- O-cell Top Telltales
- Pile Top Deflection
- Pile Bottom Telltales
- Shaft Strain Gauges
- Embedded Shaft Compression Transducers



Side Shear from Strain Gauges



Load Transfer Diagram

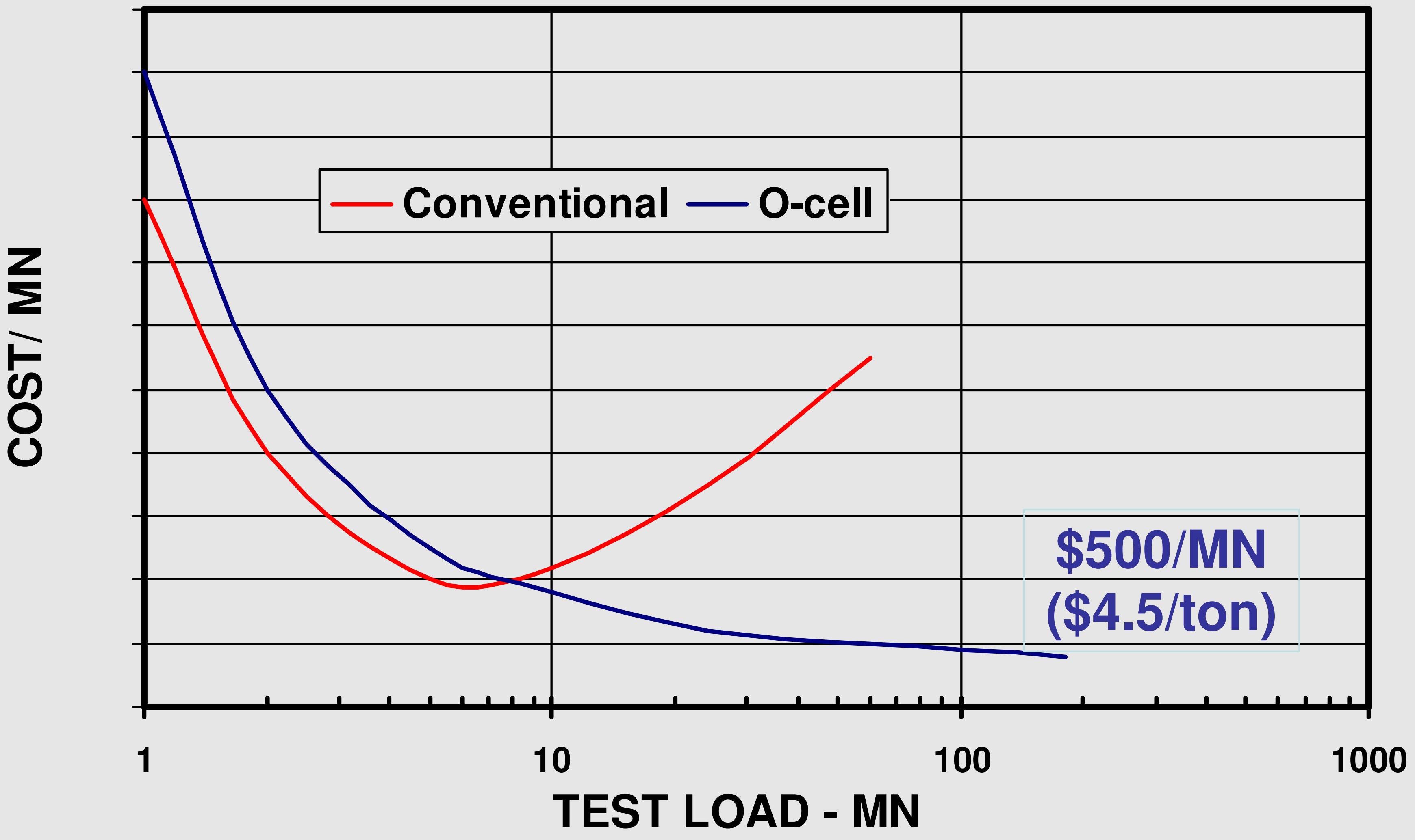


O-cell Static Load Test Advantages

- Test drilled shafts (wet/dry), CFA piles, driven concrete or steel piles, barrettes
- Separates side shear & end bearing
- Very high load capability

  (321MN / 36,000 tons, St. Louis, 2010)
- Direct loading of rock socket
- Cost, safety, and space advantages
- No additional reaction system needed
- Doubles effective jack load
- Post-test grouting for production piles

COMPARISON OF LOAD TESTING COSTS
CONVENTIONAL VS. O-CELL

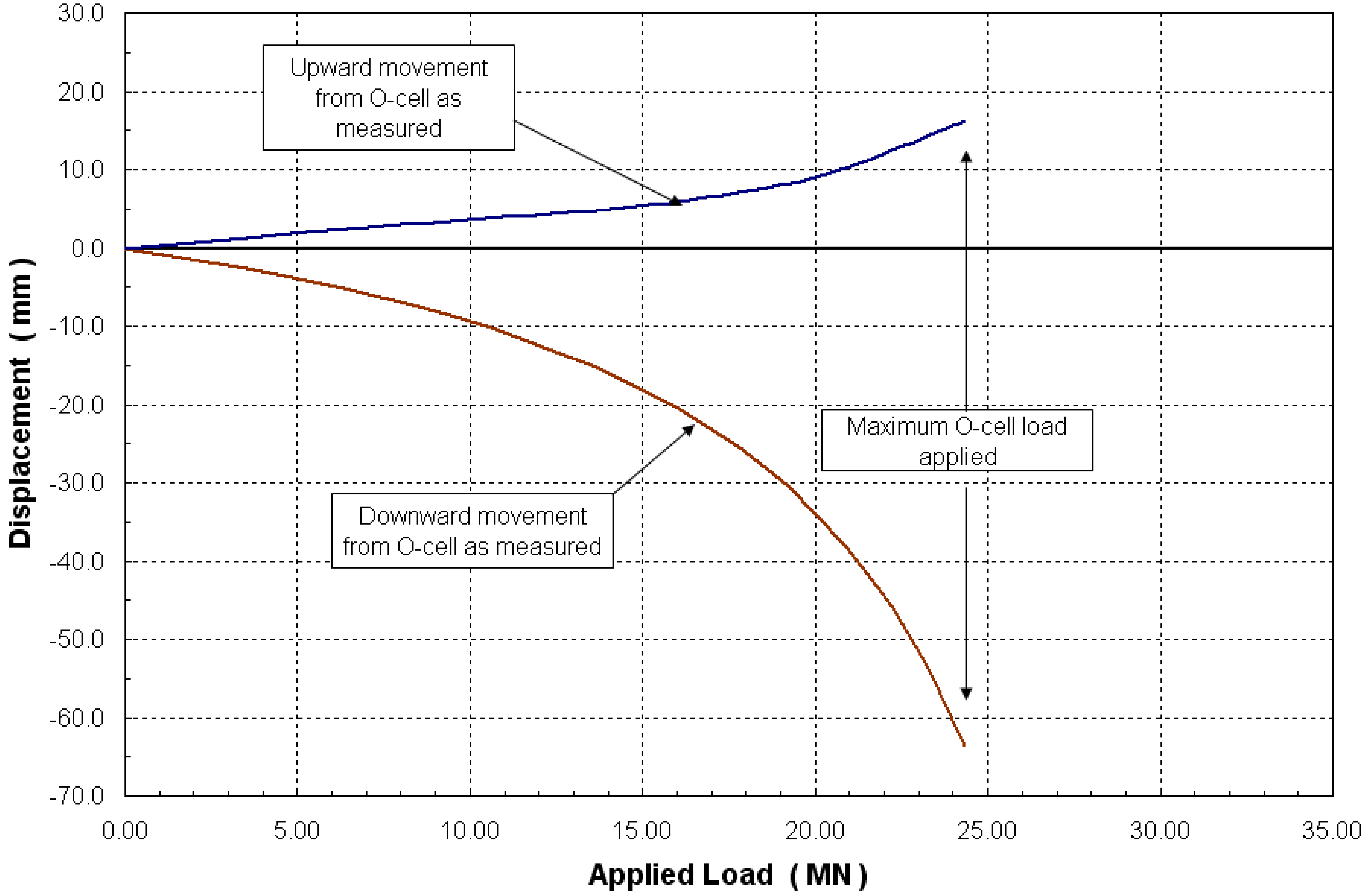


$500/MN
($4.5/ton)

O-cell Test Limitations

- Shaft preselected
- Maximum load limited by weaker of end bearing or side shear (use multi-level)
- Top of pile not structurally tested
- Must construct equivalent top load movement curve
  - use the sum of measured behavior
  - use the sum of modeled behavior
  - use from finite element, t-z approach

Typical O-cell Test Result

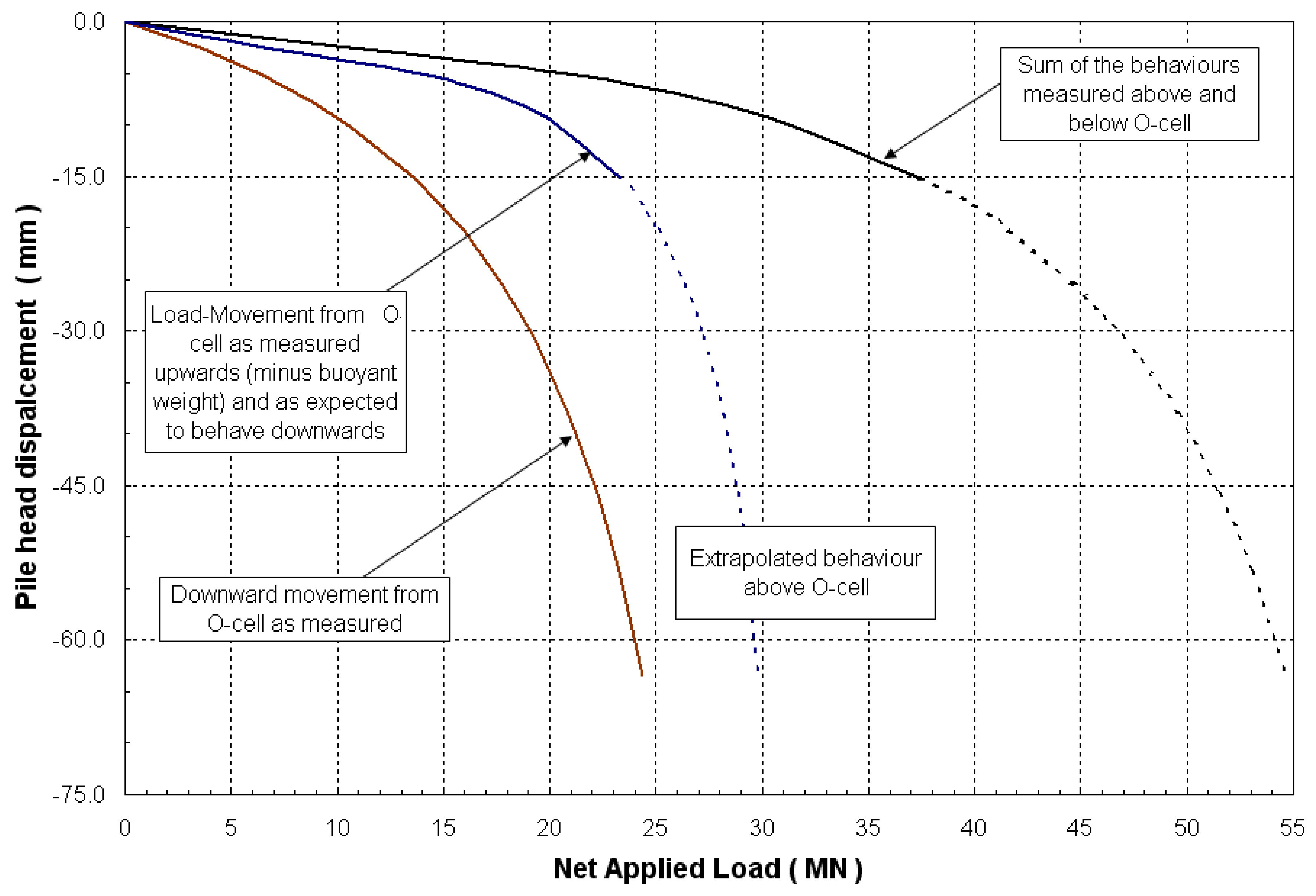


Upward movement from O-cell as measured

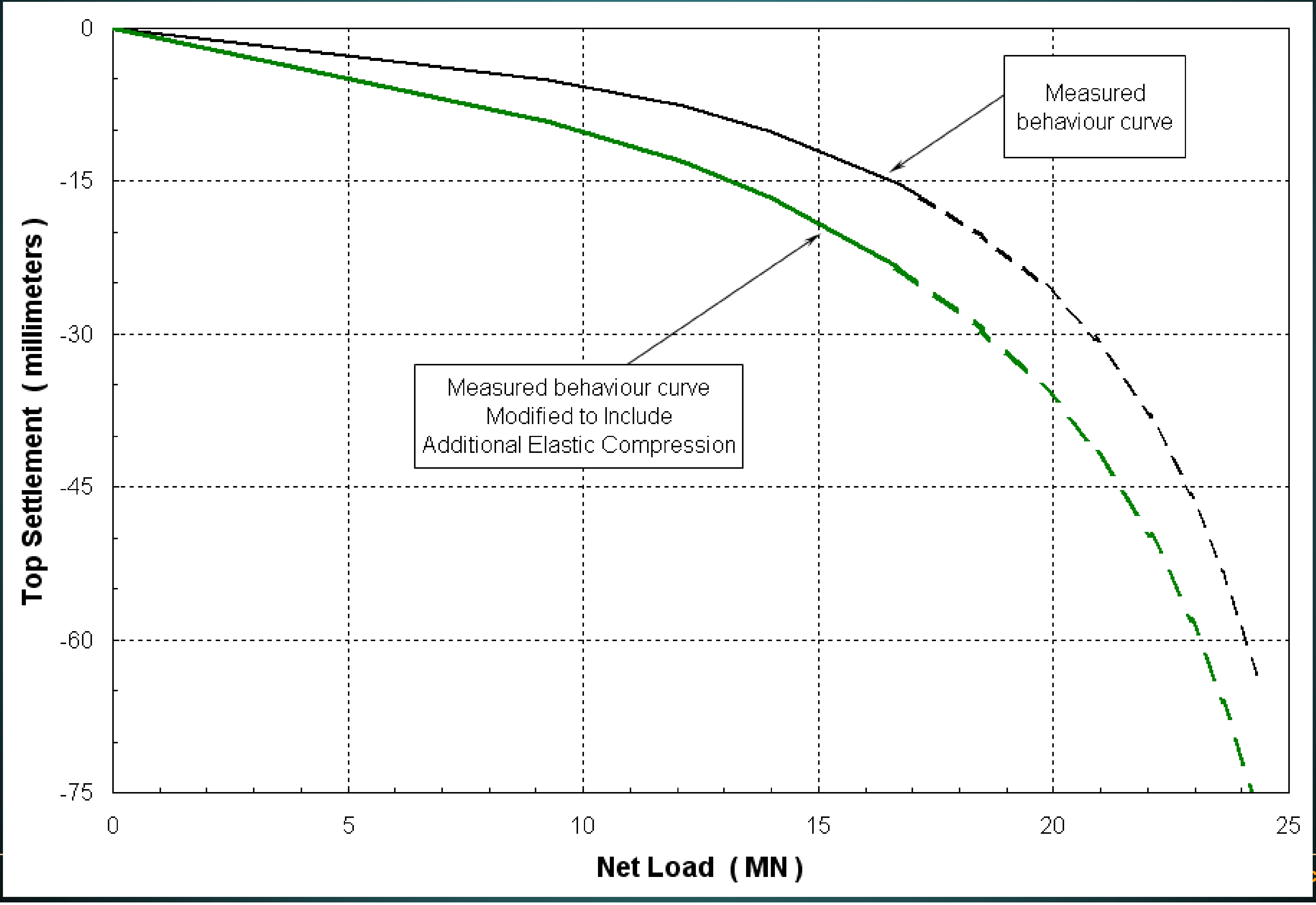
Downward movement from O-cell as measured

Maximum O-cell load applied

Equivalent Top-Load Curve



Equiv. Top-Load + Elastic Shortening



Measured behaviour curve

Measured behaviour curve
Modified to Include
Additional Elastic Compression

High Strain Dynamic Testing

Measure pile force & velocity

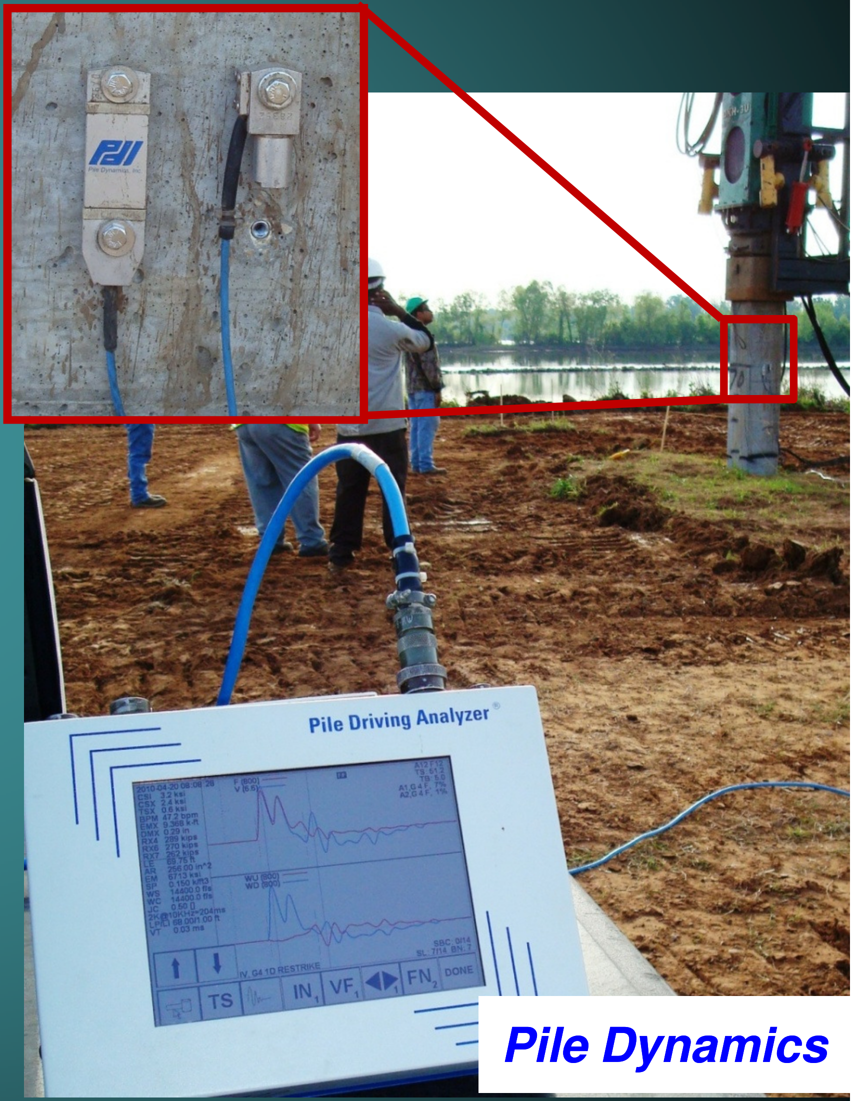
Pile Driving Analyzer® PAX

Driven or Cast-in-Place piles

ASTM D4945

For each hammer blow:

- Pile stresses
- Pile integrity
- Hammer performance
- Capacity mobilized at time of test



Pile Dynamics

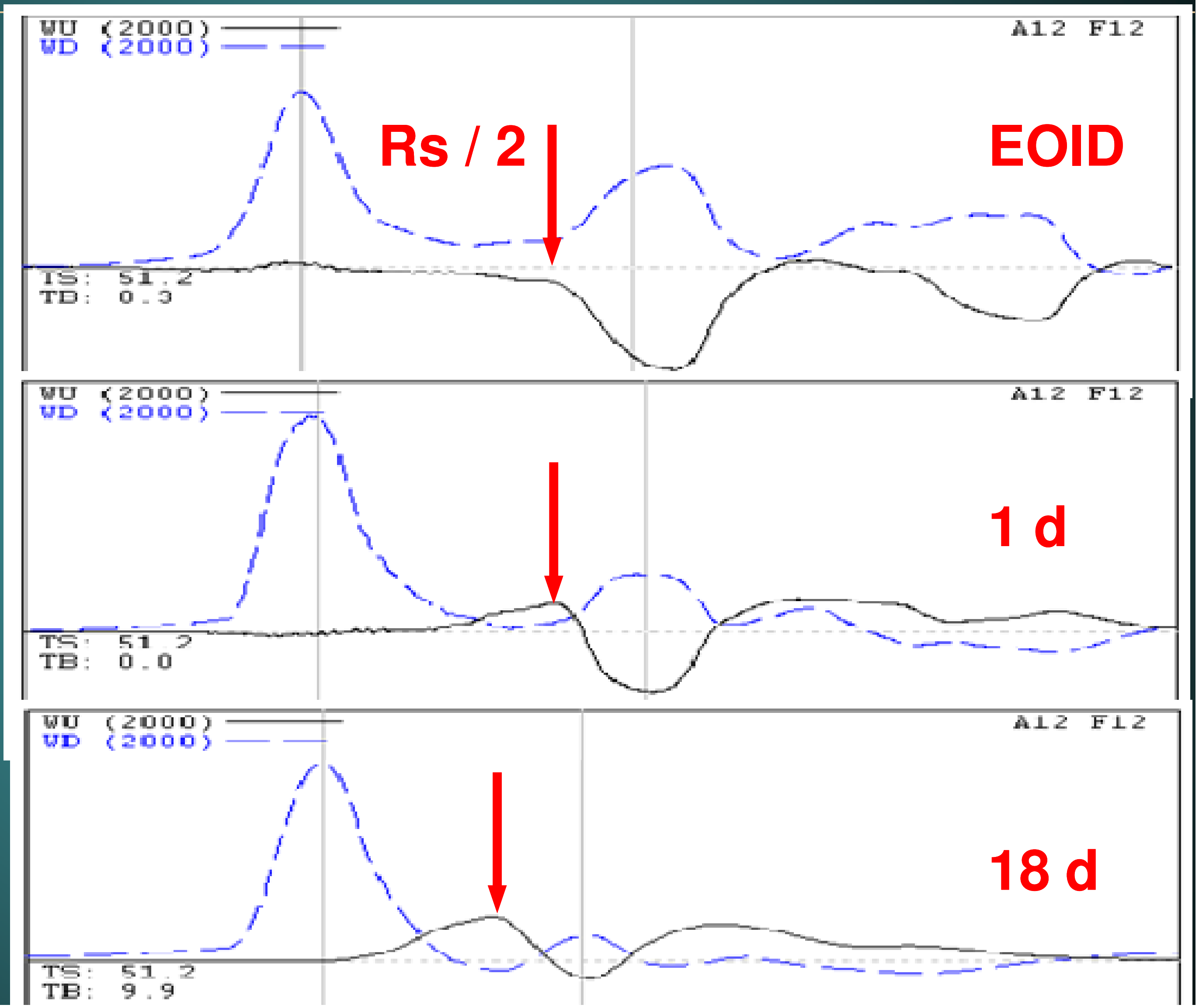
Use PDA to Measure Driven Pile Setup

SETUP is a continuing increase in side shear due to changes in pore pressure & lateral stresses, and aging effects

All soil types

RELAXATION?

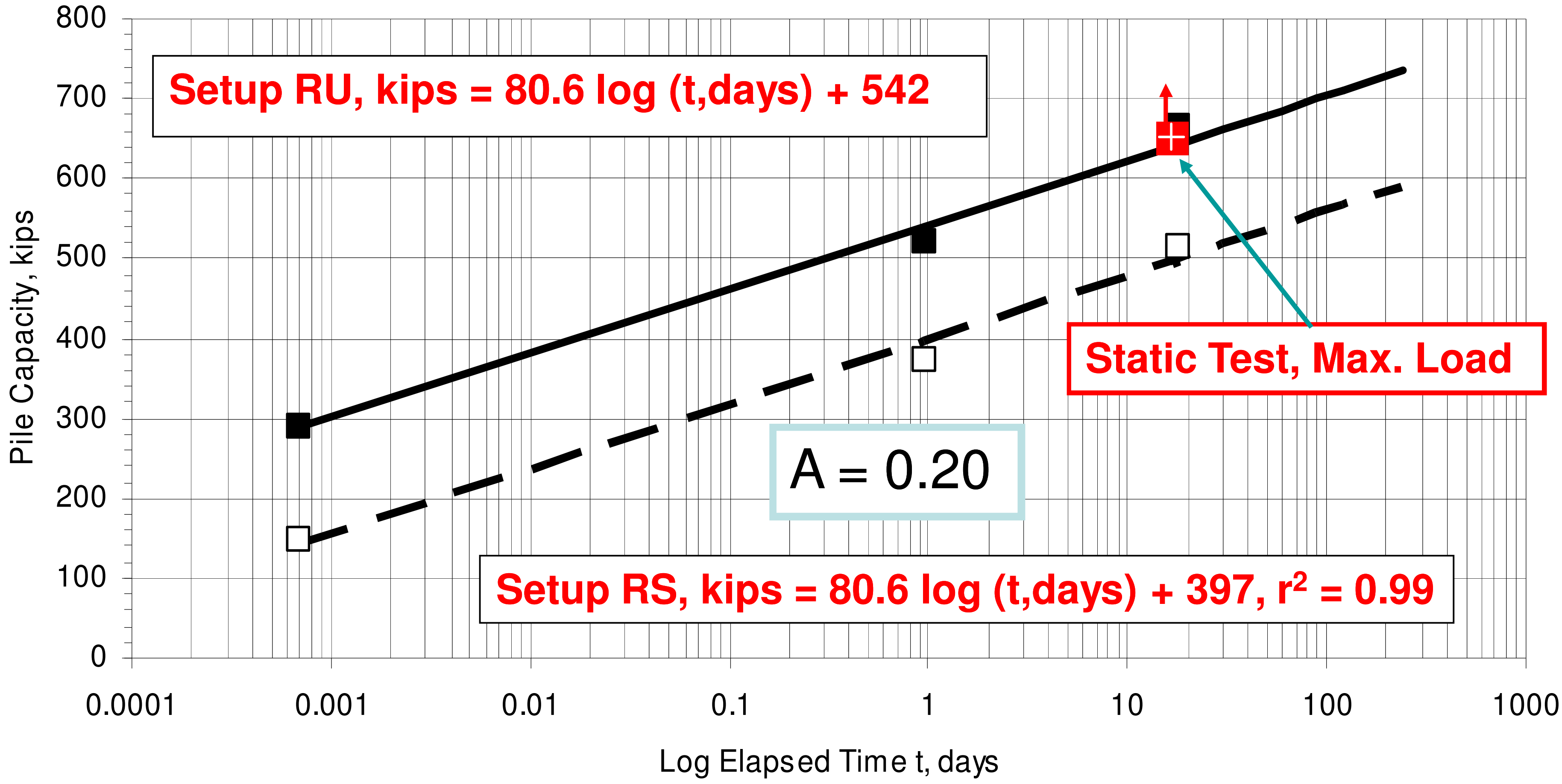
Verify with Restrikes



Baton Rouge, LA, 2008, 610mm Concrete Pile

Baton Rouge Throughway Setup

LA, 2008, 24” Concrete Pile L = 108 ft



Setup RU, kips = 80.6 log (t,days) + 542

Static Test, Max. Load

A = 0.20

Setup RS, kips = 80.6 log (t,days) + 397, r^2 = 0.99

Crosstown Expressway, HOV, Tampa, FL

3.2 mi, 204 Single-Shaft Piers, 6 ft Dia, 2500 ton Load, 11 ft "Settlement" (2004)

Crosstown Expressway Shafts, Tampa, FL

- 12 Piers Tested
- APE-750U hydraulic hammer, 60 ton ram, 6 ft drop
- "Mother of All Pile Hammers"
- 2 PDA systems used to monitor stress in pier and shaft capacity (4 strains and 4 accel. each)
- $300 mil Project
- Remediation fix for ¾ of piers added ~$100 mil
- Prevented by more testing & investigation?

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  - reduce length, size, number
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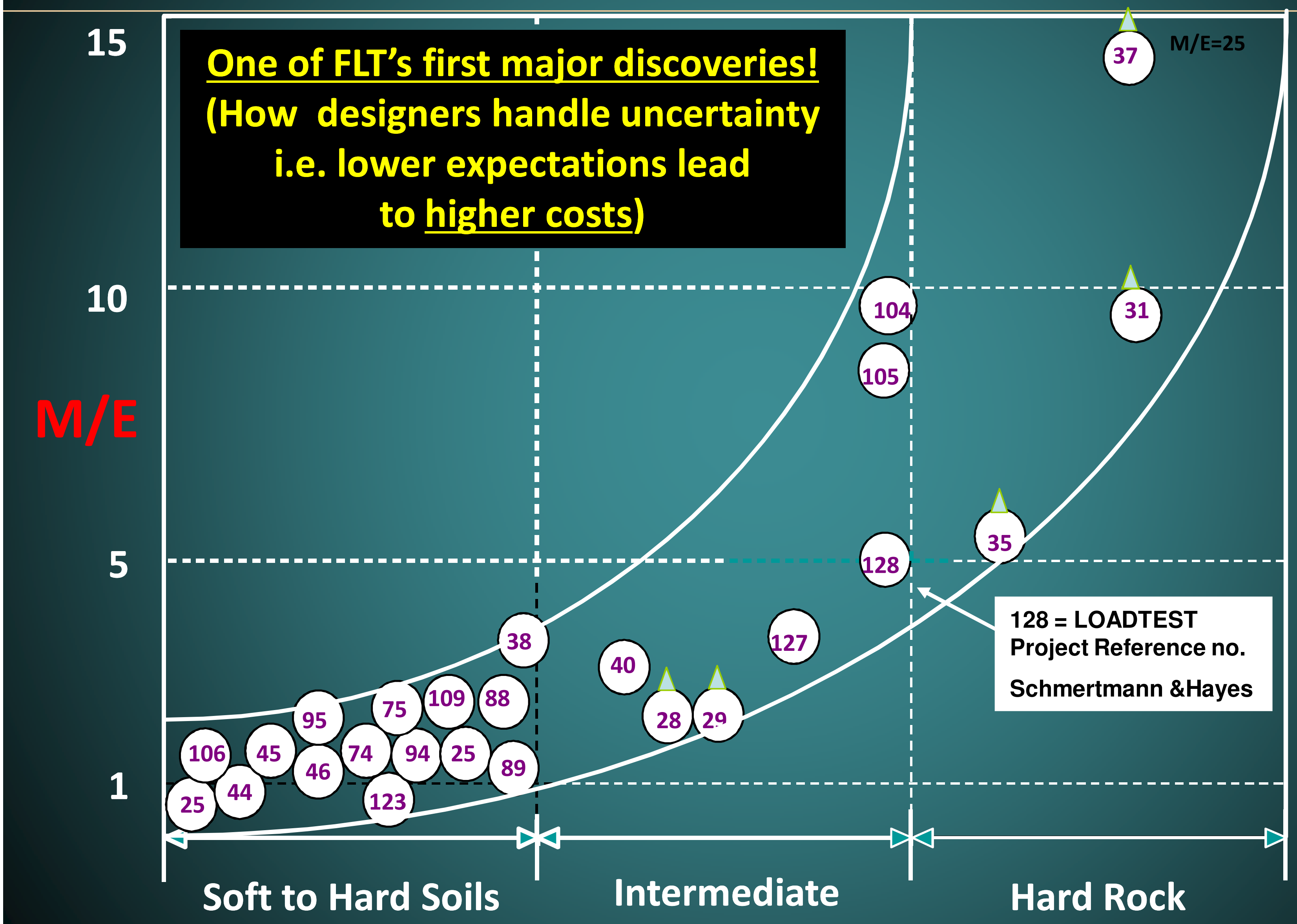
  - FLT's experience - savings >5X test cost
- Quality control testing to reduce cost of post-construction remediation

Skyway Bridge, Tampa, FL (1984)

- 4000 ft post-tension span w/ 3+ miles trestle
- Main piers 44 shafts each 5' dia x 100', 1000 ton design load
- $3 mil Site Investigation + Static & Dynamic Tests
- 10,000 ft SPT, 1000 ft CPT, 1000 ft DMT, 36 BST, 43 PMT, lab tests
- Two 1000 ton Test Frames
- Shaft Inspection Device to use end bearing saved 25ft per shaft ~$500 k

Ratio of Measured / Estimated Capacity

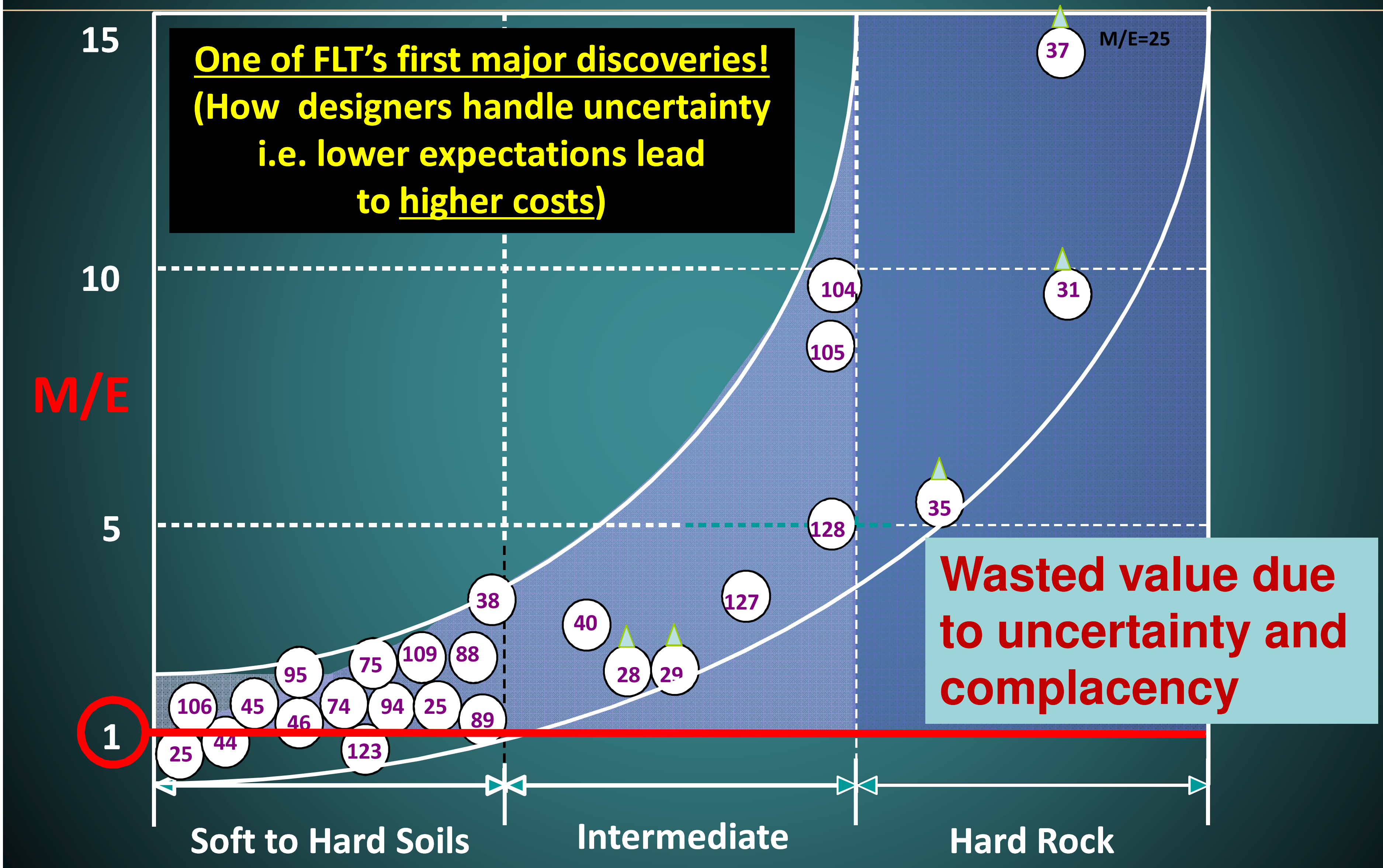


One of FLT's first major discoveries!
(How designers handle uncertainty
i.e. lower expectations lead
to higher costs)

128 = LOADTEST
Project Reference no.

Schmertmann &Hayes

Ratio of Measured / Estimated Capacity



One of FLT's first major discoveries!
(How designers handle uncertainty
i.e. lower expectations lead
to higher costs)

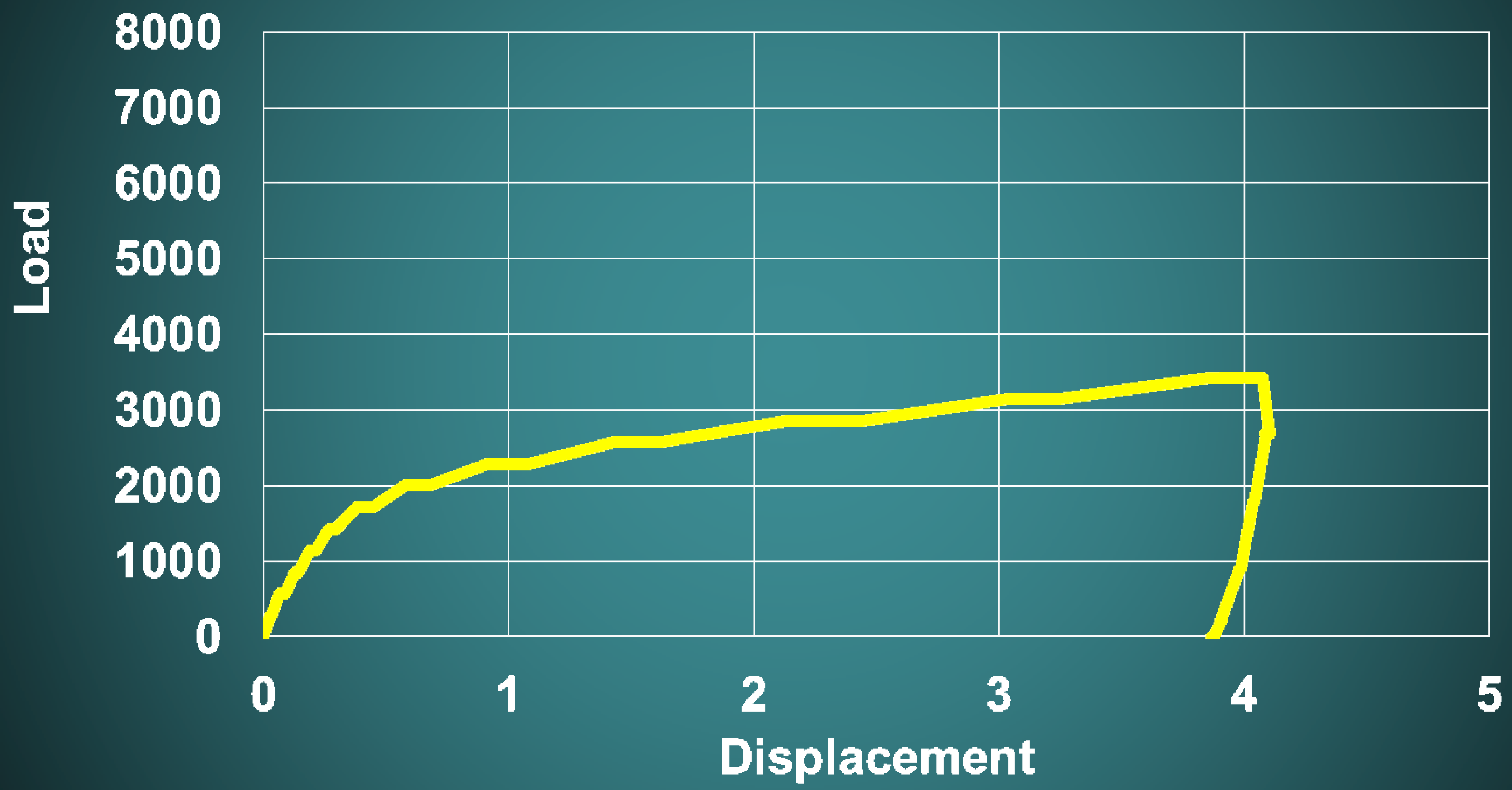
Wasted value due to uncertainty and complacency

LRFD Example

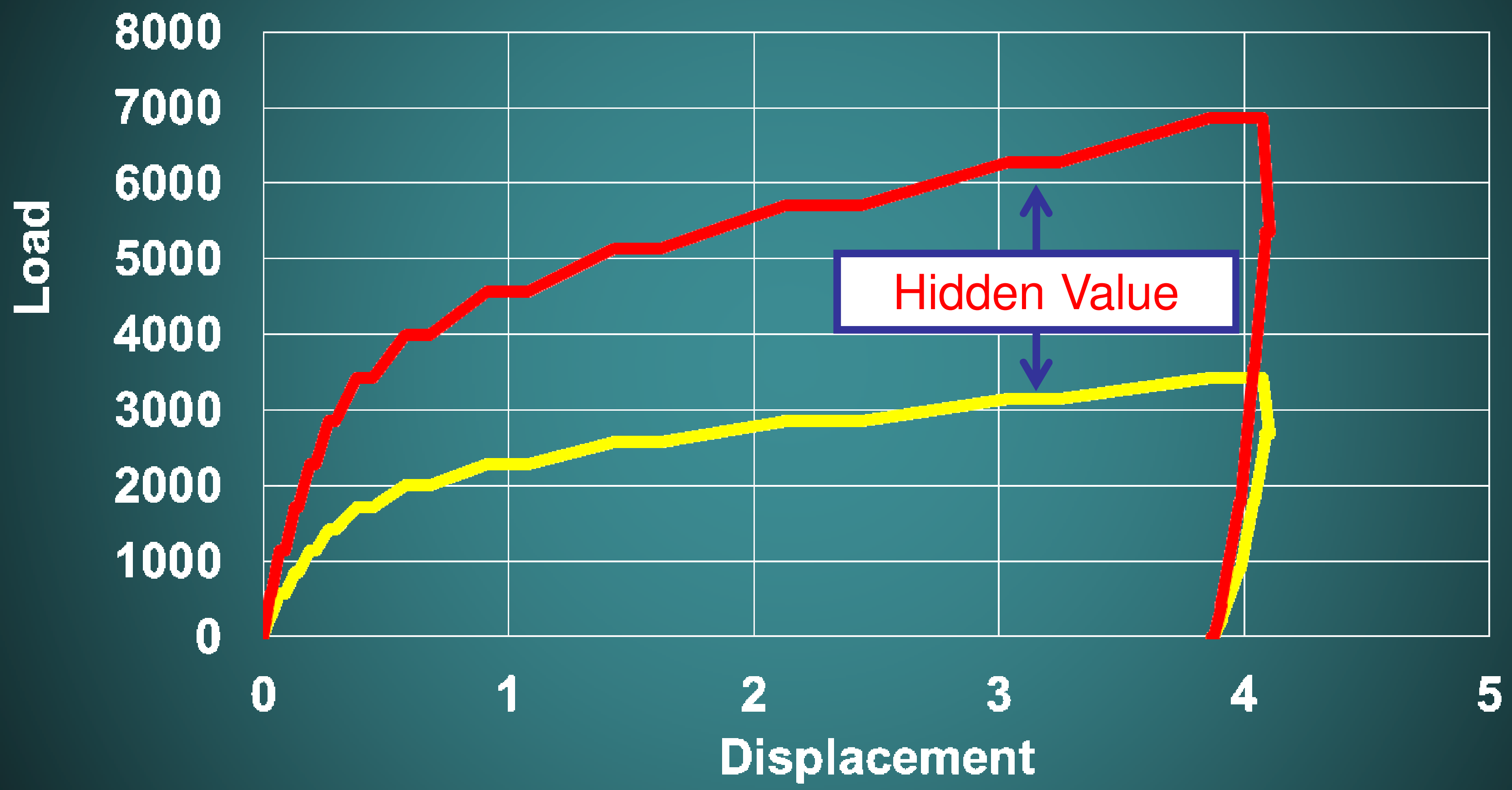
- Simple Non-redundant Foundation Design (uniform site)
- N = 100 shafts
- Length = 100 feet deep, $R = \varphi R_N$
- Unit Cost = $400 / ft
- Cost of Foundation $4,000,000
- Cost of Engineering and Site Investigation $40,000
- Total Cost = $4,040,000 (w/o load test program)
- Cost of Proposed Load Test Program $200,000
- $\varphi = 0.45$ before load test, $\varphi = 0.60$ after load test
- After load test, R increases 33% ($\varphi = 0.45 \rightarrow 0.60$)
- After load test, Length and Total Cost decrease by 25%

But we have ignored the value of the load test result …

Theoretical Capacity (design)



Measured Capacity (R_N ↑)



LRFD Example

- Simple Non-redundant Foundation Design (uniform site)
- N = 100 shafts
- Length = 100 feet deep, $R = \varphi R_N$
- Unit Cost = $400 / ft
- Foundation Cost $4,000,000
- Cost of Engineering and Site Investigation $40,000
- Total Cost = $4,040,000 (w/o load test program)
- Cost of Proposed Load Test Program $200,000
- $\varphi = 0.45$ before load test, $\varphi = 0.60$ after load test
- After load test, R_N increases 100% & R increases 33%
- Net effect - R increases by 2 x 1.33 = 2.66
- After load test, Length and Total Cost decrease by 62.5%
- Foundation Cost = ($400/ft)(37.5 ft)(100 shafts) = $1,500,00
- Total Cost = $1,500,000 + 200,000 + 40,000 = $1,740,000
- Net Savings $2,300,000

“Costs” of Testing

Foundation System 1

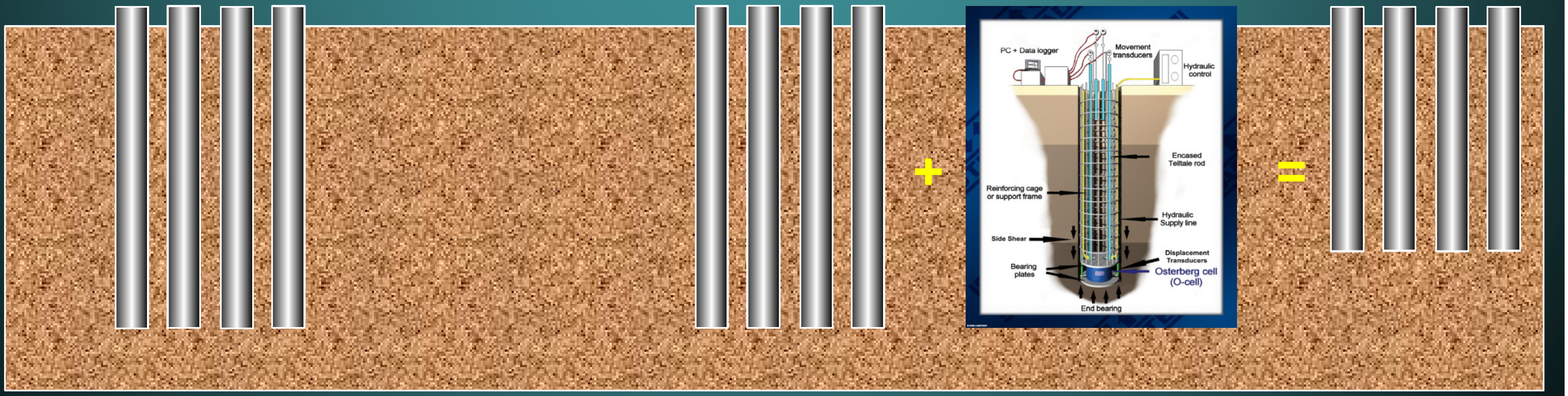
Includes Basic Engineering and Site Investigation

LRFD, φ = 0.45
Theoretical Ultimate Cost = $4,040,000

Foundation System 2

Includes Basic Engineering, Site Investigation, and O-cell Testing

LRFD, φ = 0.60
Actual Ultimate Cost = $1,740,000
(save $2,300,000)



Cost Savings: Seacaucus NJ Transfer Sta.

Initial Design

- 9 m Rock Sockets (“typical”)
- Design side shear: 1.3 MPa (code)

O-cell Tests

- 2 Shafts with 1.5 m rock sockets
- Measured side shear: 2.7 MPa

Estimated vs. Actual Costs

- Final design: 4.5 m rock sockets
- Design FS = 3, Measured FS > 5
- Redesign FS > 2

Fdn. Cost Est.:	$18,000,000
Testing cost:	$ 255,000
Fdn. redesign cost:	$ 8,900,000
Net Savings:	$ 8,845,000

O-cell Cost Savings

Foundation Savings After Testing Based On Actual Jobs Completed (Thousands)

Job Number	566	775	835	381	056*	335	426	635
State	CA	FL	NC	NJ	SC	GA	TX	FL
Fdn. Estimate	$850	$6,200	$32,500	$18,000	$160,000	$3,270	$8,500	$4,520
Fdn. Redesign	$610	$4,980	$24,500	$8,900	$125,000	$3,003	$8,500	$7,232
Savings	$240	$1,220	$8,000	$9,100	$35,000	$273	$0	-$2,712
Test Cost	$79	$360	$2,000	$255	$7,500	$240	$95	$305
Net Savings	$161	$855	$6,000	$8,845	$27,500	$33	-$95	-$3,017
Calculated FS	2.5	3.0	3.0	3.0	3.0	3.0	3.0	2.5
Measured FS	3.0	3.5	4.0	5.0	NA	3.5	9.5	0.8
Redesign FS	2.0	2.0	2.0	2.0	2.0	2.3	9.5	2.0

- More than 70% of the FLT testing saved the client money
- Half of the remaining 30%, testing done too late to realize the savings
- Only a few estimates were so close not to allow a modified foundation

Reduce Cost by Reducing Uncertainty:

- Informed design (integrated investigation: geophysics + insitu testing + sampling)
- Design verification (testing)
- Optimization (redesign)
  - reduce length, size, number
  - change type (driven, drilled, anchor)
  - reduce cost and construction time ($$)
  - FLT's experience - savings 5X test cost
- Quality control testing to assure performance & reduce remediation cost

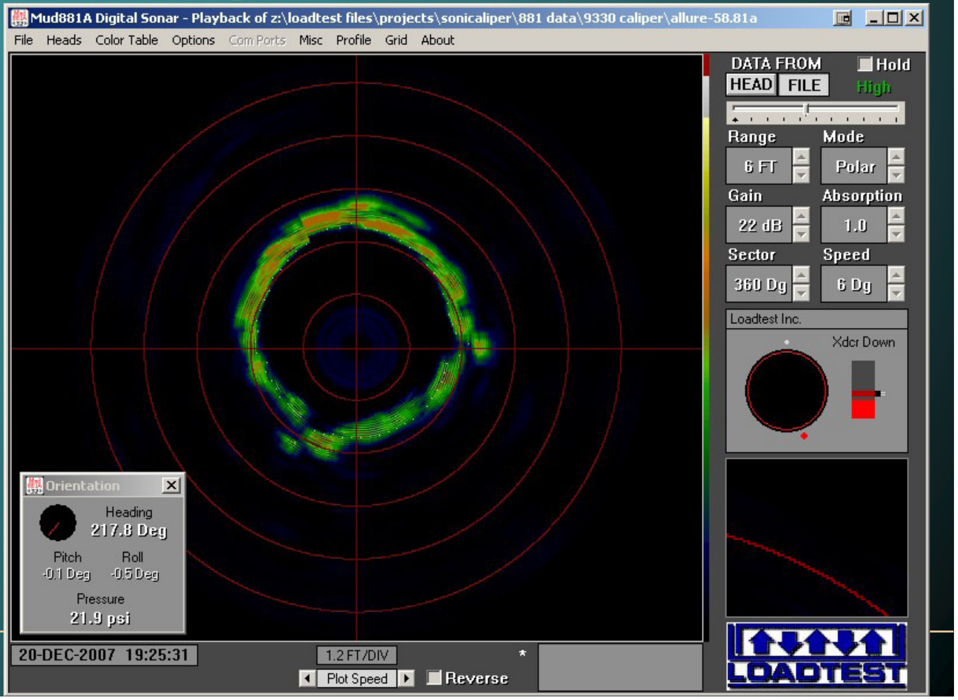
Deep Foundation Quality Control

- Driven Piles
  - Blow Count, Hammer Energy
- Drilled Shafts
  - Control Slurry Properties
  - Prepare Excavation Log
  - Shaft Profile - Sonic Caliper
  - Clean Shaft Bottom
    - MiniSID, Downhole Camera
  - Concrete Quality - Pile Integrity Test, Crosshole Sonic Logging, Thermal, Gamma

Shaft Profile - SONICALIPER

Shaft Profile - SONICALIPER

Uses sound reflection
360° profile of shaft walls
Checks hole verticality and drift
Real-time results
6 mm Accuracy, 3-D modeling
Portable and compact
Minimal impact to schedule


Mud881A Digital Sonar - Playback of z:\loadtest files\projects\sonicaliper\881 data\9330 caliper\allure-58.81a

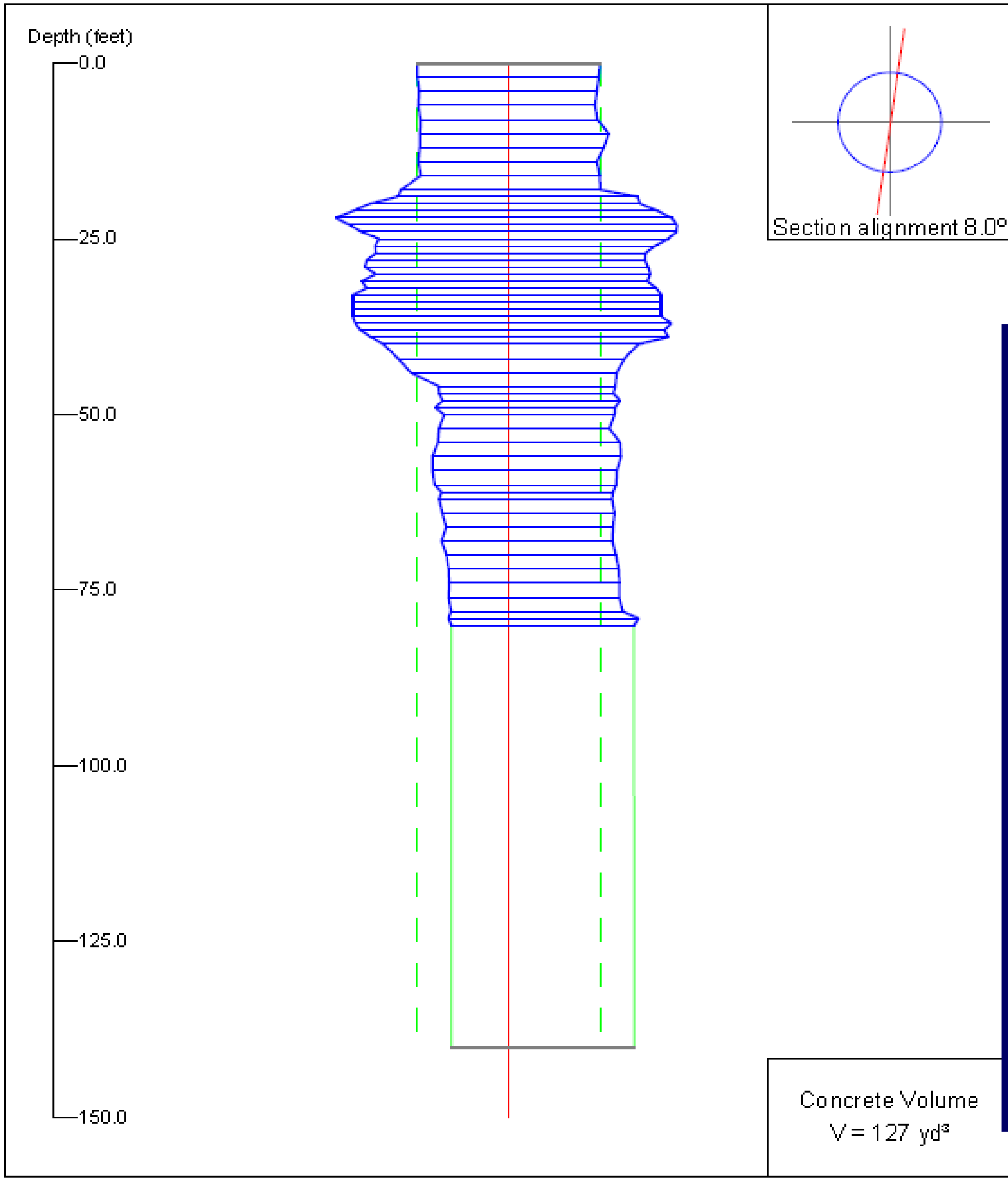
DATA FROM HEAD FILE ☐ Hold High
Range 6 FT
Mode Polar
Gain 22 dB
Absorption 1.0
Sector 360 Dg
Speed 6 Dg
Loadtest Inc.
Xdcr Down

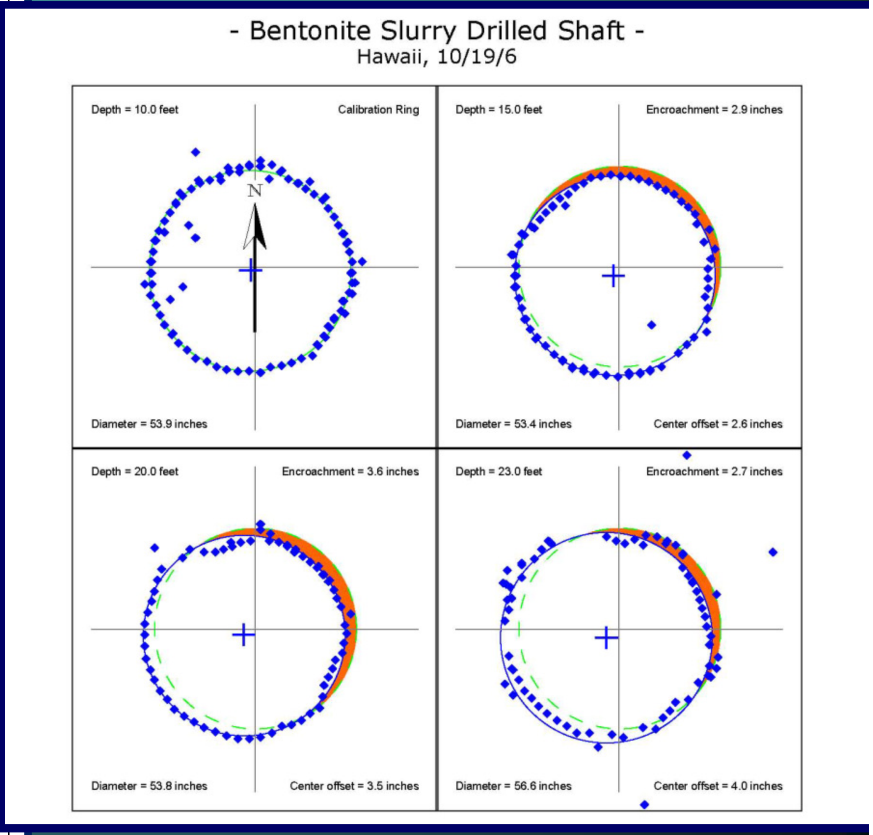
Orientation
Heading 217.8 Deg
Pitch -0.1 Deg
Roll -0.5 Deg
Pressure 21.9 psi

20-DEC-2007 19:25:31
1.2 FT/DIV

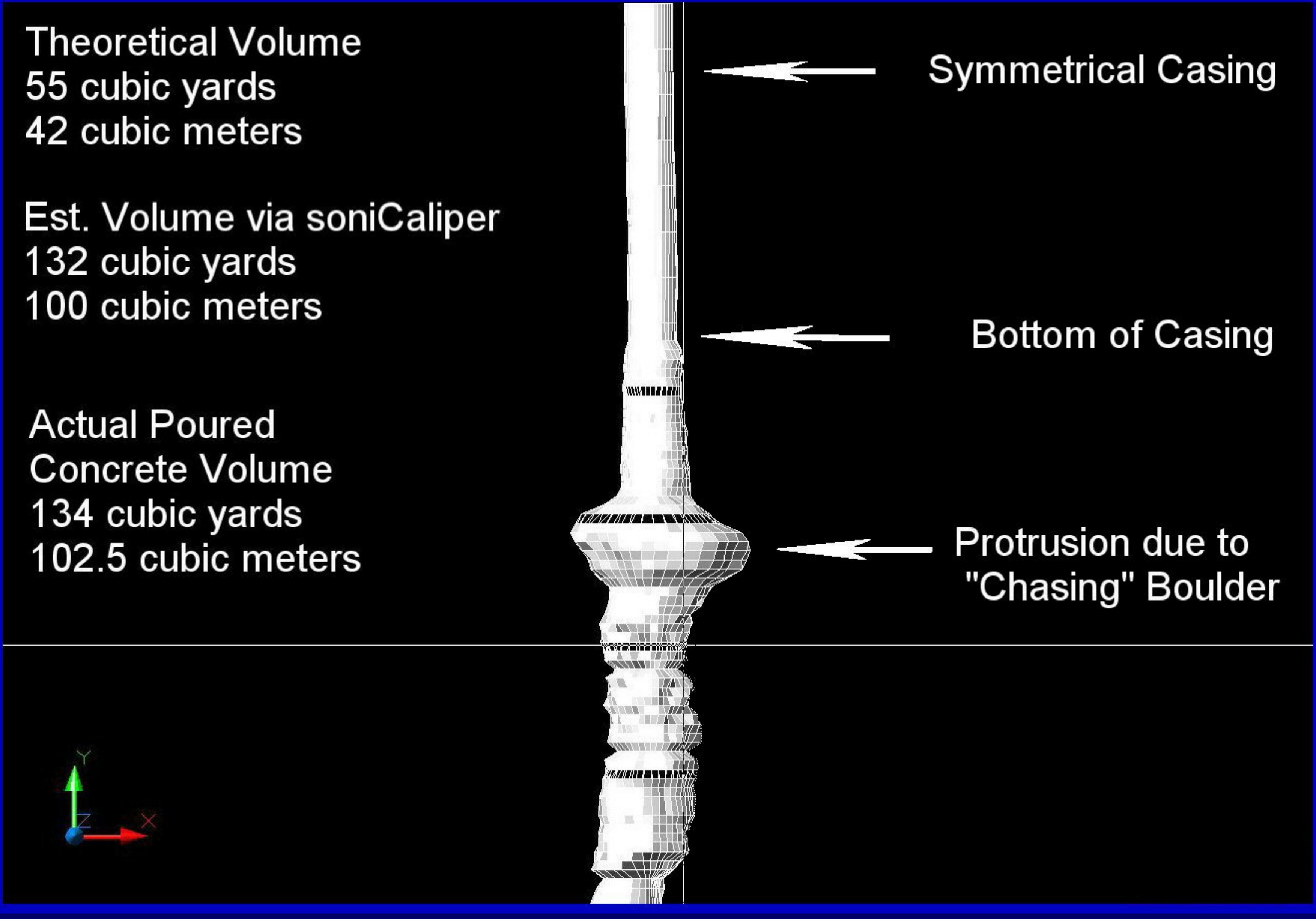
Shaft Profile Report - SONICALIPER

- Verticality
- Cage Encroachment
- Calculate Concrete Volume





Shaft Volume - SONICALIPER



Theoretical Volume
55 cubic yards
42 cubic meters

Est. Volume via soniCaliper
132 cubic yards
100 cubic meters

Actual Poured
Concrete Volume
134 cubic yards
102.5 cubic meters

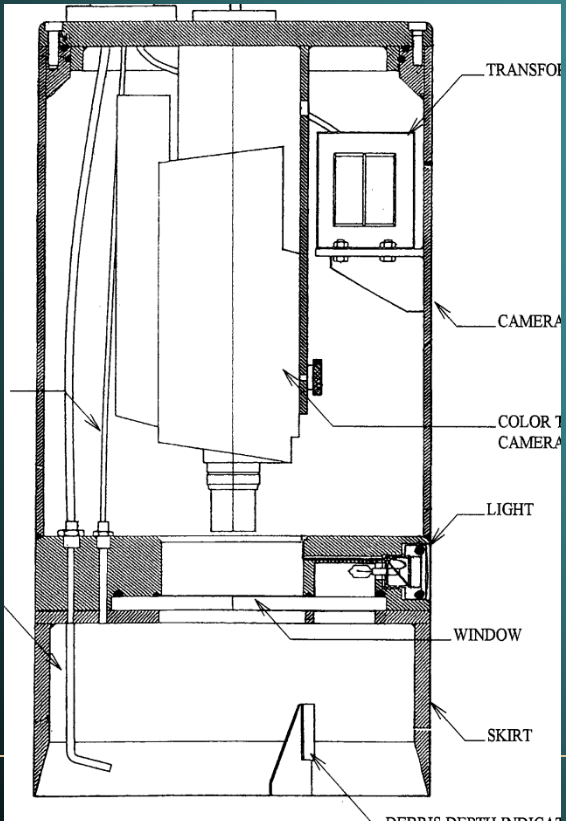
Symmetrical Casing

Bottom of Casing

Protrusion due to
"Chasing" Boulder

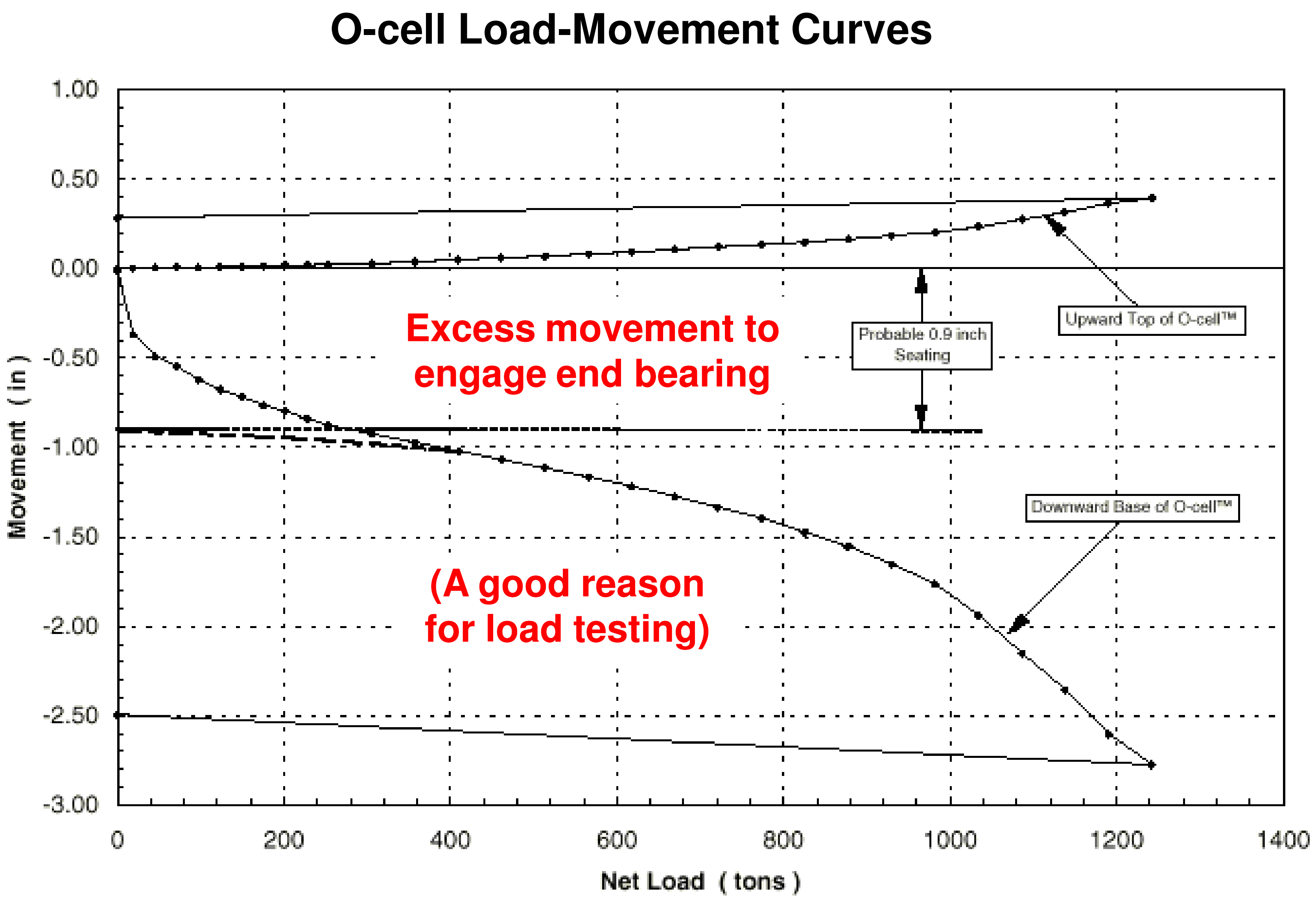
Shaft Inspection Device, Mini-SID (wet shafts)

- Inspect bottom to check sediments
- Air chamber with video camera



Dirty bottom, Orlando, FL

Soft shaft bottom



Excess movement to engage end bearing

(A good reason for load testing)

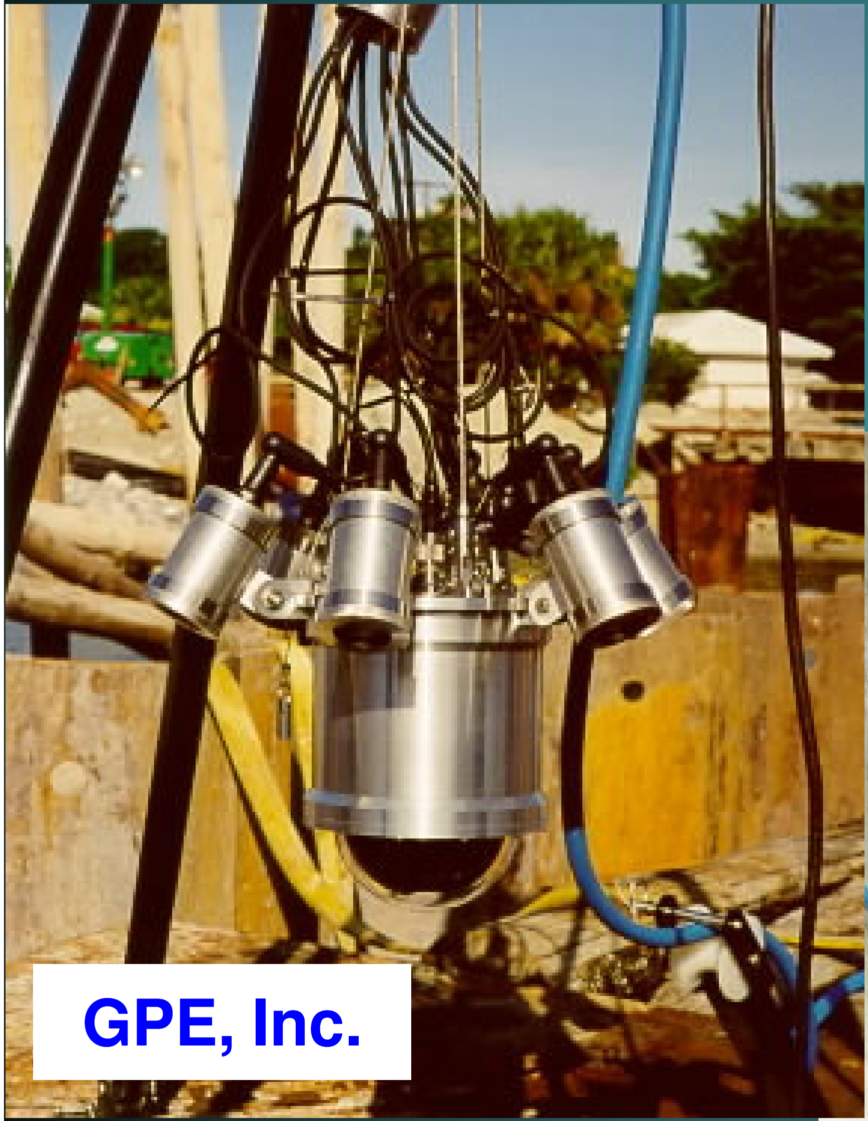
Mini-SID Video Inspection

Clean (corehole)

Dirty, Clay Lumps

Includes Water Jets & Debris Depth Indicator

Downhole Camera (dry shaft inspection)



Camera rotates and gimbles 180º

Conclusions

- Deep foundation design generally conservative due to <u>uncertainty</u>
- <u>Reduce project cost through a more efficient design that reduces uncertainty</u>
- Use a portion of the cost savings to fund the testing needed for more efficient design

"The owner pays for a good site investigation whether he does one or not."

Thank You

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