Instrumented Becker Penetration Test for Liquefaction Assessment in Gravelly Soils

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Outline

- Motivation
  - Gravel and infrastructure
  - Existing site investigation tools
  - Becker Penetration Testing
- Instrumented BPT System
  - Concept
  - Equipment
  - Results
- Correlation with SPT
  - Field variability
- Review of Earlier Methods
  - Harder and Seed (1986)
  - Sy and Campanella (1994)
  - Foundex mud-injection Becker
- Application in LADWP System
  - Projects
- Ongoing and Future Work

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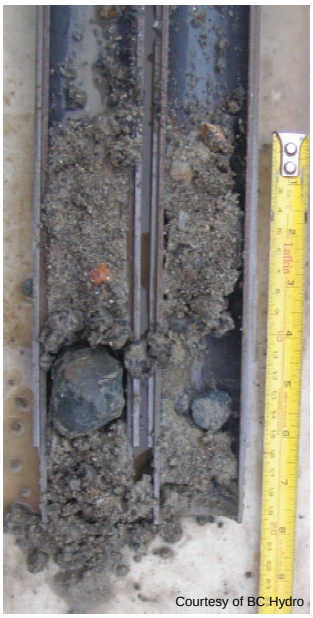
Engineering Infrastructure around Rivers

- Need for water, hydro-electricity, and transportation brings us close to rivers
- River deposits often contain gravel
- Characterisation of gravelly soils has remained a challenge
- Liquefaction, dam foundations, bridge pier and pile design

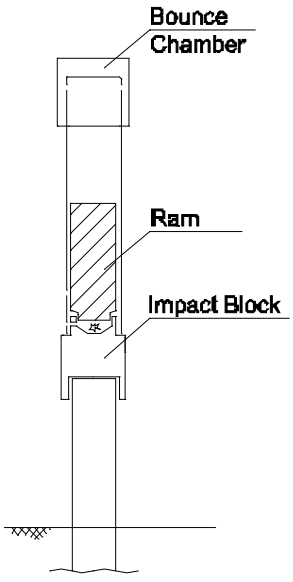
Existing Site Investigation Tools

Characterisation of Gravelly Soils

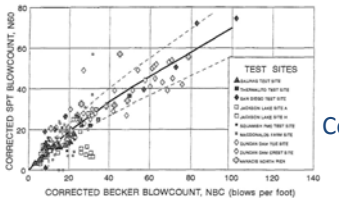


Characterisation of Gravelly Soils

Becker Penetration Test



Interpretation of the Becker Penetration Test



Harder, 1997

Blow counts per foot → N_B

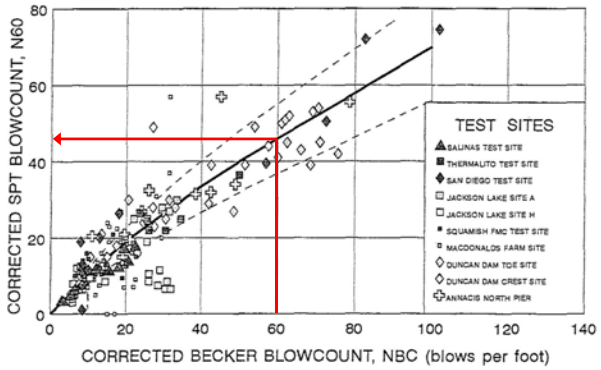
Account for effect of hammer energy → N_{BC} , N_{B30}

Account for shaft resistance

Correlate to more common penetration resistance → $SPT\ N_{60}$

Harder and Seed (1986)

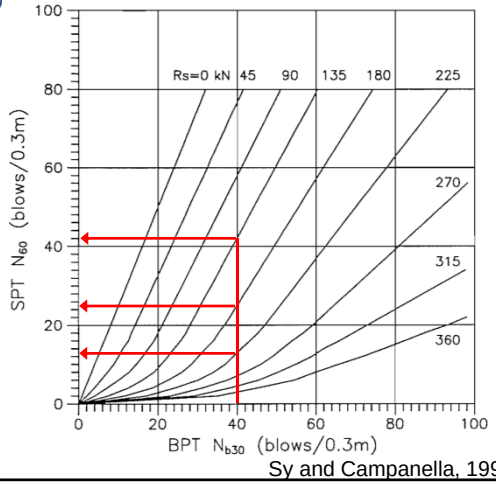
- Manual counting and measurement of Bounce Chamber Pressure (BCP)
- Measured blow counts (N_B) correction based on BCP to a reference line for "constant combustion condition", providing N_{BC}
- N_{BC} values conversion to equivalent N_{60} values using empirical correlation



Harder, 1997

Sy and Campanella (1994)

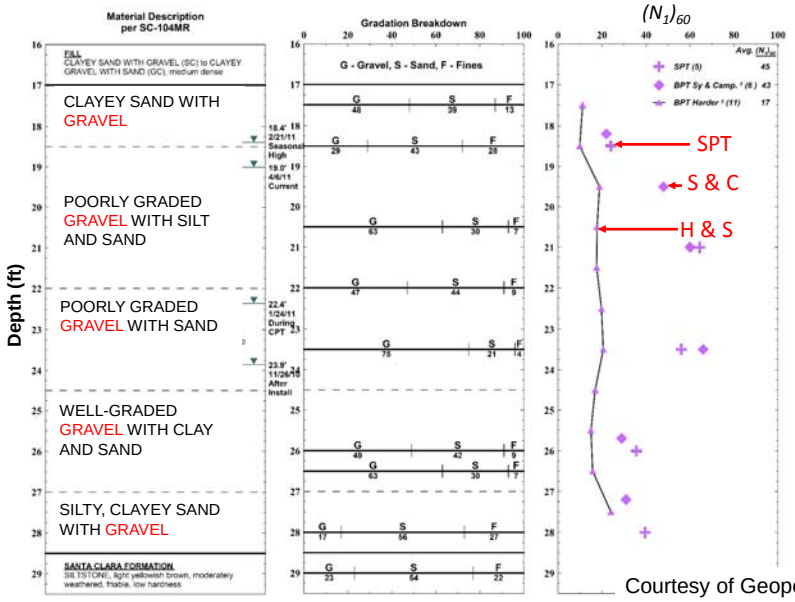
- Energy measurement by instrumenting the Becker pile below hammer
- Blow counts (N_B) correction based on maximum energy delivered by the hammer to "constant hammer energy", providing N_{B30}
- Performing wave-matching (CAPWAP) analysis on representative blows to estimate static shaft resistance (R_S)
- N_{B30} conversion to equivalent N_{60} dependent on R_S



Sy and Campanella, 1994

Current Practice

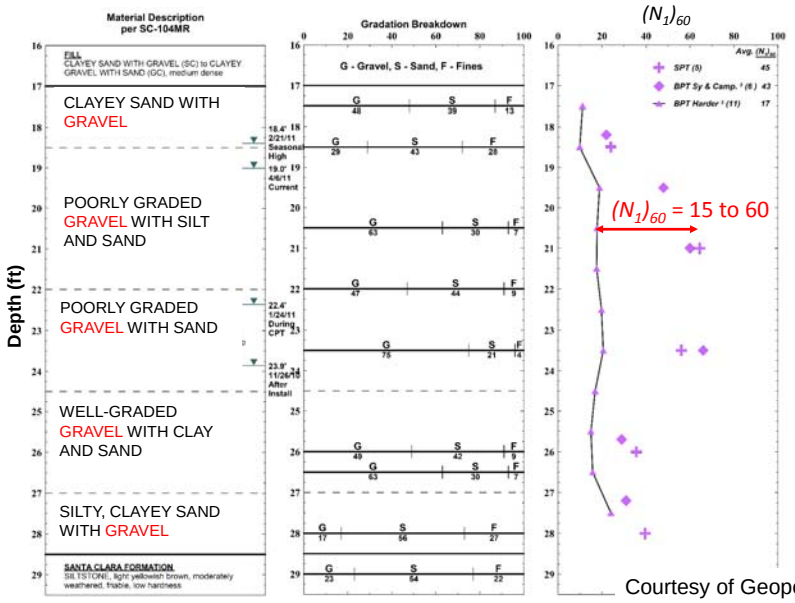
- Comparison of SPT and Becker Results at Stevens Creek Dam



Courtesy of Geopentech

Current Practice

- Comparison of CPT, SPT, and Becker Results at Stevens Creek Dam



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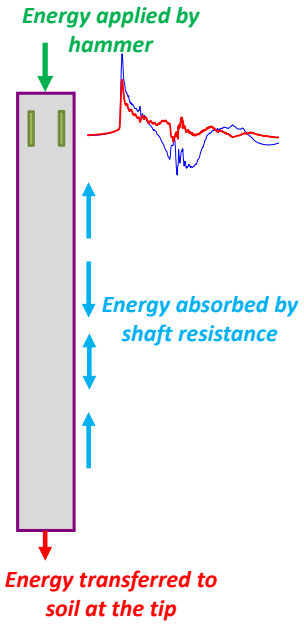
instrumented Becker Penetration Test (iBPT) Concept



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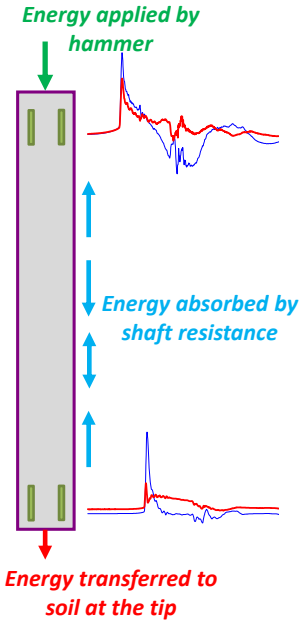

- Energy measurement performed at the tip, in addition to the above ground measurements

$$E\ (\%) = \frac{\int FVdt}{11.0\ kJ}$$

- BPT blow counts normalized based on measured energy delivered to the **tip**

$$N_{B30} = N_B \frac{E\ (\%)}{30}$$

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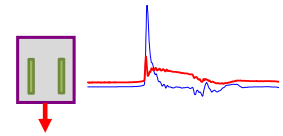
- The effect of shaft resistance is automatically eliminated



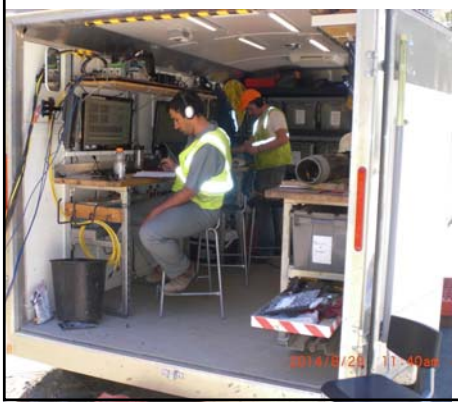
Energy transferred to soil at the tip

iBPT Sections

- 2 ft (60 cm) long instrumented sections
- Sensors and DAQ modules housed inside
  - Four strain gages
  - Two accelerometers
  - Thermistor
- Shock absorption system included to protect electronics in the DAQ

iBPT Control System

- Field control unit
  - Records forces and accelerations above ground
  - Records depth/displacement and BCP
  - Detects impacts and times downhole DAQ module
  - Collects and processes data to produce real-time penetration resistance (N_B , N_{B30} , N_{60})



iBPT Field Process

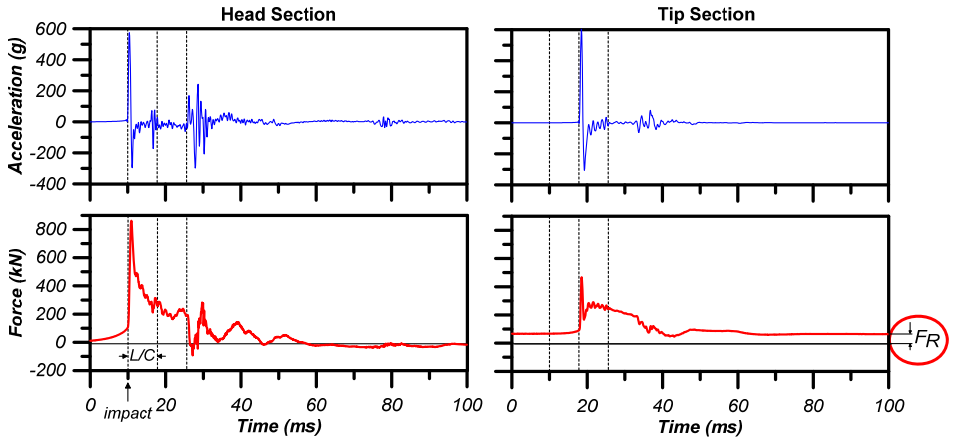
iBPT Field Performance

- The equipment has reached a commercial level performance with replaceable parts and minor maintenance
- No alteration to drilling equipment needed
- Using iBPT slows down normal closed ended Becker operation by ~ 10 %, slightly more than PDA
- More than 100 ft of testing with multiple pull-backs possible per day
- Sounding logs produced daily and full reporting completed in weeks
- Reasonable cost thanks to students!

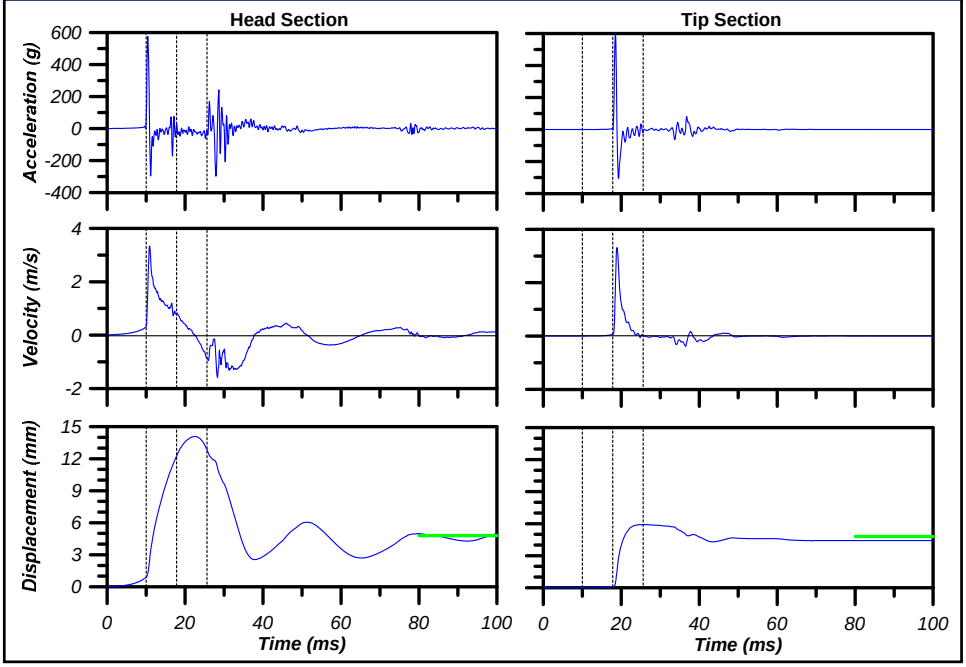


iBPT Data - Measurements

- Measurements of acceleration and force at head and tip
- Baseline correction done on acceleration and force
- Locked-in residual force a unique aspect of measurements at the tip



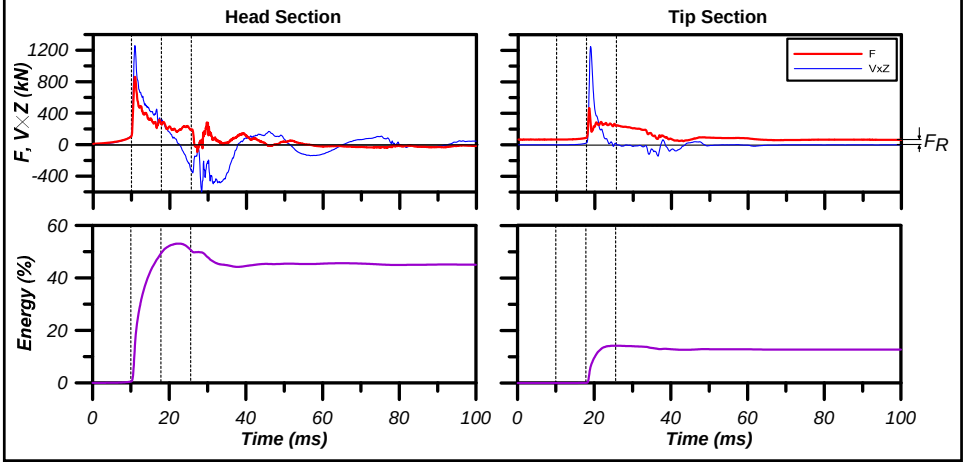
iBPT Data – Acceleration, Velocity, Displacement



iBPT Data - Energy

- Calculation of energy delivered by the hammer, and to the soil
- Energy normalized as percentage of nominal hammer energy (11.0 kJ)

$$dE = FdU = FVdt \rightarrow E = \int FVdt \rightarrow E(\%) = \frac{\int FVdt}{11kJ}$$

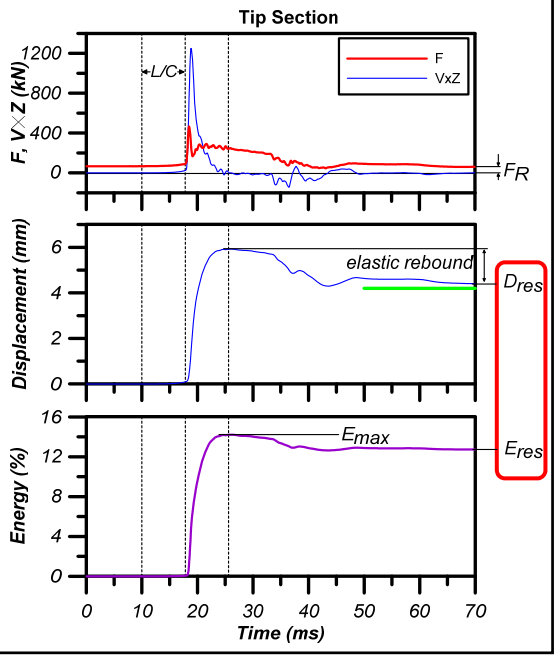


iBPT Data Processing at Tip

- Elastic rebound in the soil
- Blow counts associated with average D_{res} per foot

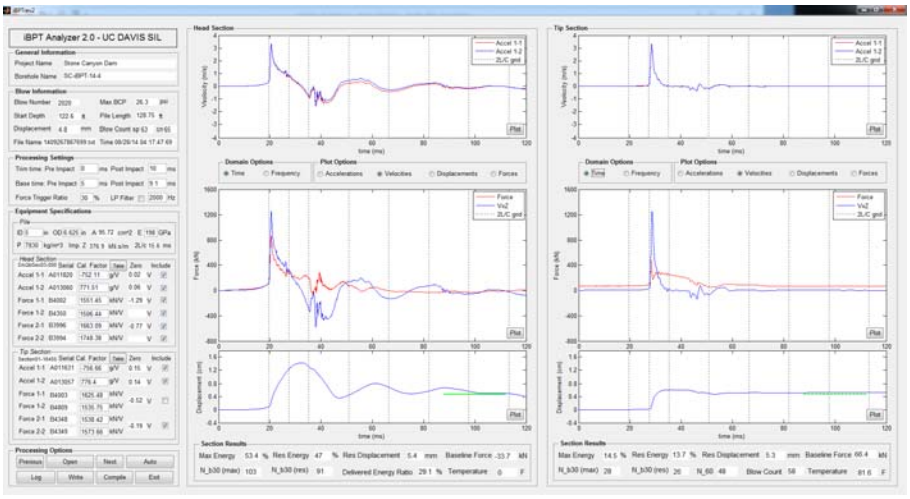
$$N_B = \frac{1\ ft}{D_{res}}$$

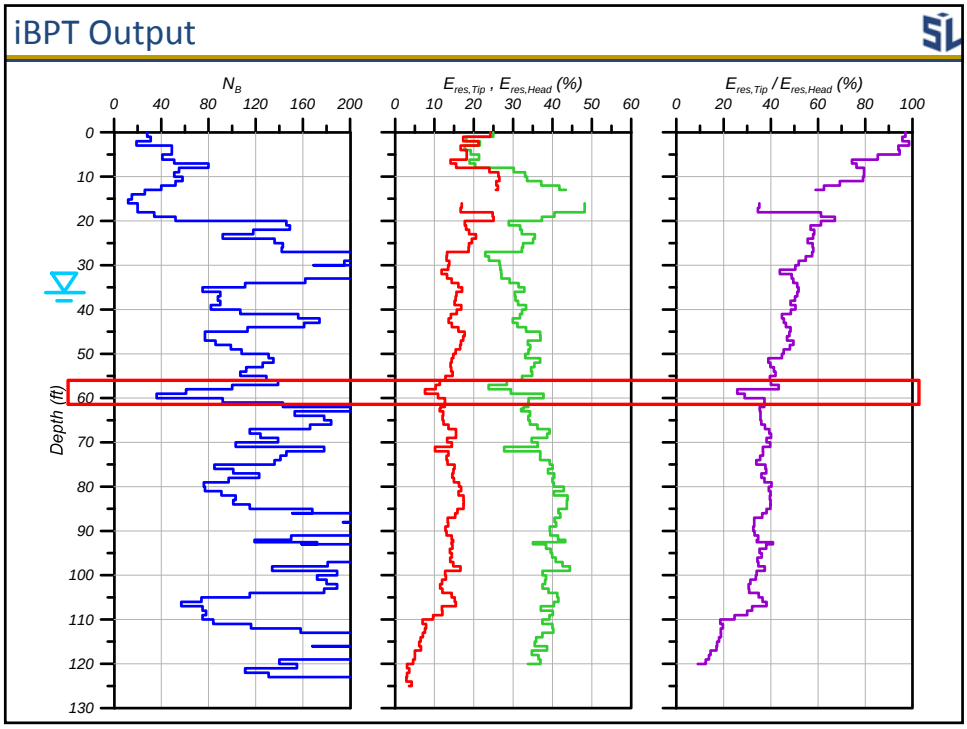
- Elastic rebound reflected in energy as well
- Maximum energy (E_{max}) traditionally used for normalization
- Residual energy (E_{res}) is the correct measure for normalization

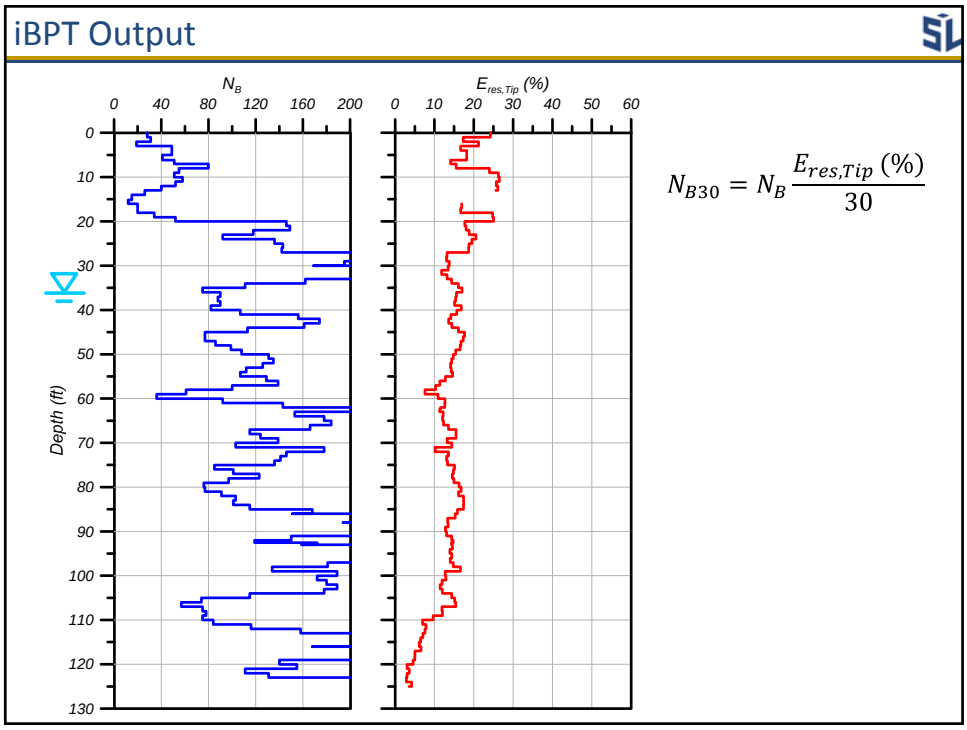


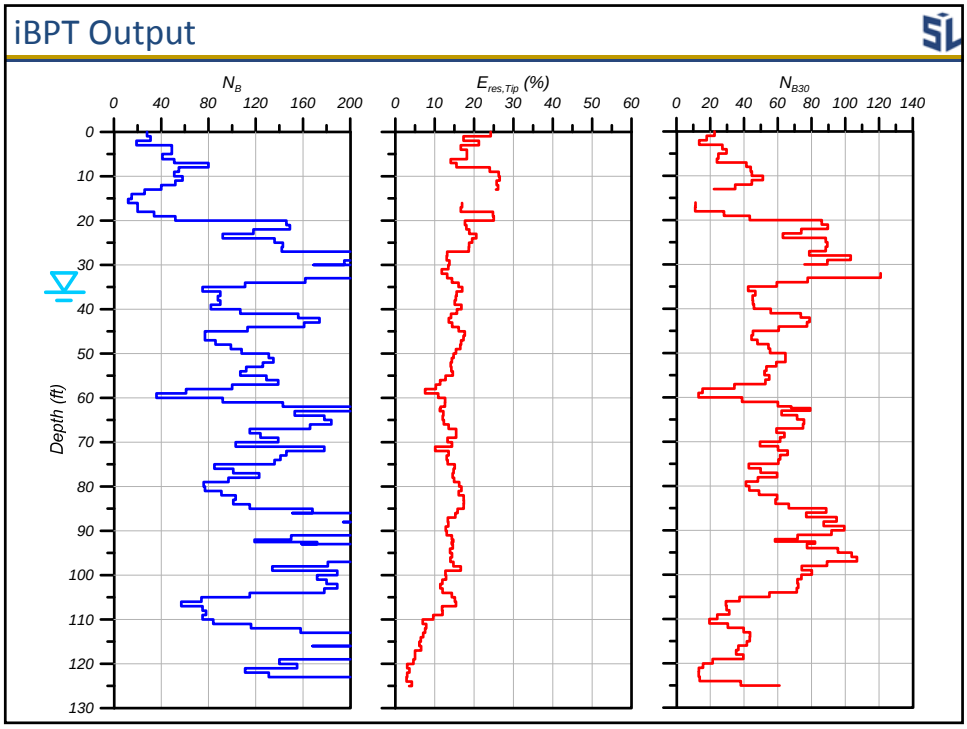
iBPT Data Analyser

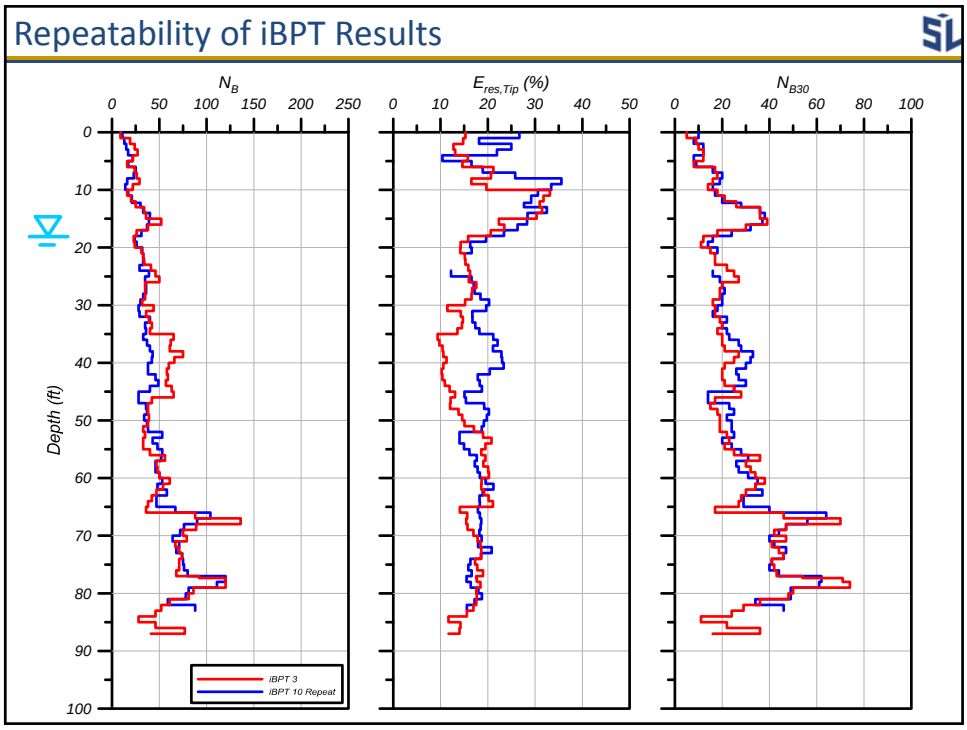
- 2,000 to 20,000 files produced each day
- Recreate events and assign depth, displacement, and BCP
- Individual blow data processed and combined into per foot averages

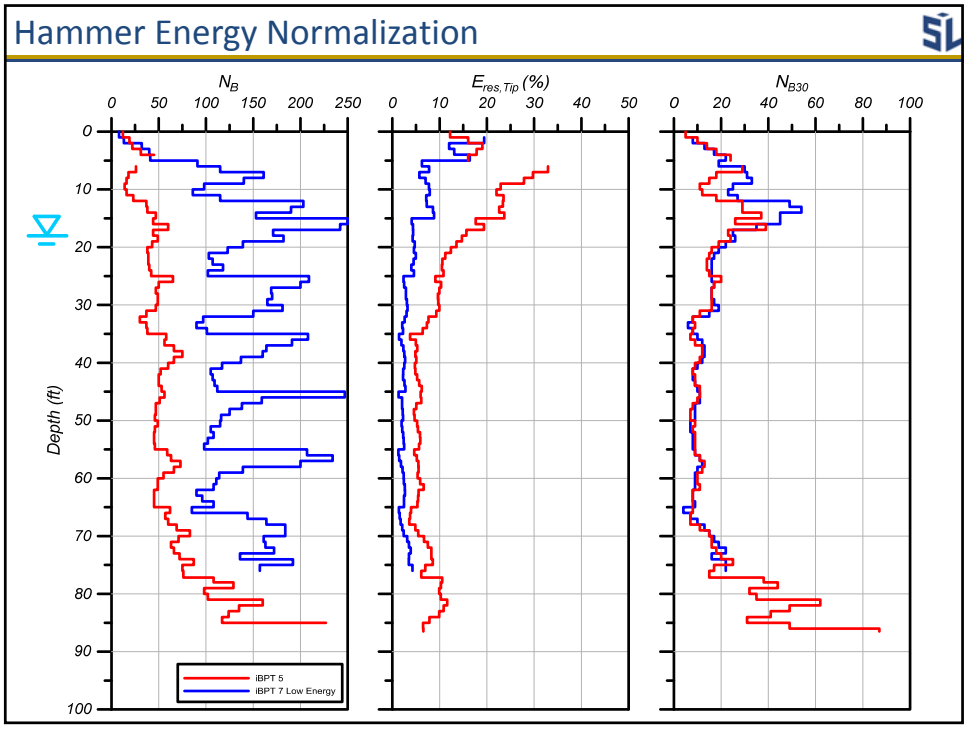


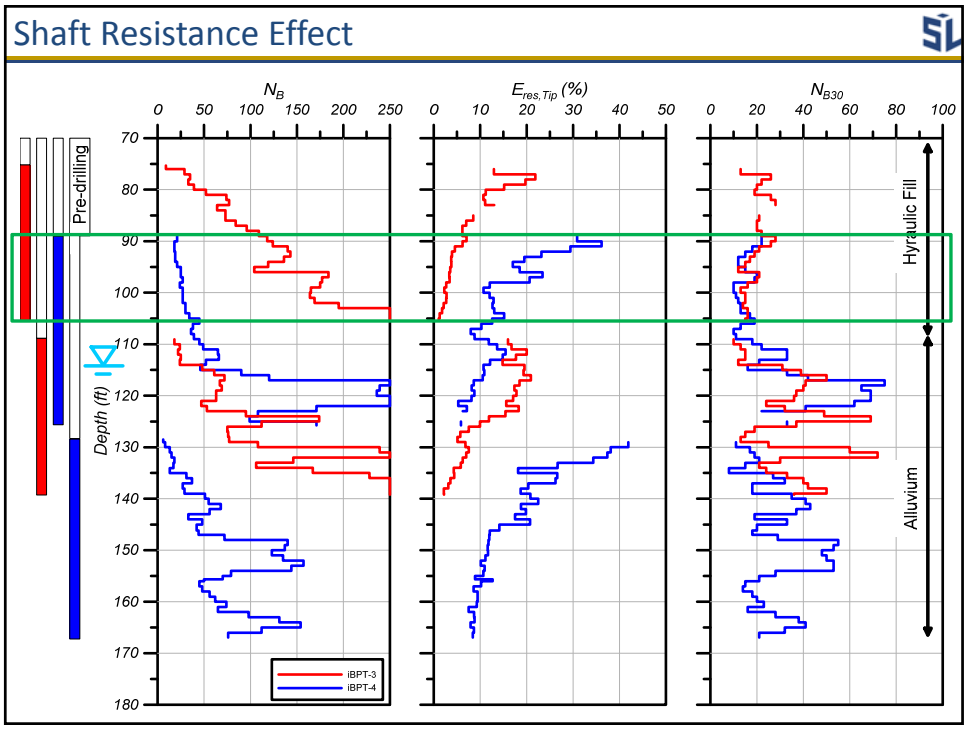

iBPT Output
N_B
$E_{res,Tip}$, $E_{res,Head}$ (%)
$E_{res,Tip}$ / $E_{res,Head}$ (%)
Depth (ft)


iBPT Output
N_B
$E_{res,Tip}$ (%)
Depth (ft)
$N_{B30} = N_B \frac{E_{res,Tip}\,(\%)}{30}$


iBPT Output
N_B
$E_{res,Tip}$ (%)
N_{B30}
Depth (ft)


Repeatability of iBPT Results
N_B
$E_{res,Tip}$ (%)
N_{B30}
Depth (ft)
iBPT 3
iBPT 10 Repeat


Hammer Energy Normalization
N_B
$E_{res,Tip}$ (%)
N_{B30}
Depth (ft)
iBPT 5
iBPT 7 Low Energy


Shaft Resistance Effect
N_B
$E_{res,Tip}$ (%)
N_{B30}
Pre-drilling
Depth (ft)
Hydraulic Fill
Alluvium
iBPT-3
iBPT-4

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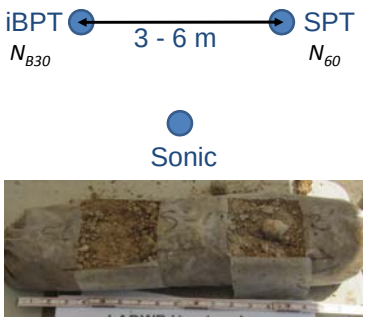
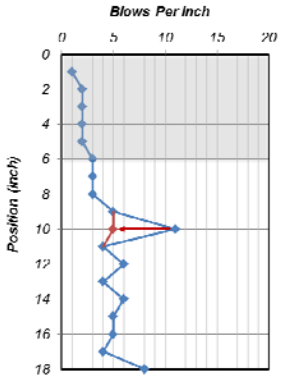
iBPT N_{B30} – SPT N_{60} Correlation

- Current focus on developing correlation with SPT N_{60}
- Side by side boreholes to develop empirical correlation
- Gravel influence on SPT and field variability are main challenges



iBPT N_{B30} – SPT N_{60} Correlation - Gravel Influence

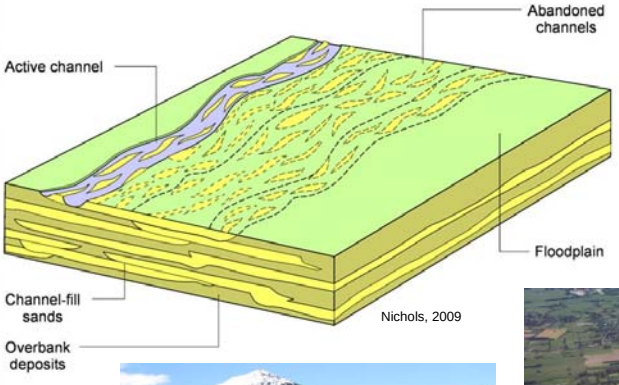
- Evaluation of each SPT includes :
  - Plotting of SPT blows per inch of penetration
  - Evaluation of field/lab description of sample obtained in SPT
  - Evaluation of field/lab description of Sonic core from matching depth
  - Consideration of percentage of gravel and maximum gravel size
  - Consideration of SPT sample recovery



High Quality

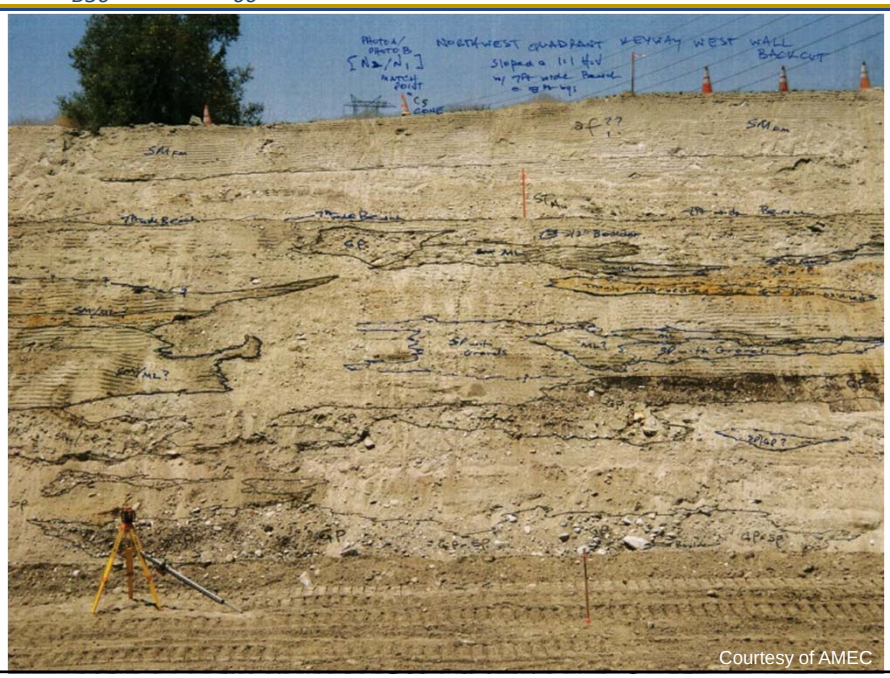
Low Quality

iBPT N_{B30} – SPT N_{60} Correlation - Field Variability

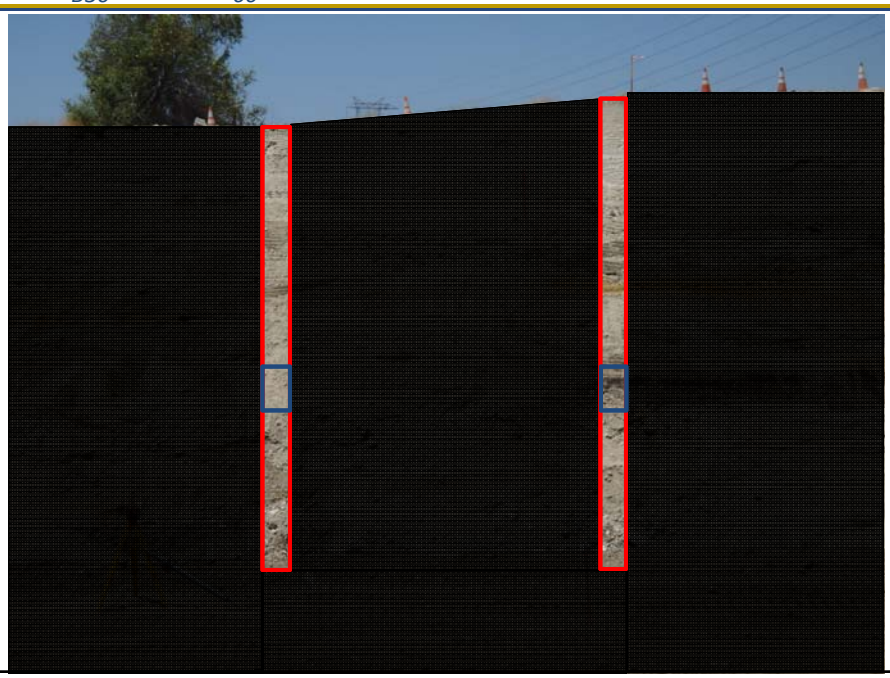


Depositional Architecture of a Braided River

iBPT N_{B30} – SPT N_{60} Correlation - Field Variability



iBPT N_{B30} – SPT N_{60} Correlation : Field Variability



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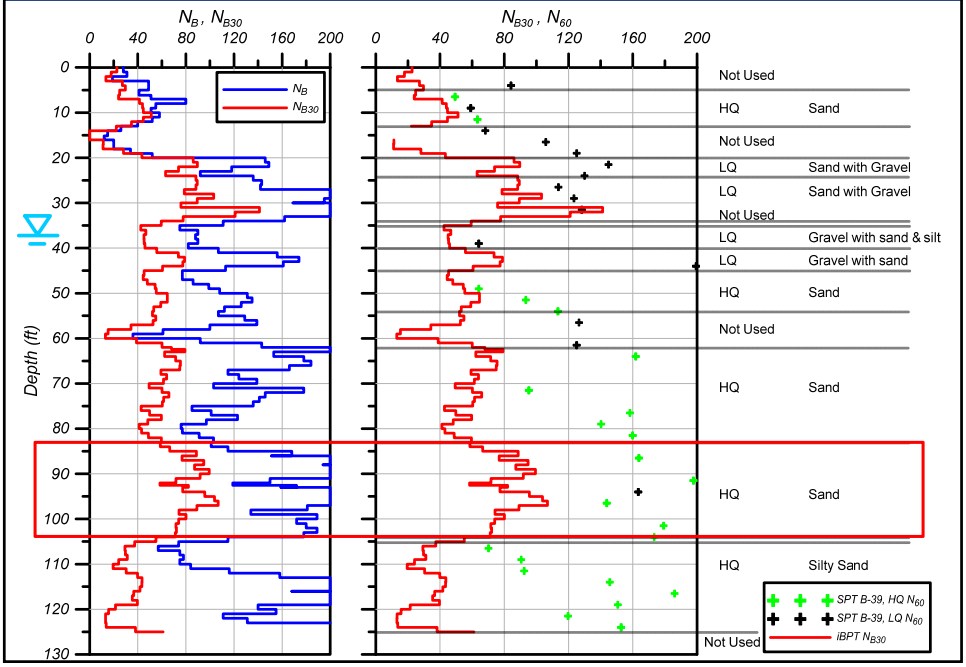
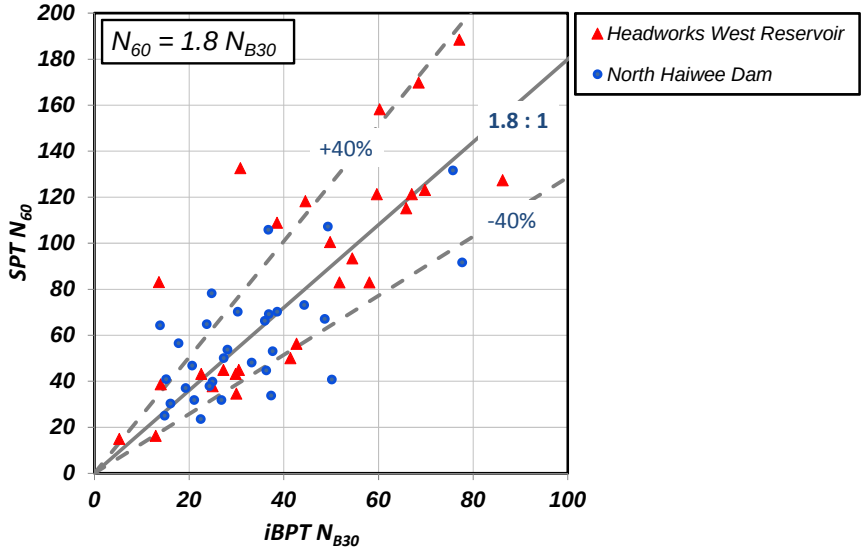
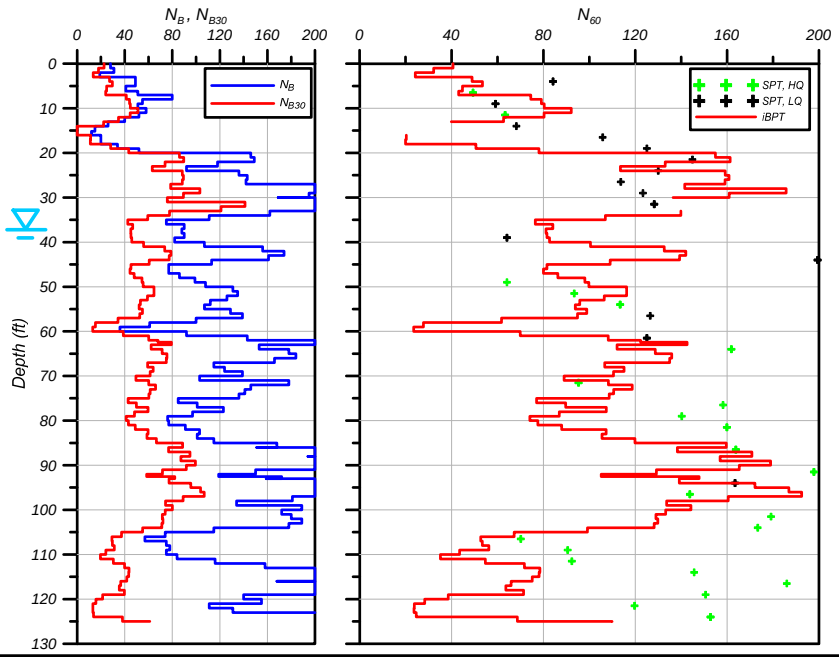


iBPT N_{B30} – SPT N_{60} Correlation

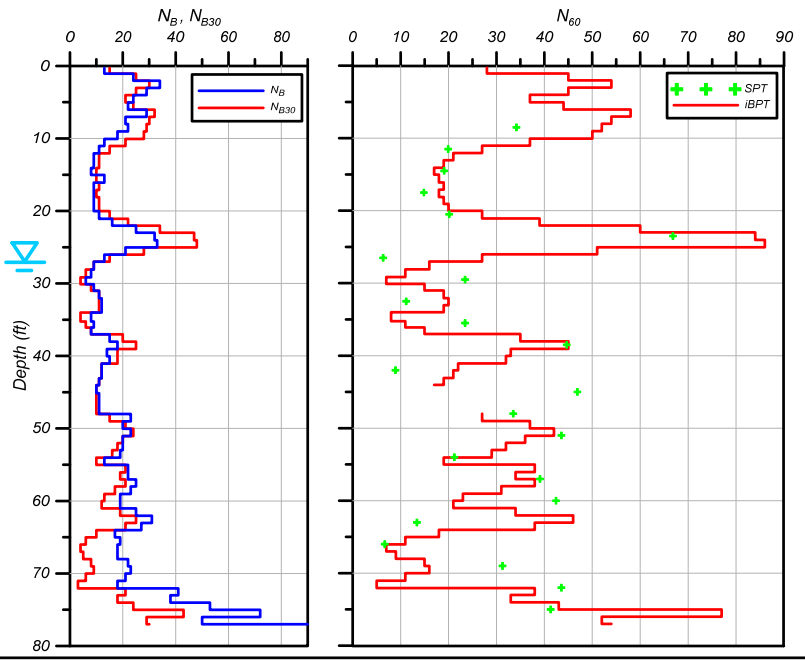
- Median values of high quality SPT N_{60} and associated median iBPT N_{B30} values used to develop correlation



iBPT Estimated N_{60}



iBPT Predicted N_{60}



iBPT Summary

- Summary of steps in iBPT method to obtain equivalent N_{60} values
  - Retrieve (automatically recorded) blow counts and compute the residual energy arriving at the tip (E_{res})
  - Use average E_{res} over *1 ft* of driving to compute N_{B30}
  - Use correlation $N_{60} = 1.8\ N_{B30}$ to obtain equivalent N_{60}
- Additional Measurements
  - Dynamic force and acceleration above ground
  - Bounce chamber pressure

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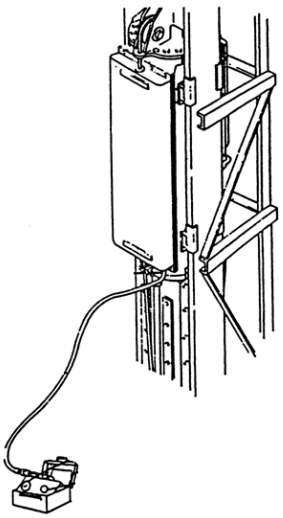
Harder and Seed (1986)

- Standardized equipment and procedures
- Bounce Chamber Pressure (BCP) used as proxy for maximum hammer energy
- Manual blow counting and measurement of BCP
- Measured blow counts (N_B) corrected based on maximum BCP to a reference line for "constant combustion condition", providing N_{BC}
- N_{BC} conversion to equivalent N_{60} values using empirical correlation



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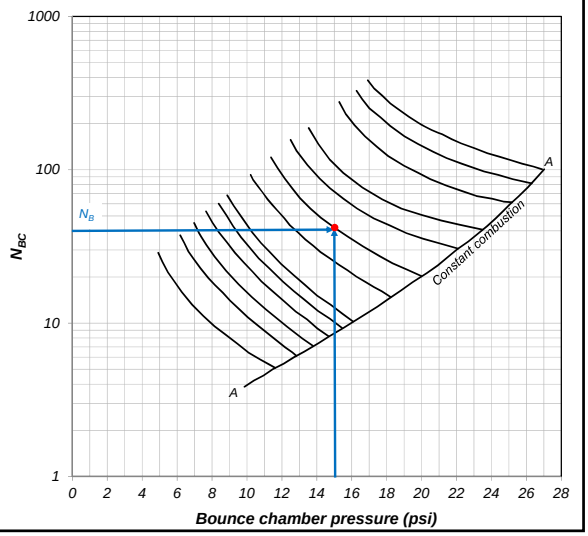

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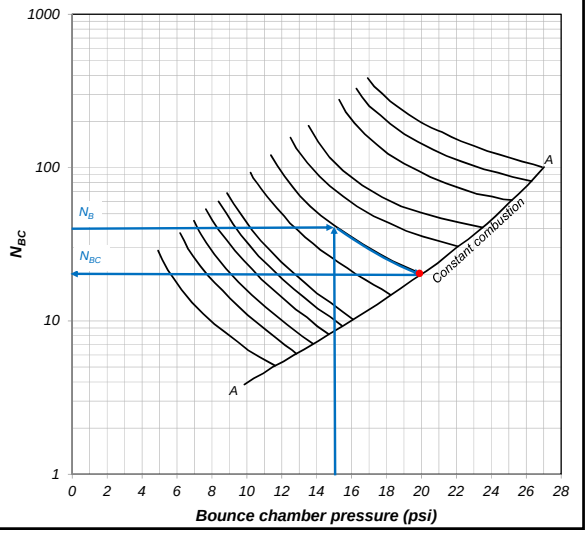
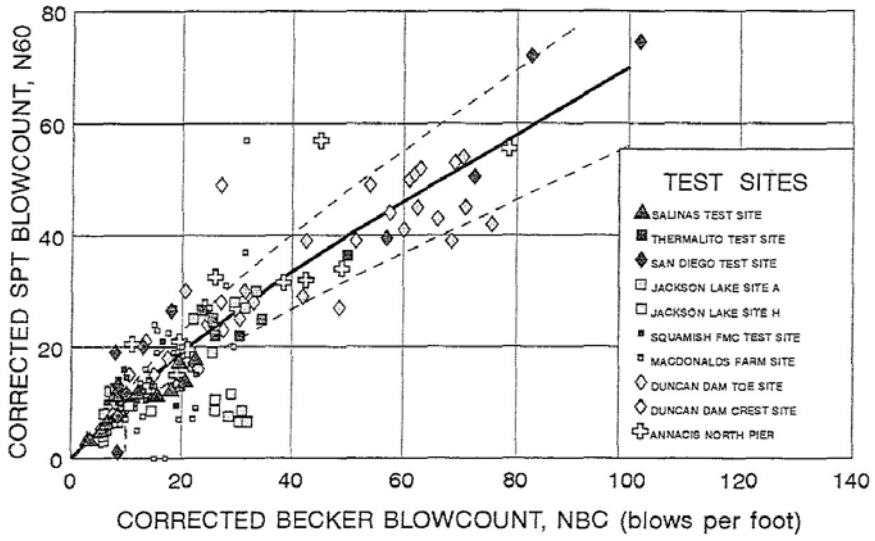


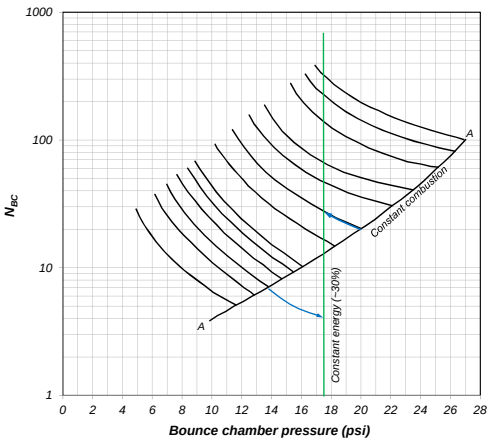
Harder and Seed (1986)

- N_{BC} values then converted to equivalent N_{60} values using non-linear relationship



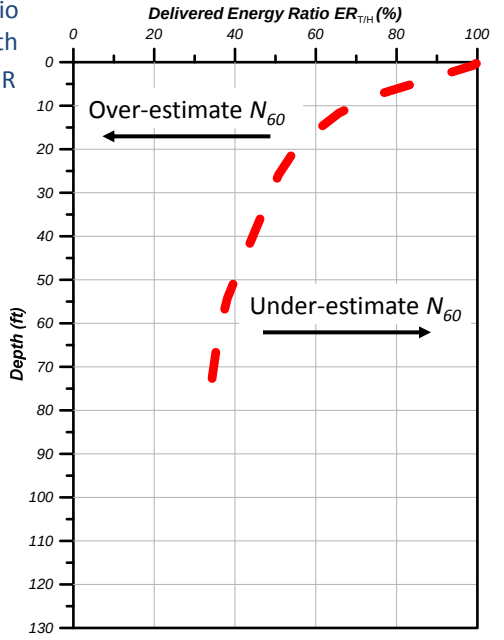
Harder and Seed (1986)

- Underlying mechanism
  - Energy instead of BCP
  - N_{B30} instead of N_{BC}
- "Constant combustion condition" line is not a constant/reference energy, but reference to hammer operation at full throttle
- 30% energy ≈ 17.5 psi BCP
- Can convert N_{BC} to N_{B30}
- Underlying tip/head energy transfer built into the empirical correlation



Harder and Seed (1986)

- The estimated Delivered Energy Ratio can be ***qualitatively*** plotted vs. depth
- Method works well, when actual DER is close to the implied DER



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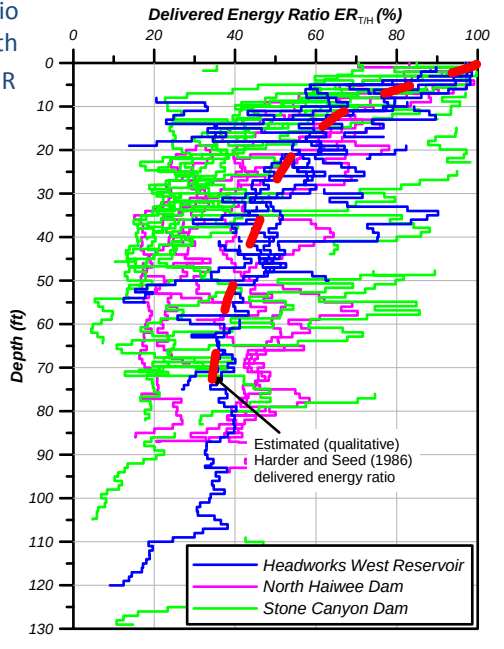
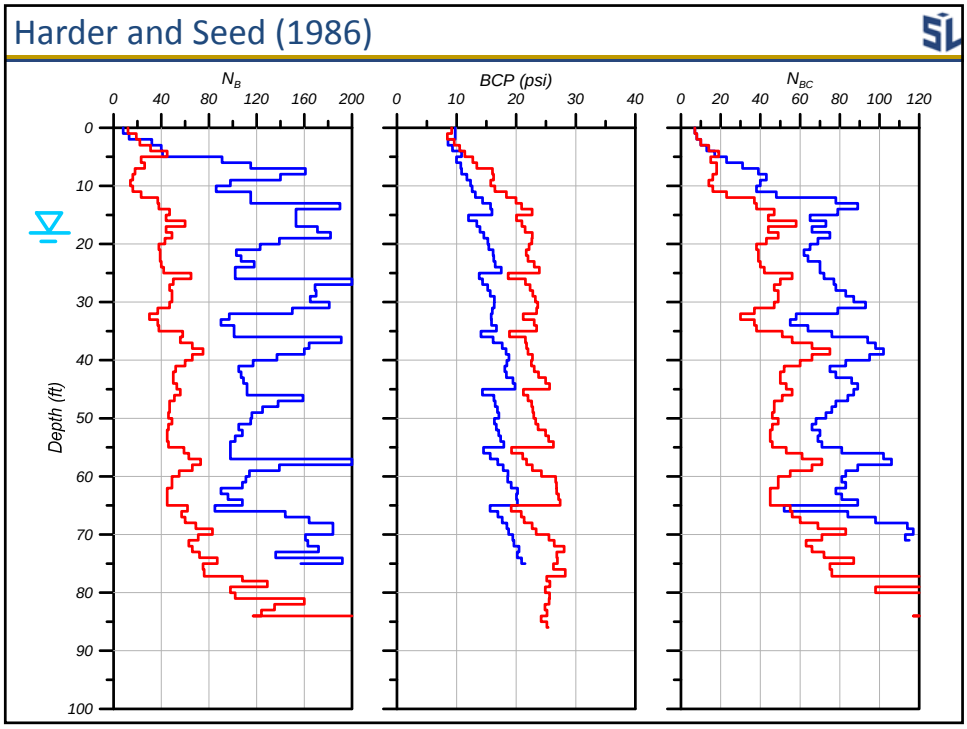
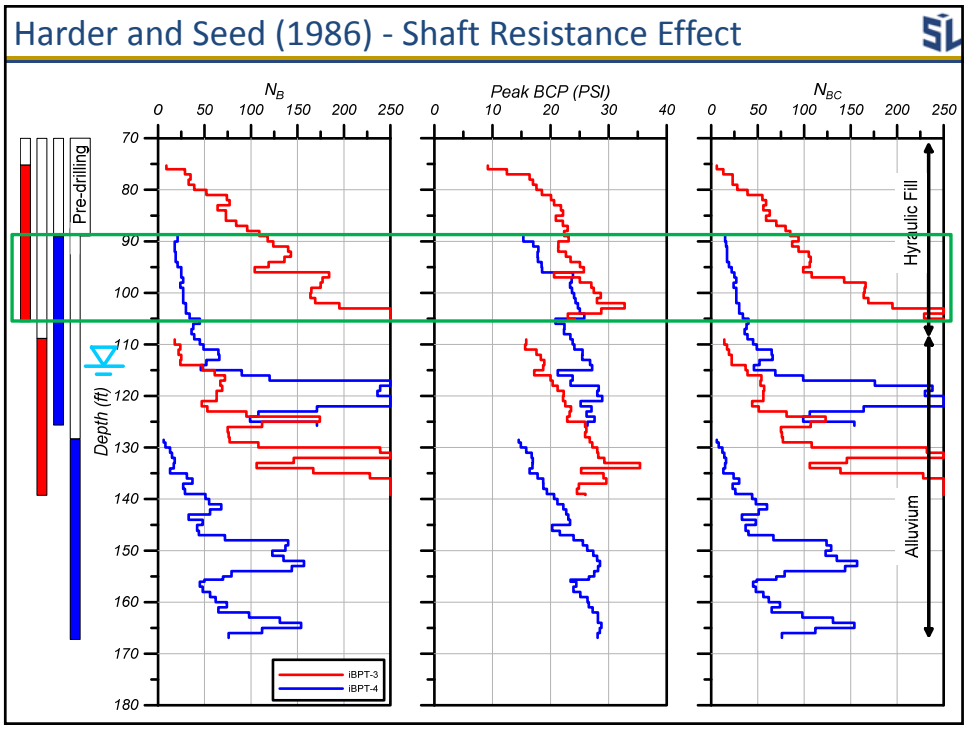
- Method works well, when actual DER is close to the implied DER

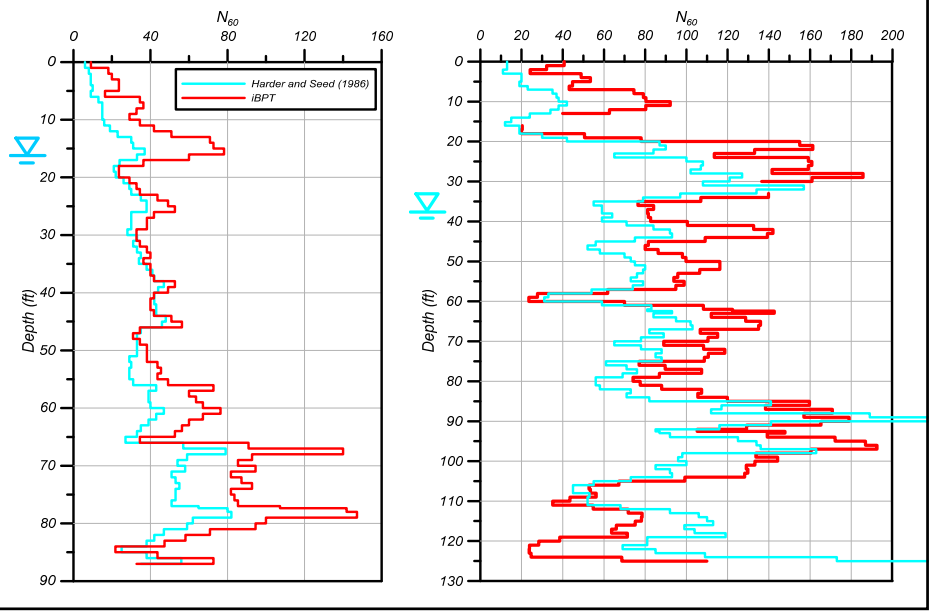



Harder and Seed (1986)
N_B
BCP (psi)
N_{BC}
Depth (ft)


Harder and Seed (1986) - Shaft Resistance Effect
N_B
Peak BCP (PSI)
N_{BC}
Pre-drilling
Depth (ft)
Hyraulic Fill
Alluvium
iBPT-3
iBPT-4

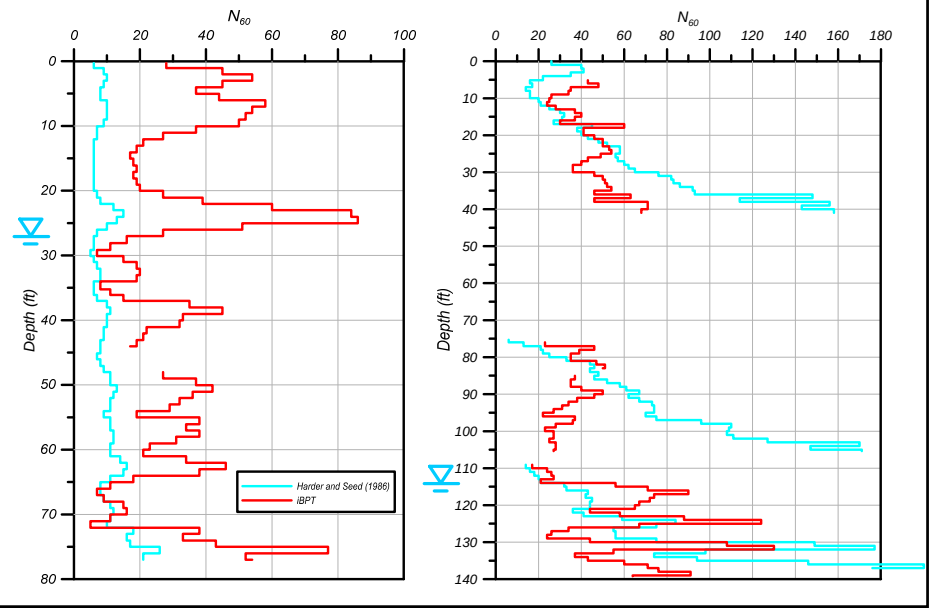
Harder and Seed (1986)

- Examples of the method working fairly well



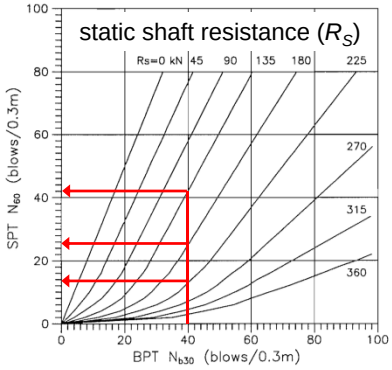
Harder and Seed (1986)

- Examples of the method under or over-estimating N_{60}



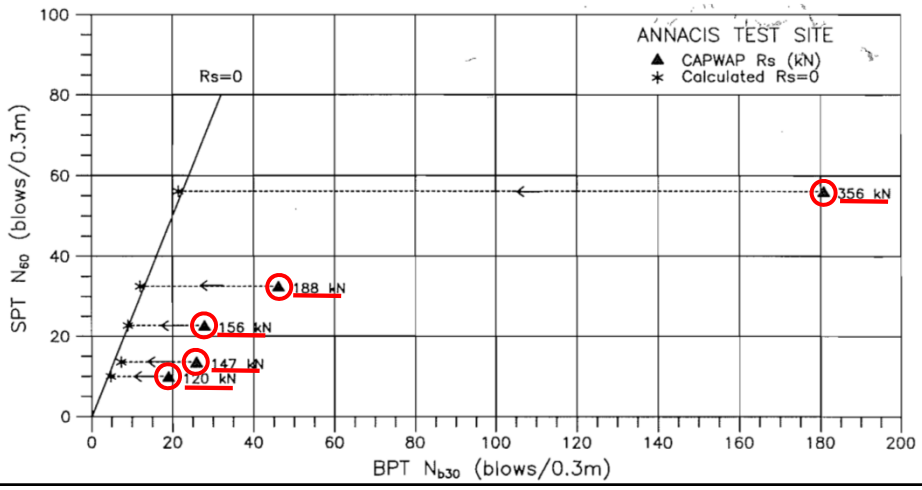
Sy and Campanella (1994)

- Theoretically rigorous method
- Directly address shaft resistance
- Implementation of the method utilizes
  - Energy transferred to the top of the drill casing during driving as measured with a PDA system to compute an energy normalized blow count (N_{B30})
  - Total static shaft resistance (R_s) along the drill string estimated by CAPWAP analysis or measured by a drill casing pull-back test



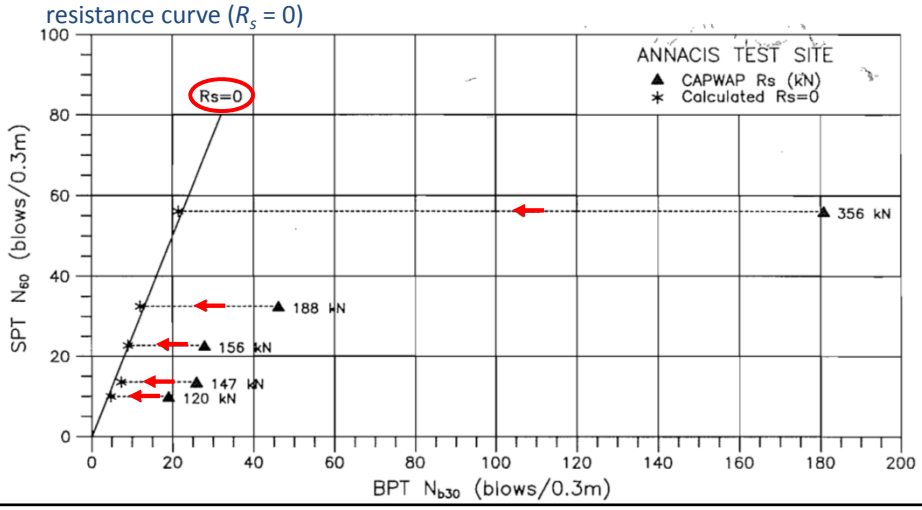
Sy and Campanella (1994)

- Five pairs of representative BPT and SPT blow counts, both tests with energy measurements, were selected
- CAPWAP analyses were performed



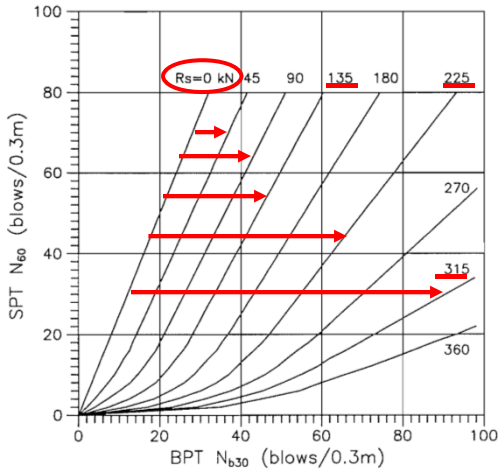
Sy and Campanella (1994)

- GRLWEAP models calibrated to match CAPWAP, including adjusting hammer efficiency to reproduce similar hammer energies to those observed in the field
- GRLWEAP analyses performed by removing the shaft resistances, and the displacements computed were converted to N_{B30} values to generate a zero shaft resistance curve (R_s = 0)



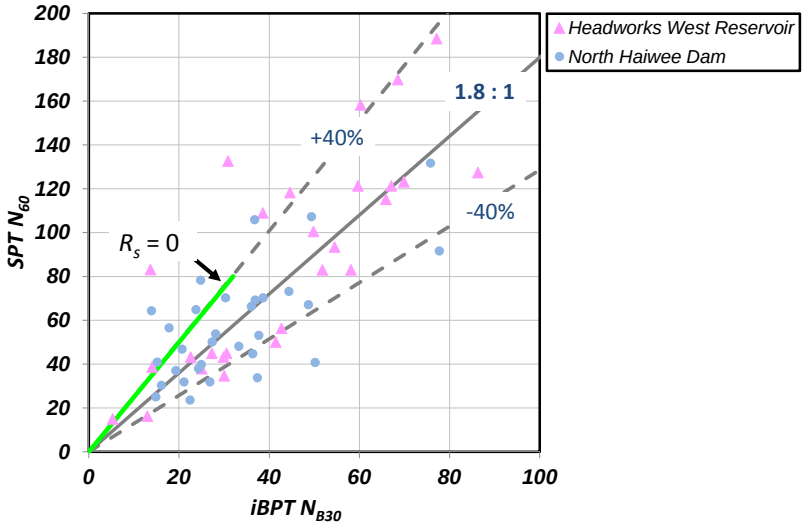
Sy and Campanella (1994)

- Additional GRLWEAP analyses by assigning different levels of static shaft resistance R_s to generate a range of curves



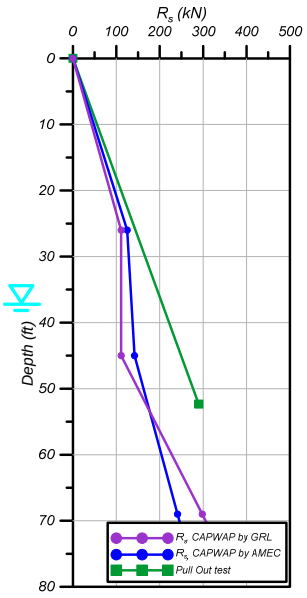
Sy and Campanella (1994)

- The R_s = 0 is in concept comparable to the iBPT Correlation
- The slope of the R_s = 0 line is 2.5:1.0 while the iBPT correlation in 1.8:1.0
- Note: iBPT uses residual energy, while Sy and Campanella use maximum energy

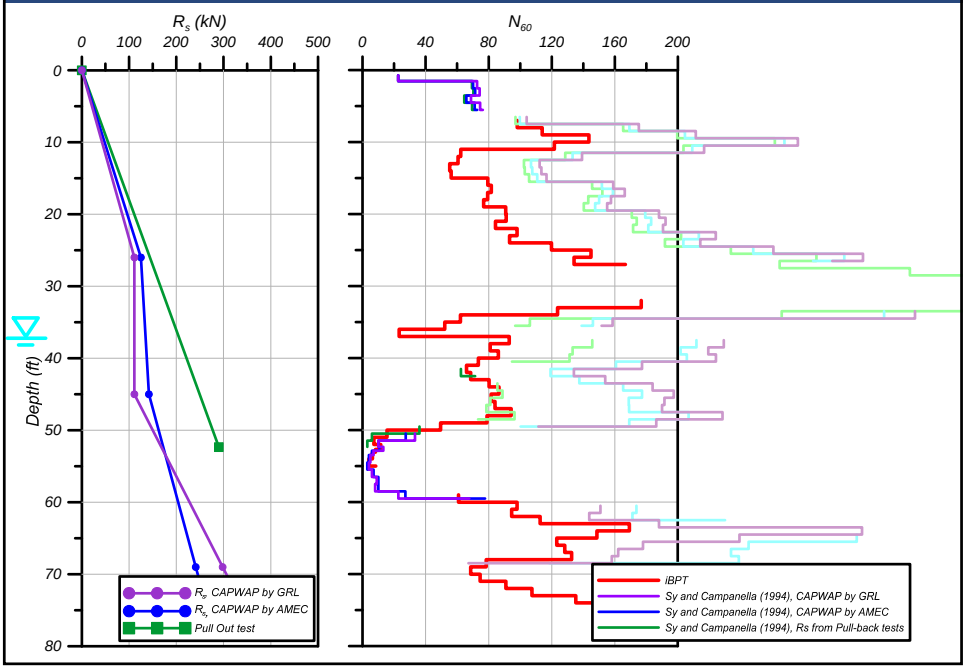


Sy and Campanella (1994)

- Comparison between CAPWAP analyses by different companies

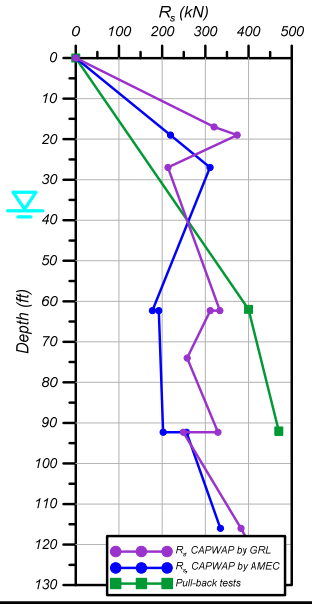


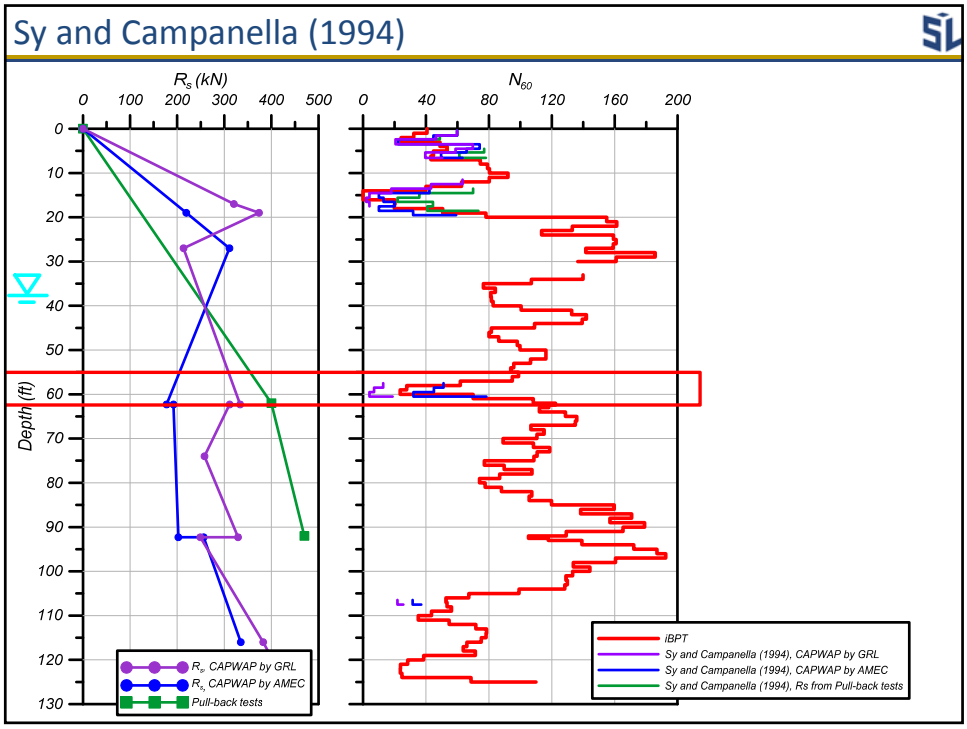
Sy and Campanella (1994)

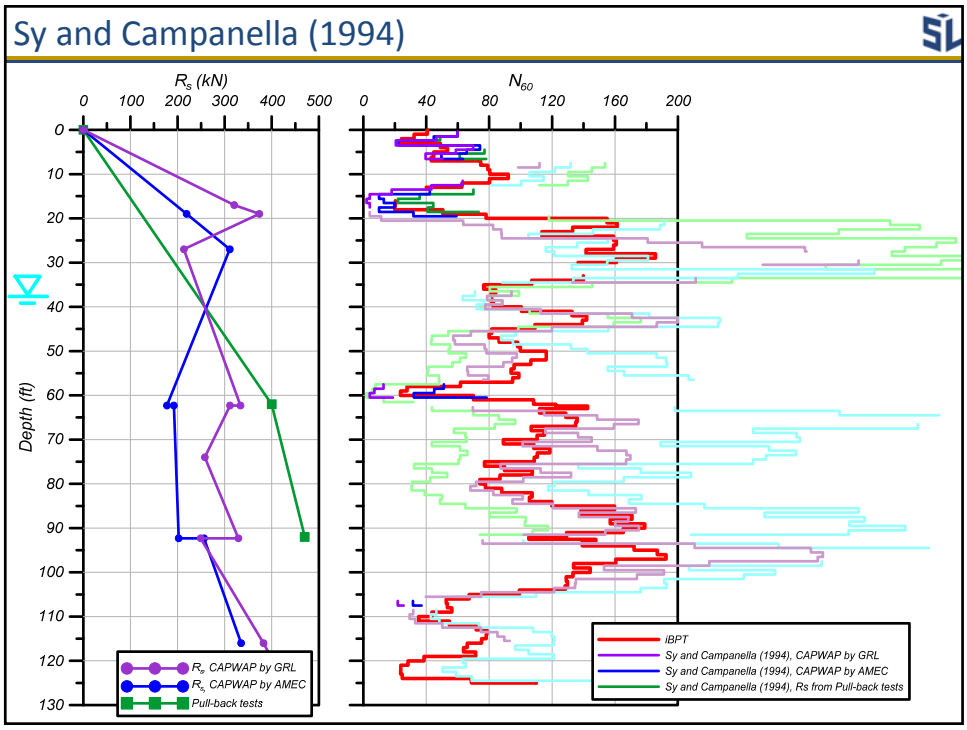


Sy and Campanella (1994)

- Comparison between CAPWAP analyses by different companies




Sy and Campanella (1994)
R_s (kN)
0 100 200 300 400 500
N_{60}
0 40 80 120 160 200
Depth (ft)
0 10 20 30 40 50 60 70 80 90 100 110 120 130
R_s CAPWAP by GRL
R_s CAPWAP by AMEC
Pull-back tests
iBPT
Sy and Campanella (1994), CAPWAP by GRL
Sy and Campanella (1994), CAPWAP by AMEC
Sy and Campanella (1994), Rs from Pull-back tests


Sy and Campanella (1994)
R_s (kN)
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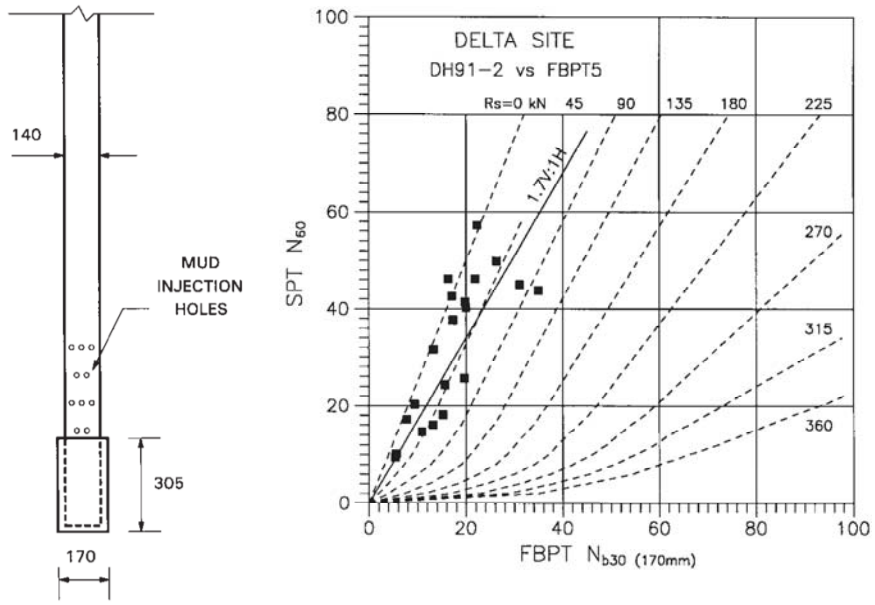
iBPT
Sy and Campanella (1994), CAPWAP by GRL
Sy and Campanella (1994), CAPWAP by AMEC
Sy and Campanella (1994), Rs from Pull-back tests

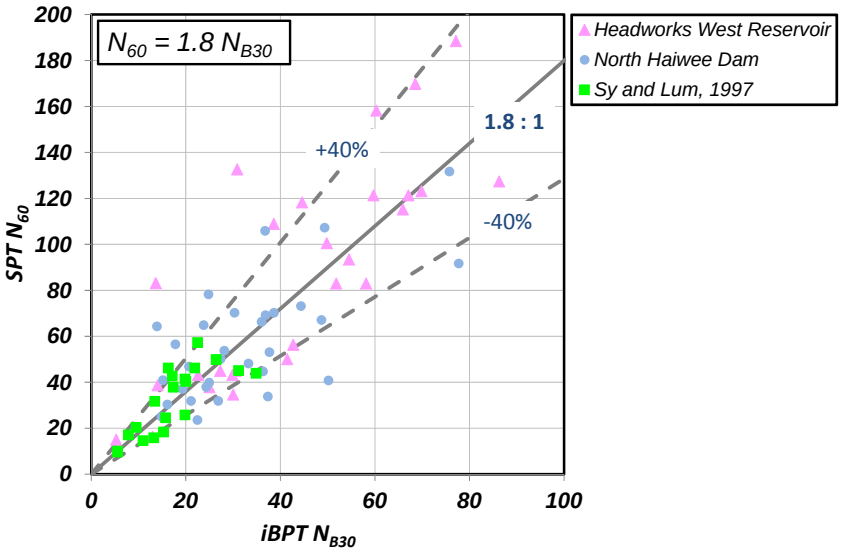
Foundex Mud-injection Becker



Sy and Lum, 1997

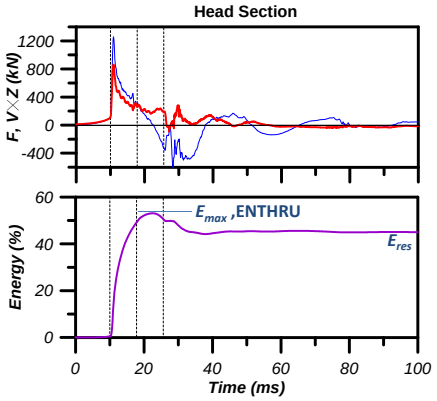
Foundex Mud-injection Becker

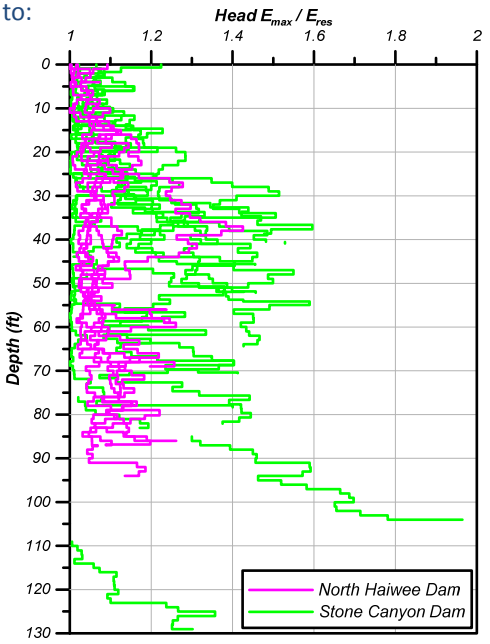
- Note: iBPT correlation is obtained with residual energy, while Sy and Lum (1997) data use maximum energy (ENTHRU)



Note: Maximum and Residual Energies above Ground

- Difference between E_{max} and E_{res} due to:
  - Soil rebound
  - Pile rebound
- Increasing trend with
  - Penetration resistance (e.g. N_{B30})
  - Depth



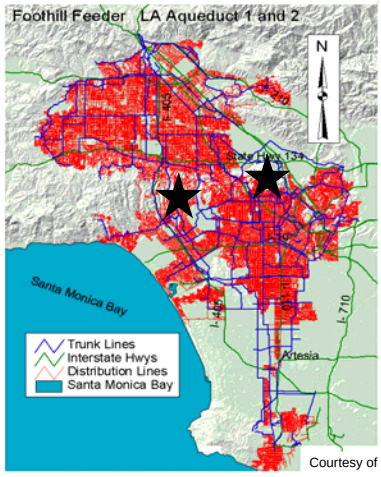


Outline

- Motivation
  - Gravel and infrastructure
  - Existing site investigation tools
  - Becker Penetration Testing
- Instrumented BPT System
  - Concept
  - Equipment
  - Results
- Correlation with SPT
  - Field variability
- Review of Earlier Methods
  - Harder and Seed (1986)
  - Sy and Campanella (1994)
  - Foundex mud-injection Becker
- **Application in LADWP System**
  - **Projects**
- Ongoing and Future Work

LA Department of Water and Power System

- LADWP largest municipal utility in USA
- Serves 4.0 million people
- 465 square mile service area
- 215 billion gallons annual water supply



Courtesy of LADWP

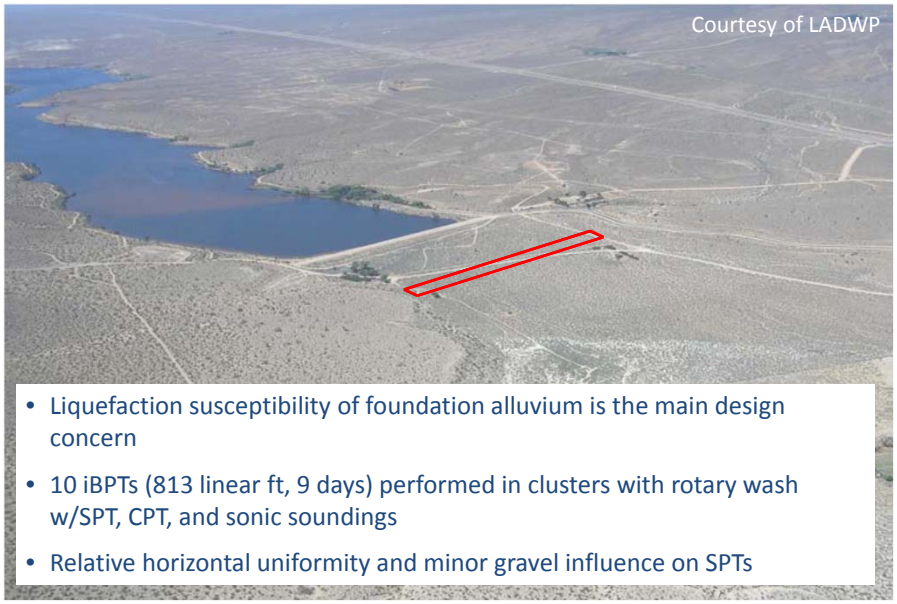
Field Testing

Headworks West Reservoir

- Post liquefaction differential settlements are main design concern
- 12 iBPTs (907 linear ft, 12 days) performed in clusters with rotary wash w/SPT, and sonic soundings
- Field variability and gravel influence on SPTs were main challenges

Field Testing

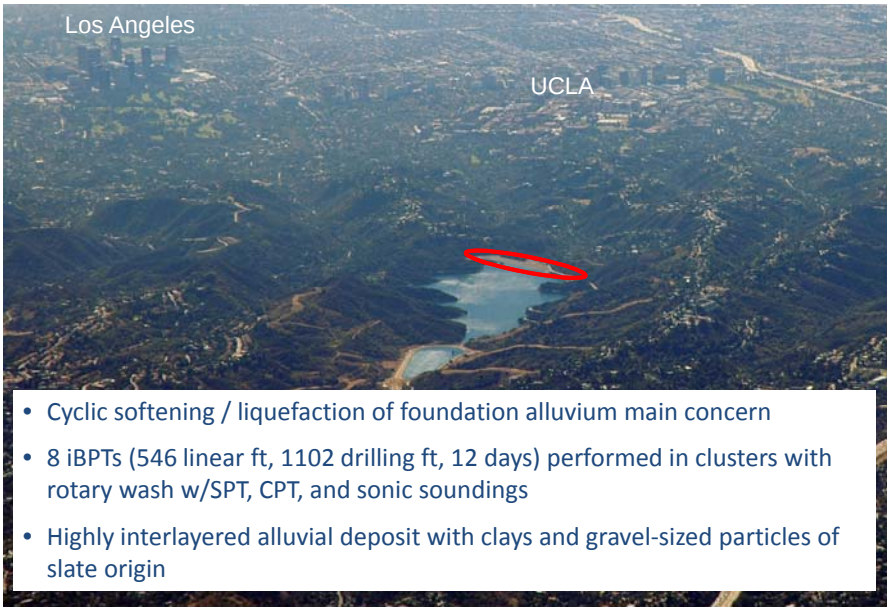
North Haiwee Dam



- Liquefaction susceptibility of foundation alluvium is the main design concern
- 10 iBPTs (813 linear ft, 9 days) performed in clusters with rotary wash w/SPT, CPT, and sonic soundings
- Relative horizontal uniformity and minor gravel influence on SPTs

Field Testing

Lower Stone Canyon Dam



- Cyclic softening / liquefaction of foundation alluvium main concern
- 8 iBPTs (546 linear ft, 1102 drilling ft, 12 days) performed in clusters with rotary wash w/SPT, CPT, and sonic soundings
- Highly interlayered alluvial deposit with clays and gravel-sized particles of slate origin

Outline

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- **Ongoing and Future Work**

Ongoing and Future Work

- More projects planned: Bouquet Canyon Dam, 250 ft Channel Dam
- Correlation between iBPT and CPT
- Investigation into behaviour of gravelly materials
- Application as Retrievable Test Pile (RTP)
  - Multiple modules along the pile
  - Four sites with pile load tests
- Wave equation analyses and development of new models

Project Summary

- iBPT completes the geotechnical engineering site investigation toolbox by extending reliable measurements to gravelly soils
- The equipment has reached commercial level performance with replaceable parts and automated data processing
- The energy normalization framework for dynamic penetration tests has been improved by replacing the maximum energy (E_{max}) with the residual energy (E_{res})
- A linear correlation exists between iBPT N_{B30} and SPT N_{60} values; N_{60} = 1.8 N_{B30}
- iBPT implementation continues with 2250 ft of testing completed over 30 soundings to date, and more planned

References

Existing Publications

- Ghafghazi M., DeJong J.T., Sturm A.P., Wilson D.W., Davis C., Perez A., and Armstrong R. 2014. Characterization of gravelly soils for liquefaction potential assessment at dam sites using the iBPT. United States Society on Dams, Annual Meeting and Conference, San Francisco, California.
- Ghafghazi M., Thurairajah A., DeJong J.T., Wilson D.W., and Armstrong R. 2014. Instrumented Becker Penetration Test for improved characterization of gravelly deposits. Geo-Characterization and Modeling for Sustainability, ASCE G-I Geo-Congress, Atlanta, Georgia.
- DeJong J.T., Ghafghazi M., Sturm A.P., Armstrong R., Perez A., Davis C. 2014. A new instrumented Becker Penetration Test (iBPT) for improved characterization of gravelly deposits within and underlying dams. The Journal of Dam Safety, Association of State Dam Safety Officials, 12(2).

Upcoming Publications

- DeJong J.T., Ghafghazi M., Sturm A.P., Wilson D.W, denDulk J., Perez A., and Davis C. 2014. Instrumented Becker Penetration Test: Equipment, operation, and performance. In preparation for Journal of Geotechnical and Geoenvironmental Engineering, ASCE.
- Ghafghazi M., and DeJong J.T. 2014. Application of SPT and instrumented Becker Penetration Test for liquefaction assessment in gravelly soils. In preparation for Journal of Geotechnical and Geoenvironmental Engineering, ASCE.

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  - Jon Pearson
  - Alex Sturm
  - Chase Temple

Thank you!