FHWA GeoGauge Workshop

29 & 30 November, 2000

Background & Theory

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Why The GeoGauge?

- To Meet A Need
  - Relentless Pursuit of Lower Cost & Higher Quality
- By Achieving A Goal
  - Increased Precision of Design & Construction
    - Mechanistic Designs
    - Performance Specifications
    - Process Control
  - Increased Continuity Between Design & Construction
    - Design Parameters Used to Evaluate Construction
    - Contractor Warranties
- Through A Historically Successful Path
  - Structural Stiffness & Material Modulus

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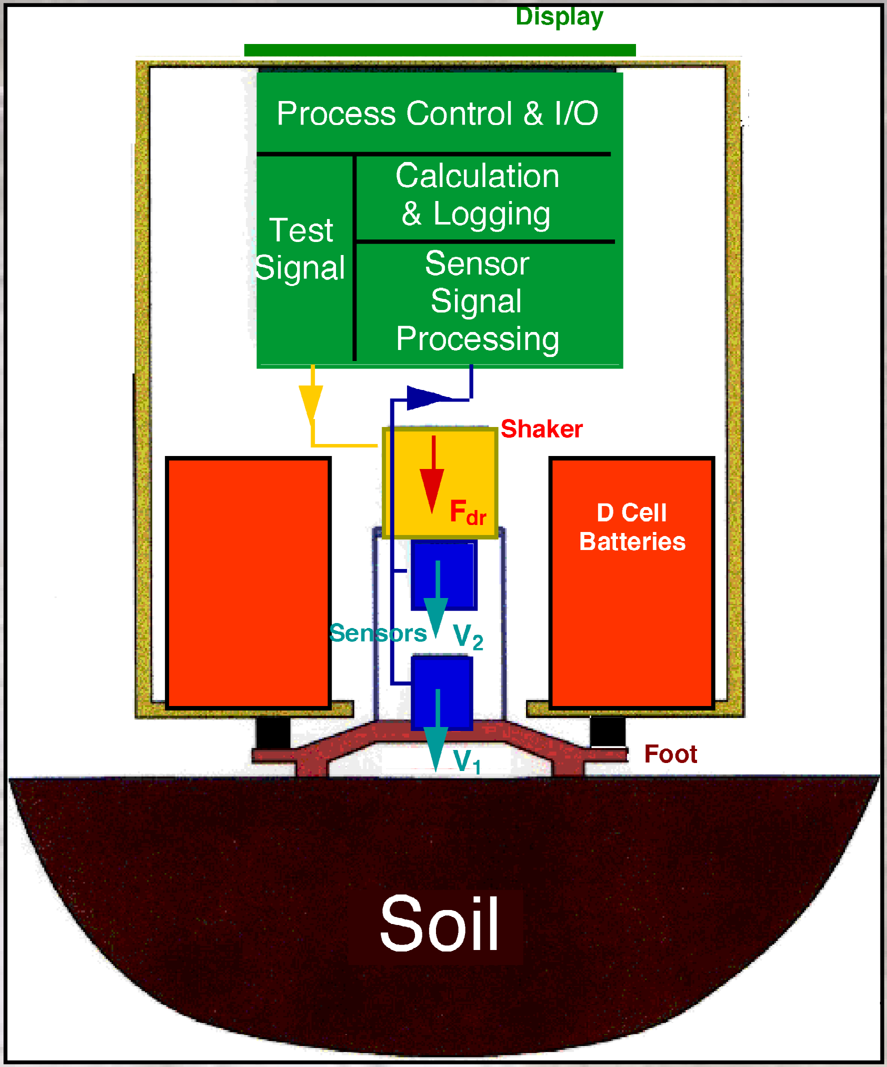
Design Description

- Physical Attributes
- Principle of Operation
- Operating Procedure
- Performance
- Alternatives

Physical Attributes

- Size: 11" OD x 10" tall
- 4.5" OD x 3.5" ID Foot
- Weight: 22 lb.
- Powered by 6 D-Cell Batteries
- IR Data Downloading
- Keypad User Interface



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Operating Principle

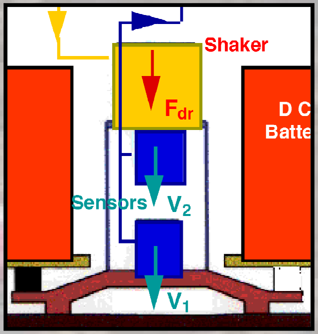
Stiffness

Resistance of a Lift to Deformation

Foot Radius & Poisson's Ratio

Modulus

Resistance of a Material to Deformation



- At GeoGauge Frequencies & Stress, Impedance is Predominately Stiffness
- No Need for a Non-moving Displacement Reference
- Permits the Accurate Measurement of Small Displacements

$$F_{dr} = K_{flex}\,(X_2 - X_1)$$

$$K_{gr} = \frac{F_{dr}}{X_1}$$

$$\overline{K_{gr}} = K_{flex}\,\frac{\sum_{1}^{n}\frac{(X_2 - X_1)}{X_1}}{n} = K_{flex}\,\frac{\sum_{1}^{n}\frac{(V_2 - V_1)}{V_1}}{n}$$

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Operating Procedure

- Inspect GeoGauge
- Power On
- Select Mode & Poisson's Ratio
- Seat the Foot
  - ≥ 60% Direct Contact
  - Moist Sand Assisted (1/4" to 1/8")
    - Rough & Irregular Surfaces
    - Smooth Hard Surfaces
- Take the Measurement: 75 Sec.
  - 15 Sec. of Noise
  - 60 Sec. of Signal
  - Results Displayed
    - Signal/Noise: ≥ 3/1 (10 db)
    - Standard Deviation: a Measure of Foot Contact
    - Average Stiffness or Modulus (English or SI)
- Examine the Foot Print
- Save Data

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Performance

Specification

Precision

Bias

Validation & Correlation

Standardization

Specification

- **Stiffness:** 3 (17) to >70 (399) MN/m (klb/in)
- **Young's Modulus:** 26.2 (3.8) to > 607 (88) MPa (kpsi)
- **Poisson's Ratio:** Variable in 0.05 Increments
- **Precision:** Typically 3.9% Coefficient of Variation
- **Bias:** < 1% Coefficient of Variation
- **Depth of Measurement:** 22.9 cm (9 in)
- **Battery Life:** > 1,500 measurements
- **Operating Temperature:** 0°C to 38°C (32°F to 100°F)

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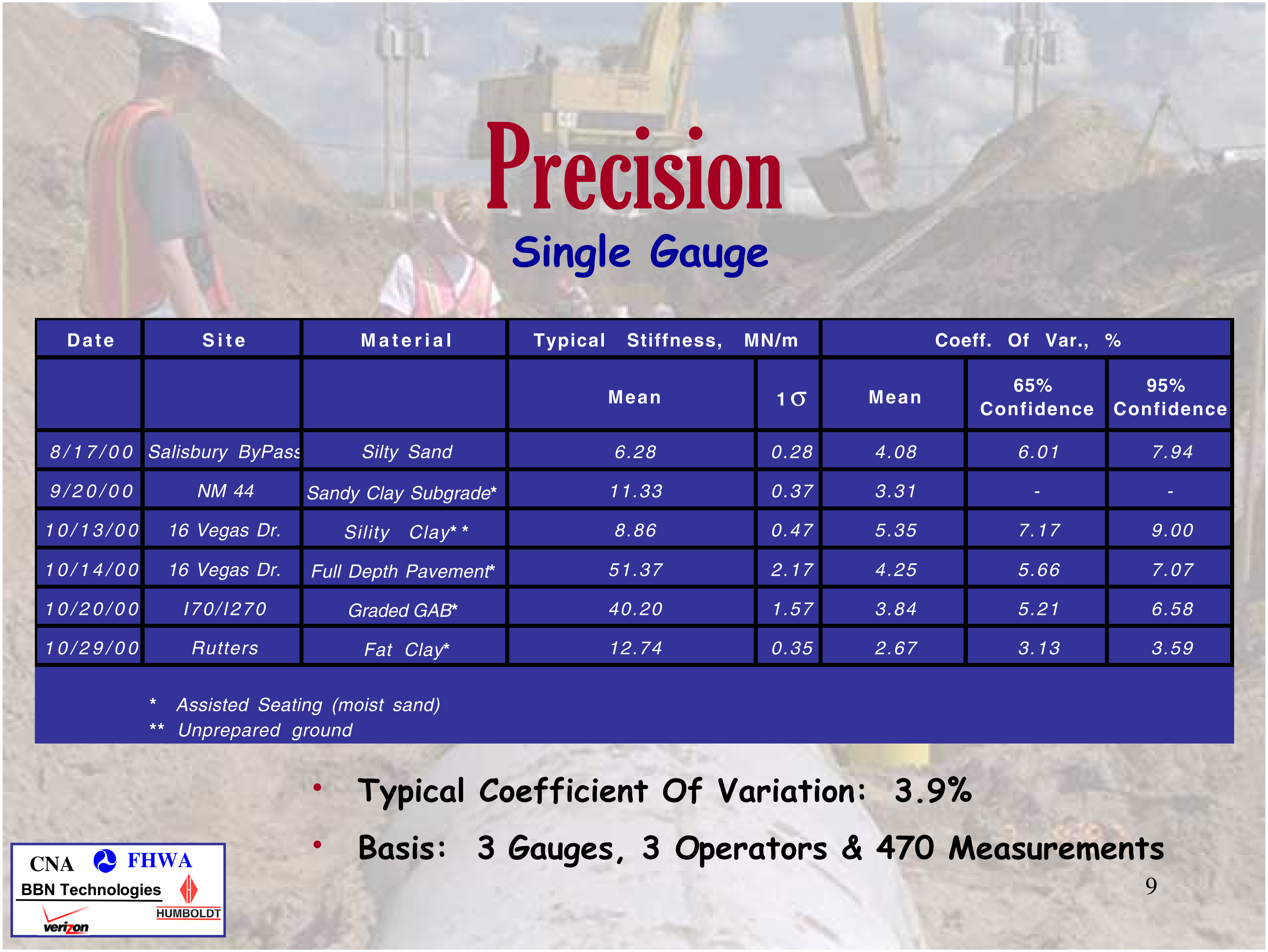

Precision

Single Gauge

Date	Site	Material	Typical Stiffness, MN/m		Coeff. Of Var., %		
			Mean	1σ	Mean	65% Confidence	95% Confidence
8/17/00	*Salisbury ByPass*	*Silty Sand*	*6.28*	*0.28*	*4.08*	*6.01*	*7.94*
9/20/00	*NM 44*	*Sandy Clay Subgrade**	*11.33*	*0.37*	*3.31*	*-*	*-*
10/13/00	*16 Vegas Dr.*	*Sility Clay***	*8.86*	*0.47*	*5.35*	*7.17*	*9.00*
10/14/00	*16 Vegas Dr.*	*Full Depth Pavement**	*51.37*	*2.17*	*4.25*	*5.66*	*7.07*
10/20/00	*I70/I270*	*Graded GAB**	*40.20*	*1.57*	*3.84*	*5.21*	*6.58*
10/29/00	*Rutters*	*Fat Clay**	*12.74*	*0.35*	*2.67*	*3.13*	*3.59*

* *Assisted Seating (moist sand)*
** *Unprepared ground*

- **Typical Coefficient Of Variation: 3.9%**
- **Basis: 3 Gauges, 3 Operators & 470 Measurements**

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Precision

Multiple Gauges

Date	Site	Material	No. of Measurements	Stiffness, MN/m		Coeff. of Var.
				Mean	1σ	%
11/7/00	16 Vegas Dr.	Sility Clay* *	12	8.50	0.33	3.89
11/7/00	16 Vegas Dr.	Sility Clay* *	30	9.94	0.39	3.91
11/8/00	16 Vegas Dr.	Full Depth Pavement*	16	44.83	1.72	3.83
11/24/00	16 Vegas Dr.	Sility Clay* *	10	10.06	0.59	5.84

* *Assisted Seating (moist sand)*

** *Unprepared ground*

- **Statistics Based on Combined Measurements From Both Gauges**
- **Basis: 2 Gauges, 1 Operator & 68 Measurements**

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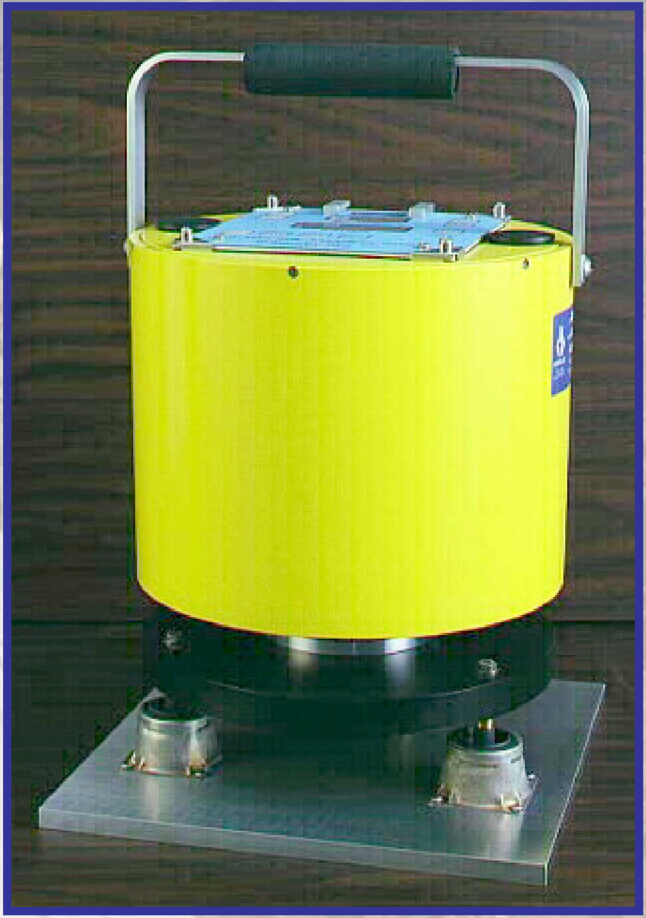
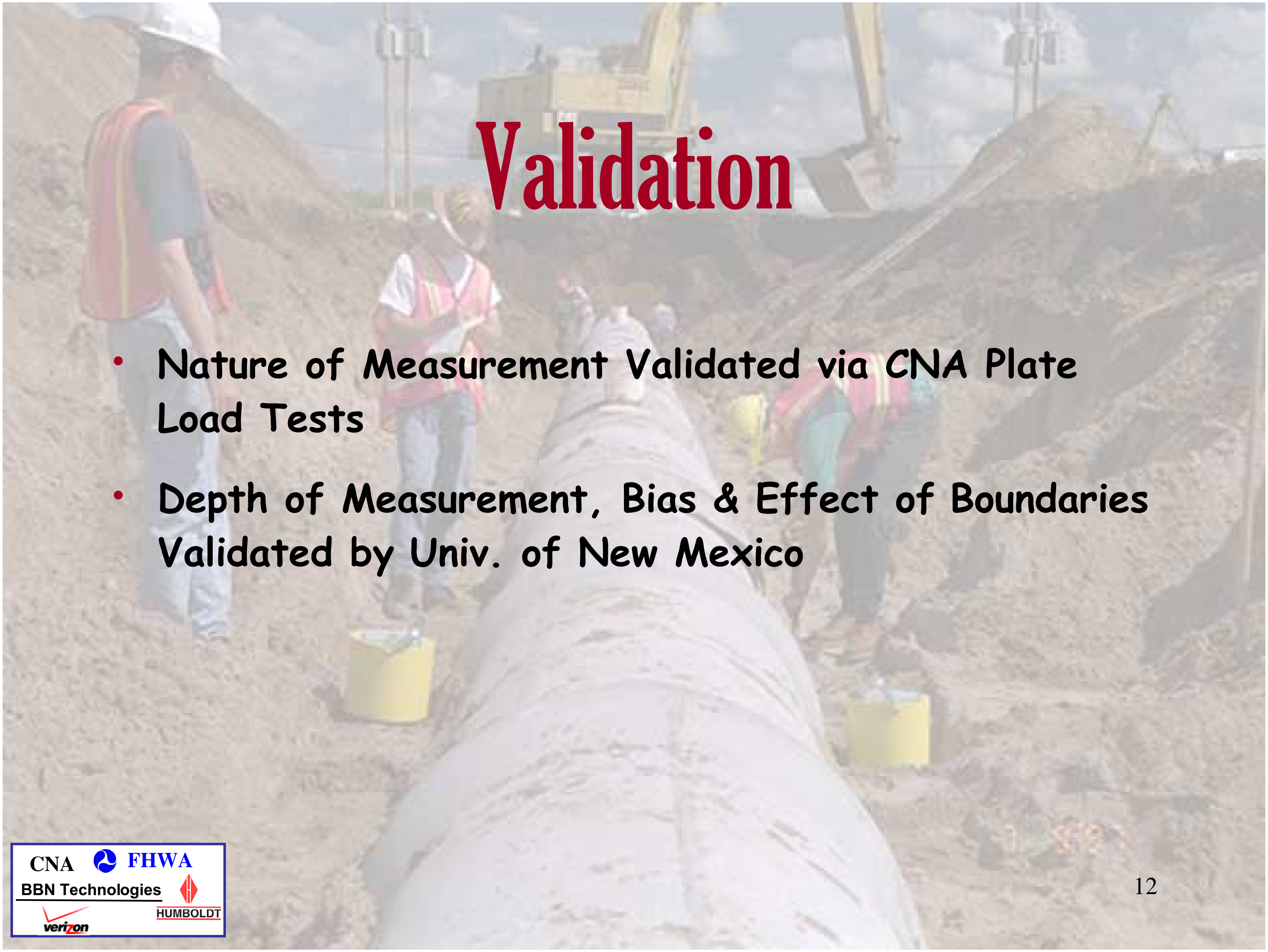
Bias

- Reference: Moving Mass
  - Known Mass: 10 kg (22 lb)
  - 25 Known Frequencies: 100 to 196 Hz
  - Stiffness = $-j\omega^2 M$
- Coefficient of variation: < 1%
- Basis: 100+ Measurements Over 18 Months





Validation

- Nature of Measurement Validated via CNA Plate Load Tests
- Depth of Measurement, Bias & Effect of Boundaries Validated by Univ. of New Mexico

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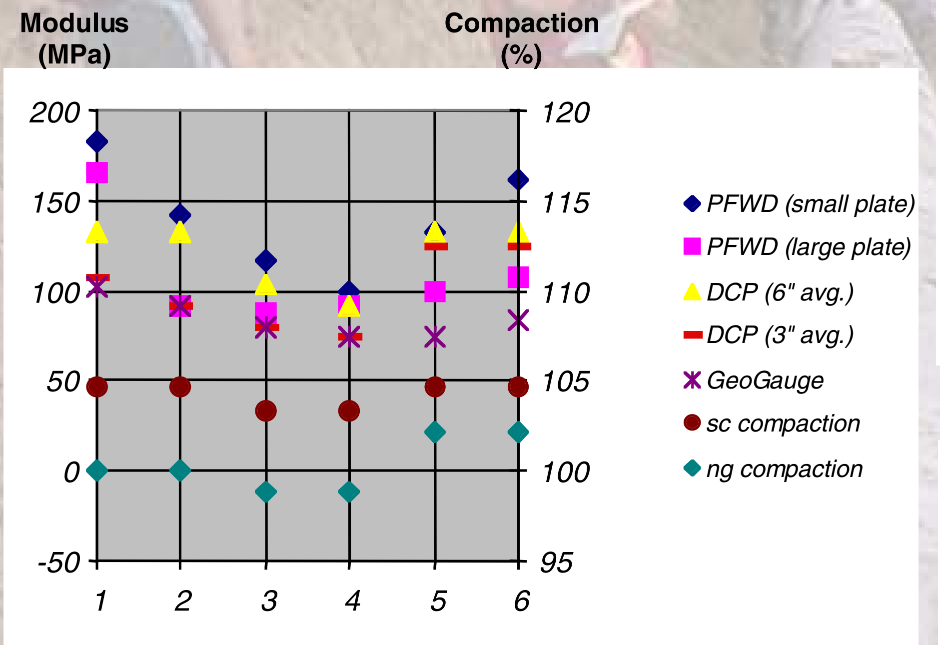
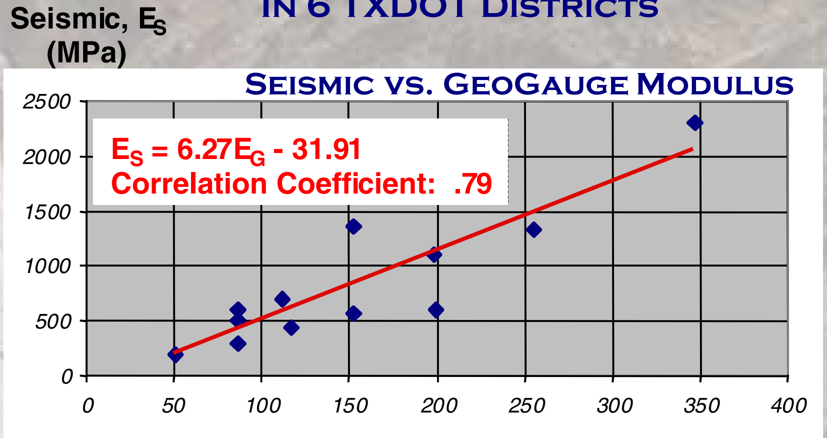
Correlation to Other Moduli

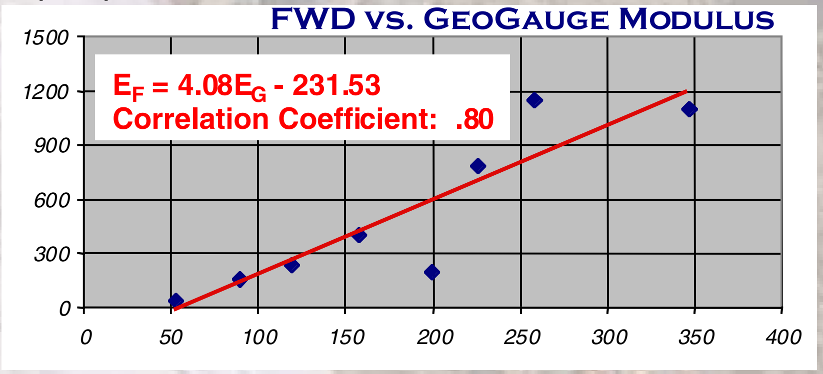
SECTION 17, MN/ROAD



13 PAVEMENT SECTIONS
AT 5 MNDOT SITES

SUBGRADE & BASE MATERIALS IN 6 TXDOT DISTRICTS





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Correlation to Dry Density

1

Analytical-Empirical Relationship

$$\rho_D = \frac{\rho_0}{1 + 1.2\left[\frac{mC}{K} - .3\right]^{.5}}$$

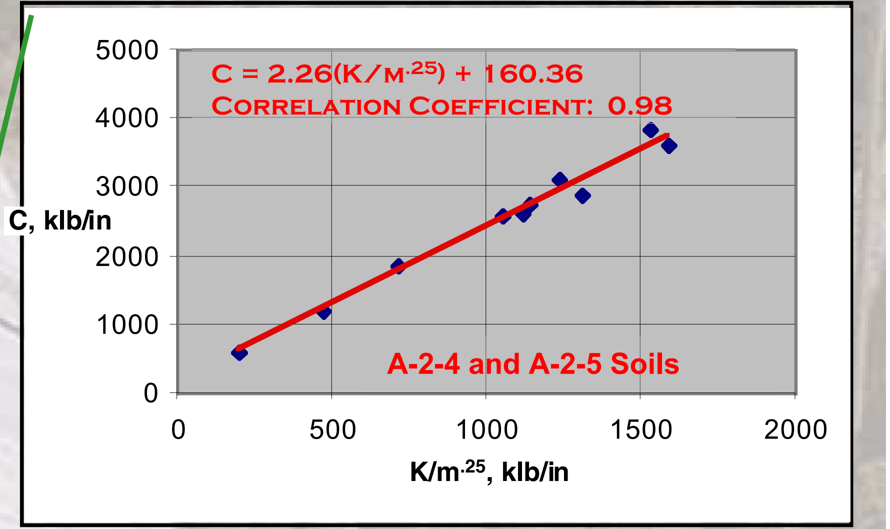
2

Calculate C From Regional Companion Measurements of Stiffness, Moisture Content & Dry Density

$$C = (K/m)\left\{\left[(\rho_0/\rho_D - 1)/1.2\right]^2 + 0.3\right\}$$

3

Define Several Linear Relationships Between C and $K/m^{.25}$ For Groups of Regional Soil Classes



$C = 2.26(K/m^{.25}) + 160.36$

Correlation Coefficient: 0.98

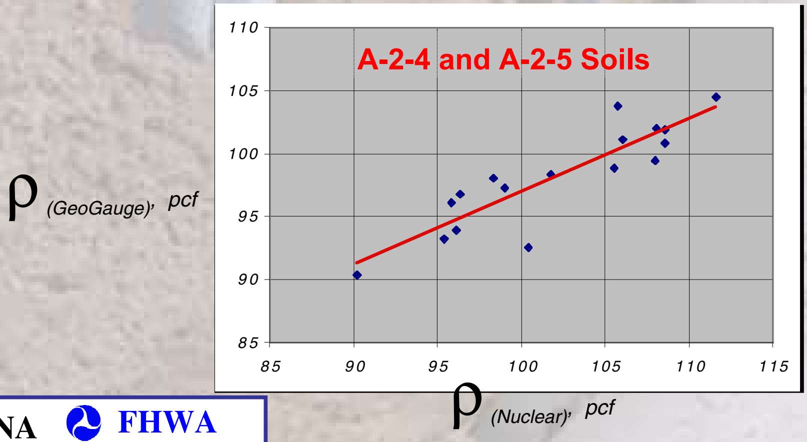
4

From Measurements of Stiffness & Moisture Content And A Calculated C, Estimate Dry Density Using the Same Analytical-Empirical Relationship

$\rho_{(GeoGauge.)} = 0.58(\rho_{(Nuc)}) + 39.39$

Correlation Coefficient: 0.78

Estimated Density Re Measured Density



Data from MODOT, November, '99

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Other Correlations

- Resilient Modulus
- Unconfined Compressive Strength
- CBR
- Binkelman Beam
- Static Cone Penetrometer

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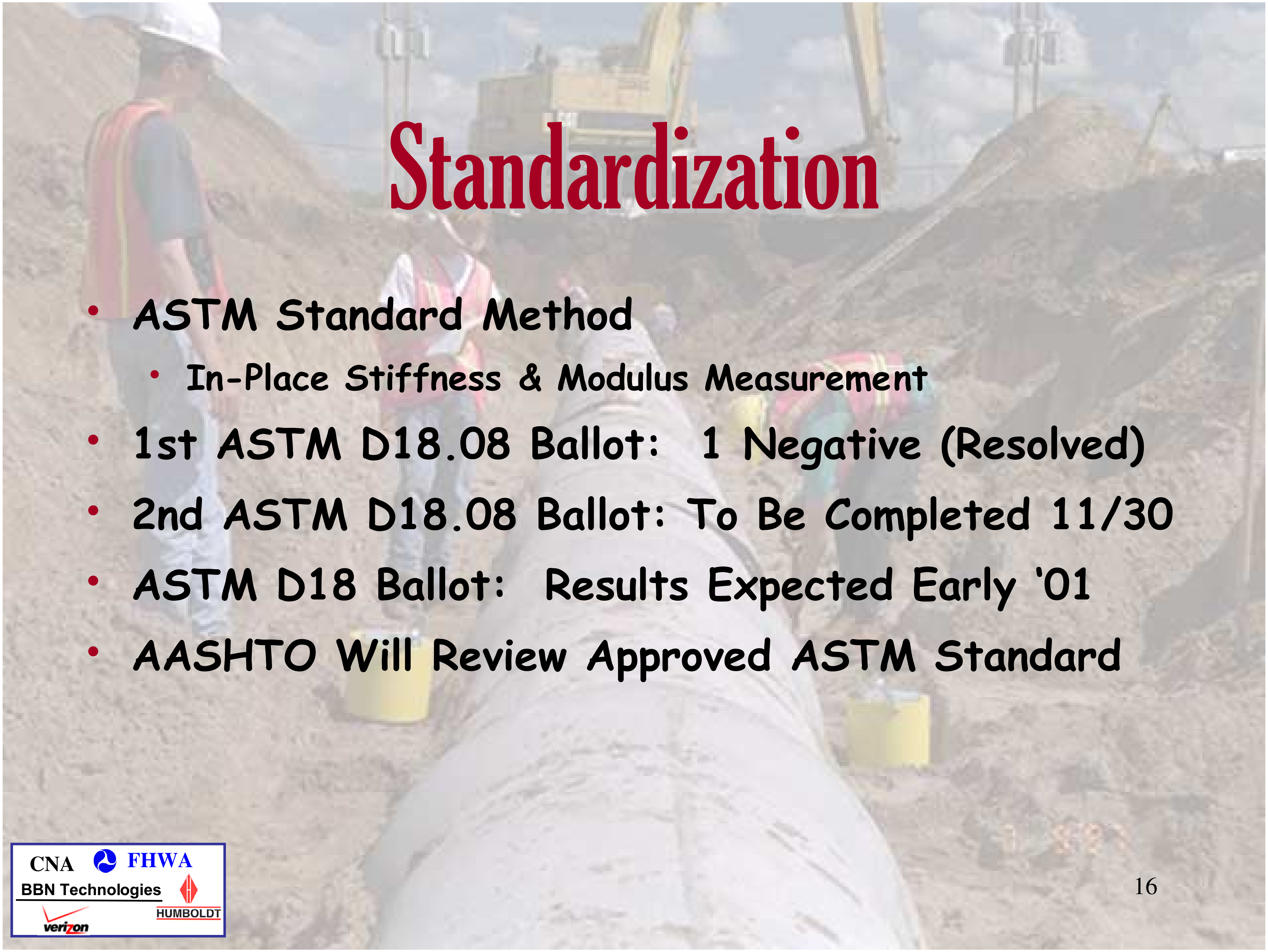

Standardization

- ASTM Standard Method
  - In-Place Stiffness & Modulus Measurement
- 1st ASTM D18.08 Ballot: 1 Negative (Resolved)
- 2nd ASTM D18.08 Ballot: To Be Completed 11/30
- ASTM D18 Ballot: Results Expected Early '01
- AASHTO Will Review Approved ASTM Standard

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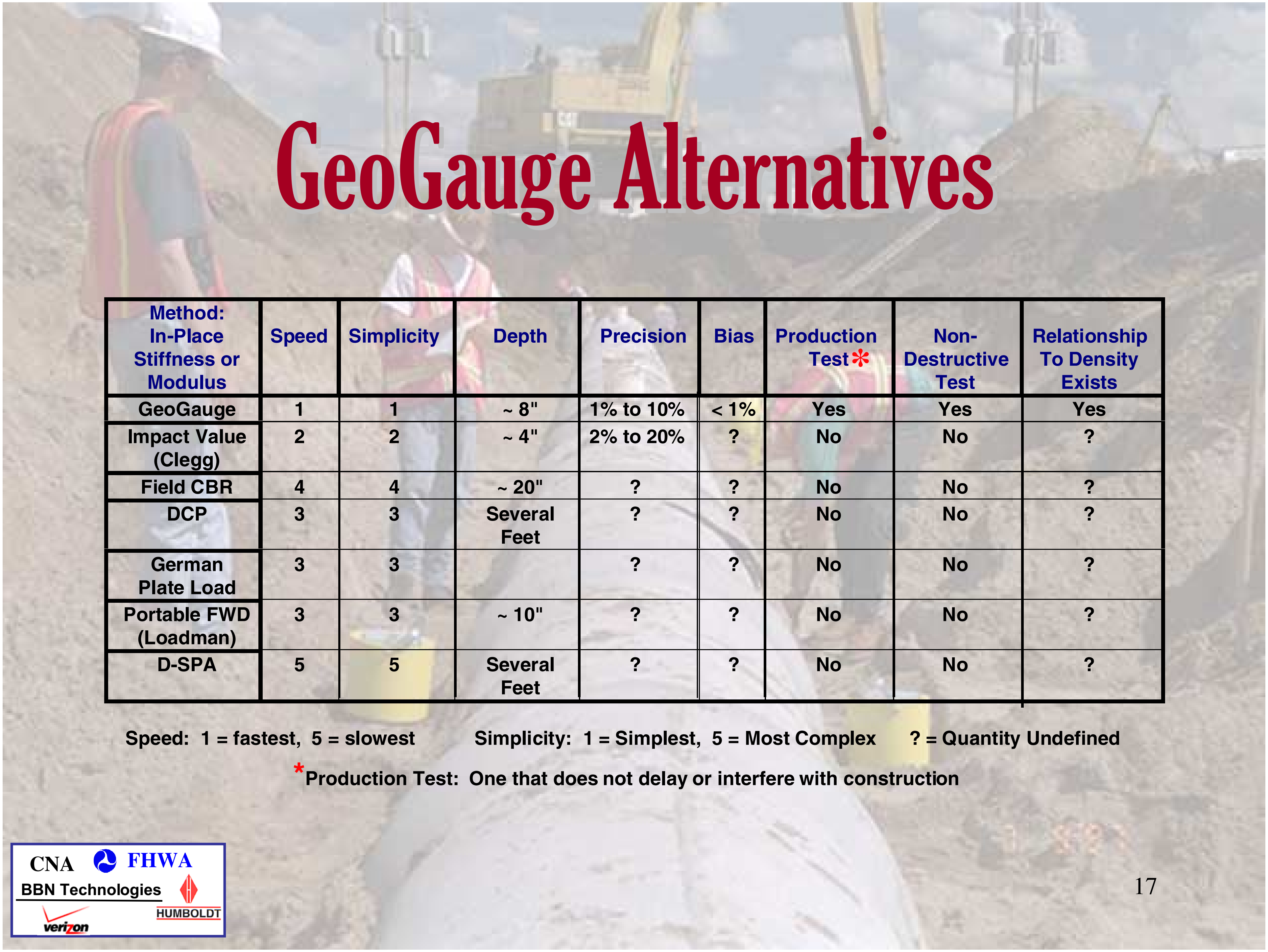

GeoGauge Alternatives

Method: In-Place Stiffness or Modulus	Speed	Simplicity	Depth	Precision	Bias	Production Test*	Non-Destructive Test	Relationship To Density Exists
GeoGauge	1	1	~ 8"	1% to 10%	< 1%	Yes	Yes	Yes
Impact Value (Clegg)	2	2	~ 4"	2% to 20%	?	No	No	?
Field CBR	4	4	~ 20"	?	?	No	No	?
DCP	3	3	Several Feet	?	?	No	No	?
German Plate Load	3	3		?	?	No	No	?
Portable FWD (Loadman)	3	3	~ 10"	?	?	No	No	?
D-SPA	5	5	Several Feet	?	?	No	No	?

Speed: 1 = fastest, 5 = slowest

Simplicity: 1 = Simplest, 5 = Most Complex

? = Quantity Undefined

*Production Test: One that does not delay or interfere with construction

Design History

The Origin of the Technology
Dual Use Technology
Development Approach

- Concept Formulation
- Proof-of-Principle Demonstration
- Commercialization

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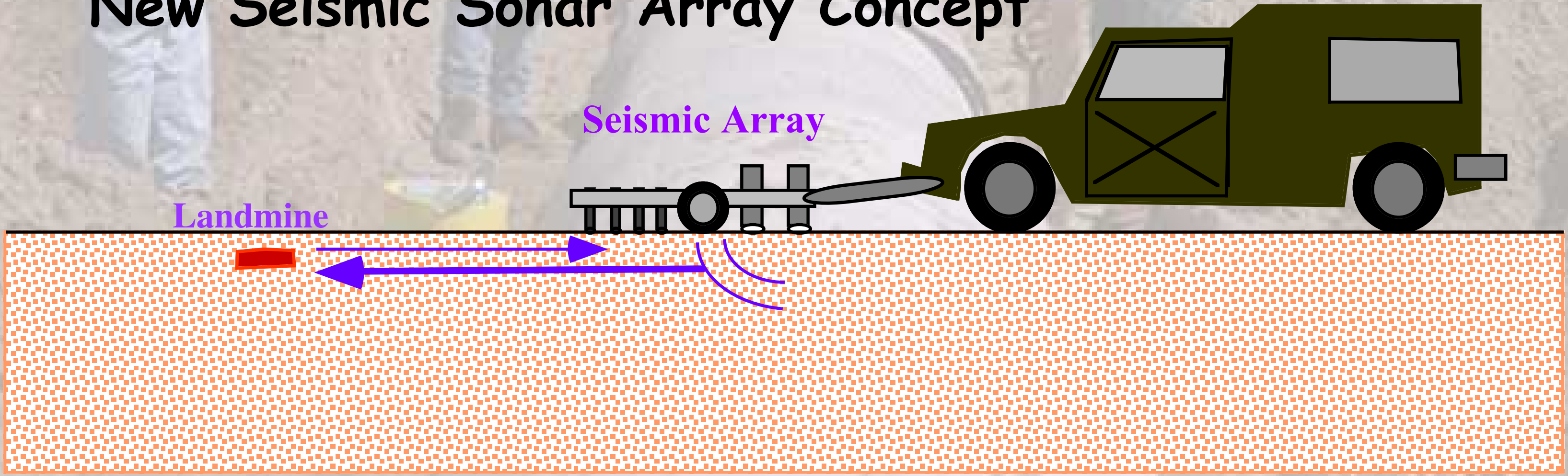
The Origin of The Technology

Seismic Landmine Detection

BBN Seismic Landmine Detection Research

For Army Belvoir R & D Center, '88 to '92

- Goal: Detect Buried, Non-Metallic Mines With Seismic/Acoustic Waves From a Safe Distance
- Feasibility Demonstrated of Mine Detection with New Seismic Sonar Array Concept



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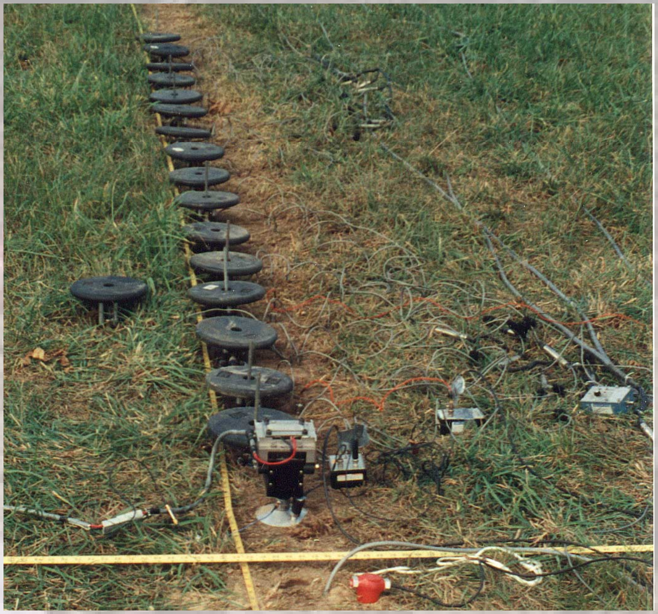
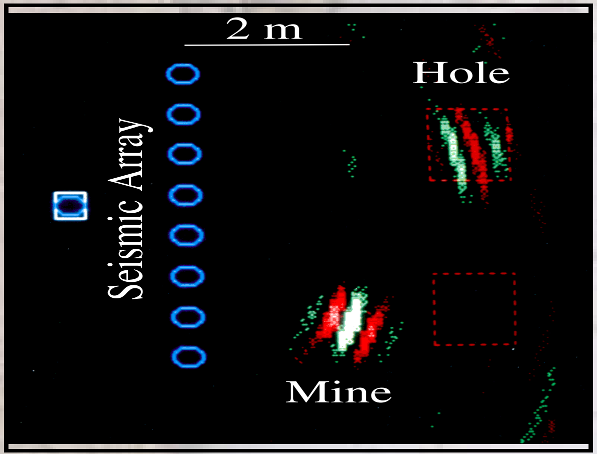
BBN Shallow Soil Seismic/Acoustic Research

- Soil Physics & Measurements
  - Soil Impedance
  - Wave Propagation
- Transducer Coupling Research
- System Development & Displays



BBN Proprietary Weight-biased Geophones and Compact Vibrator Source



Seismic Sonar Display of Response of Mine

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Dual Use Technology

- Logical Transfer to Civil Application
- Transfer via DARPA TRP: '93 to '96
  - BBN, CNA, MTS & MnDOT Team
  - FHWA Designated Program Manager
  - Goal: Use of Stiffness for Evaluating Compaction
  - Approach
    - Define Engineering Requirements
    - Define Sales Potential
    - Prototype
    - Commercialize

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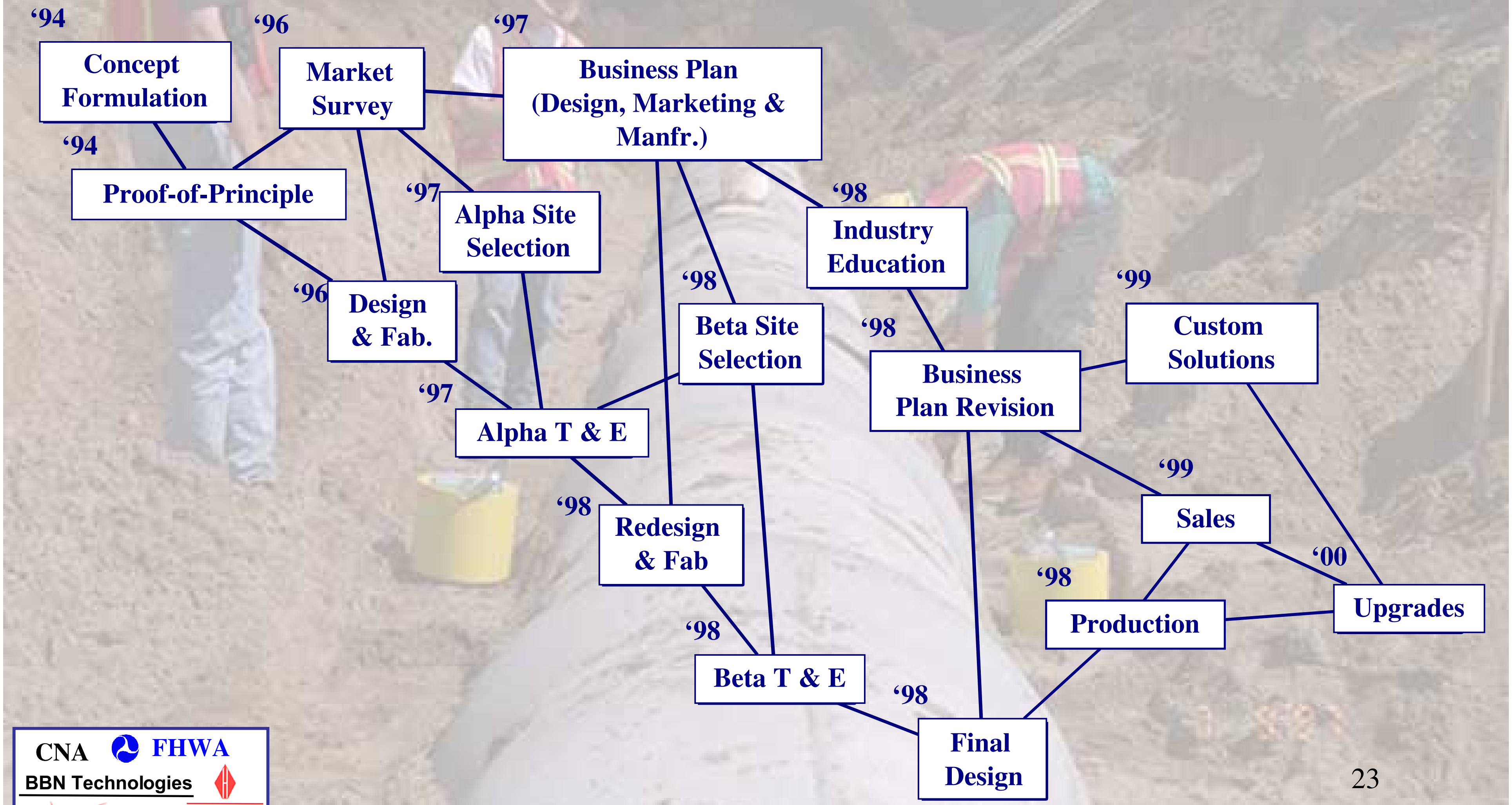
Development Approach



‘94
Concept Formulation

‘96
Market Survey

‘97
Business Plan (Design, Marketing & Manfr.)

‘94
Proof-of-Principle

‘97
Alpha Site Selection

‘98
Industry Education

‘96
Design & Fab.

‘98
Beta Site Selection

‘98
Business Plan Revision

‘99
Custom Solutions

‘97
Alpha T & E

‘99
Sales

‘98
Redesign & Fab

‘00
Upgrades

‘98
Production

‘98
Beta T & E

‘98
Final Design

Concept Formulation

Objectives

- Dynamically Measure Stiffness
  - No Absolute Reference Needed
  - Minimize Degradation by Noise & Physical Anomalies
- Suitable for Widespread Field Use
  - Materials & Process Control
  - Materials Characterization
- Real-Time, Statistically Meaningful Sampling
- Reasonable Time-to-Market

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Concept Formulation

Selected Attributes

- Accurate Over 3.8 to 28 kpsi min.
- Measurement Depth Typical of Lift Thickness (~8")
- Measurement Period of ~ 1 min.
- Precision: Coefficient of Variation ≤ 5%
- Easy to Use: One Person Operation, No Penetration
- Portable: Small & Weighing ≤ 30 lb.
- Rugged: As Good or Better Than Current Equip.
- Affordable: ≤ $6,000

Concept Formulation

Design Issues

- Functional Requirements
- Test Signal Design
- Ground Coupling
- Transducers
- Signal Generation & Processing
- Mechanical Design & Packaging
- User Interface
- Calibration & Field Verification
- Basis: Soil Physics From Army & TRP Work

Functional Requirements

- Overburden Biasing Pressure: 4 to 5 psi
- Dynamic Force Level
  - Sufficient for Signal-to-Noise of 3/1
  - Insufficient to Change Material Properties
- Dynamic Range to Be Measured
- Ambient Ground Vibration: Amplitude & Frequency

Test Signal Design

- Frequency Range: 100 to 200 Hz
  - Adequately High
    - Avoiding Ambient Vibration
    - Allowing Static Coupling of Biasing Pressure
  - Adequately Low
    - Avoiding All But Stiffness In Ground Impedance
    - Avoiding Internal Resonances
  - Adequately Broad
    - Enhancing Signal-to-Noise
    - Avoid Resonances From Physical Anomalies
- Wave Form
  - Stepped Steady-State
  - Duration: 2 Sec.

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Ground Coupling

- Foot Geometry: Ring Shaped Plate
  - Depth of Measurement
  - Quality of Soil Contact (Coupling)
- Foot Properties
  - Low Mass
  - High Stiffness
- Static Biasing Weight: 22 lb.
  - Quality of Soil Contact (Coupling)
  - Meaningful Overburden Pressure
- Resilient Mounts
  - Dynamic Decoupling
  - Physical Stability

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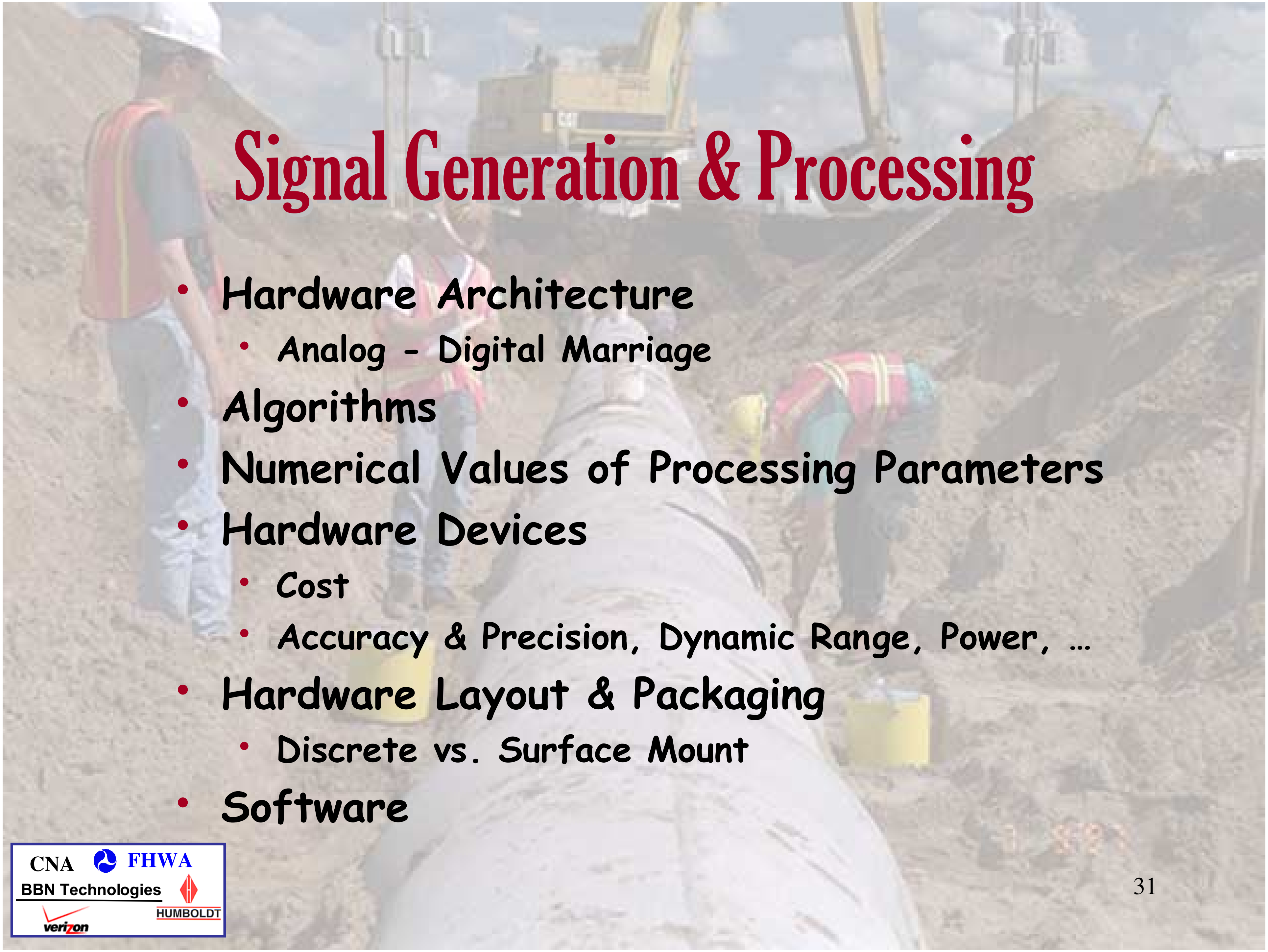
Transducers

Trade-Offs

- **Shaker**
  - Cost
  - Output Level, Bandwidth, Linearity, Ruggedness
- **Motion & Force Sensors**
  - Cost
  - Sensitivity, Noise, Dynamic Range, Bandwidth, Linearity, ...
- **Mass Loaded Geophones Selected**
  - Statically Coupled to Ground
  - Dynamically Decoupled From Ground

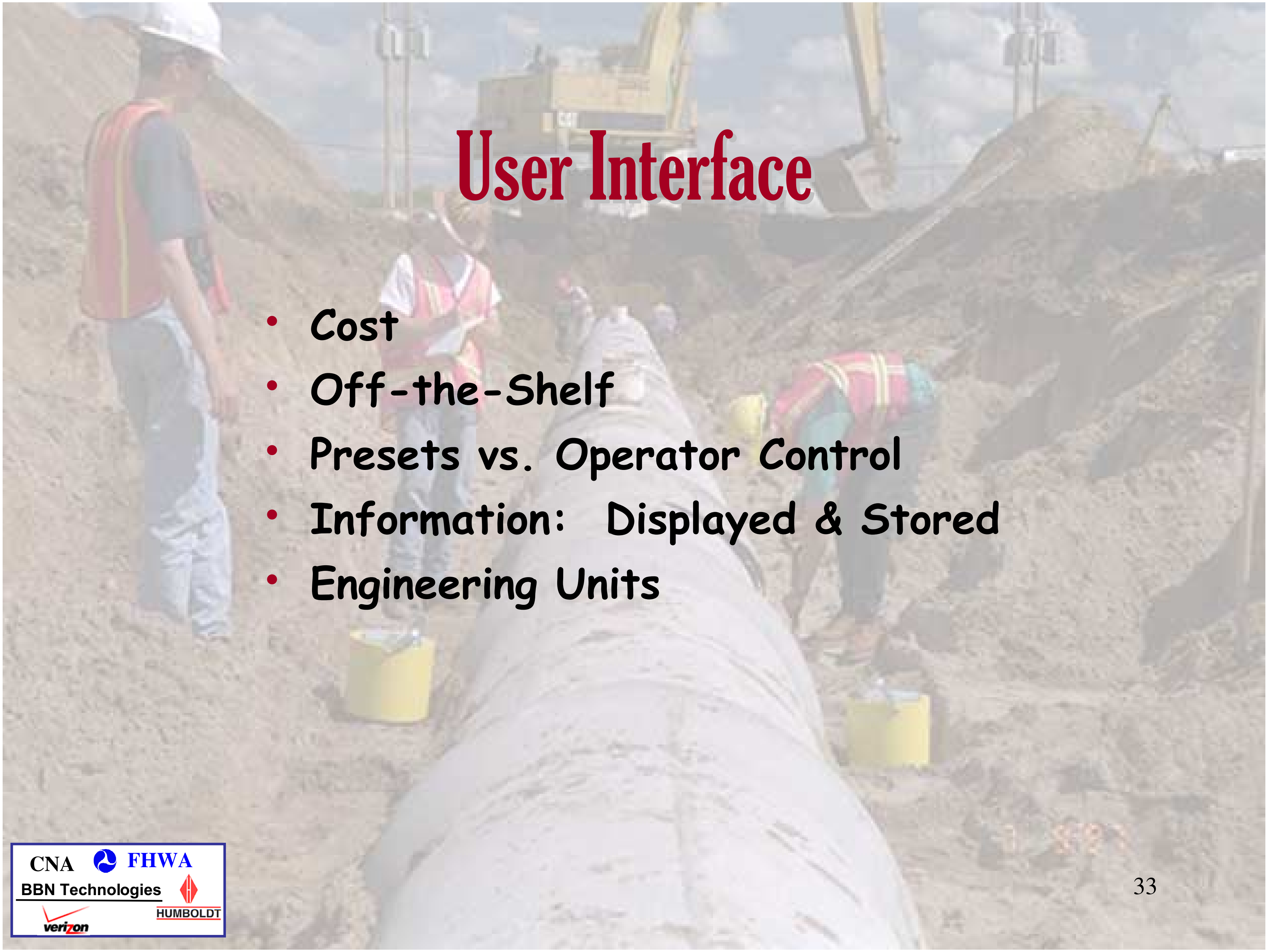


Signal Generation & Processing

- Hardware Architecture
  - Analog - Digital Marriage
- Algorithms
- Numerical Values of Processing Parameters
- Hardware Devices
  - Cost
  - Accuracy & Precision, Dynamic Range, Power, …
- Hardware Layout & Packaging
  - Discrete vs. Surface Mount
- Software

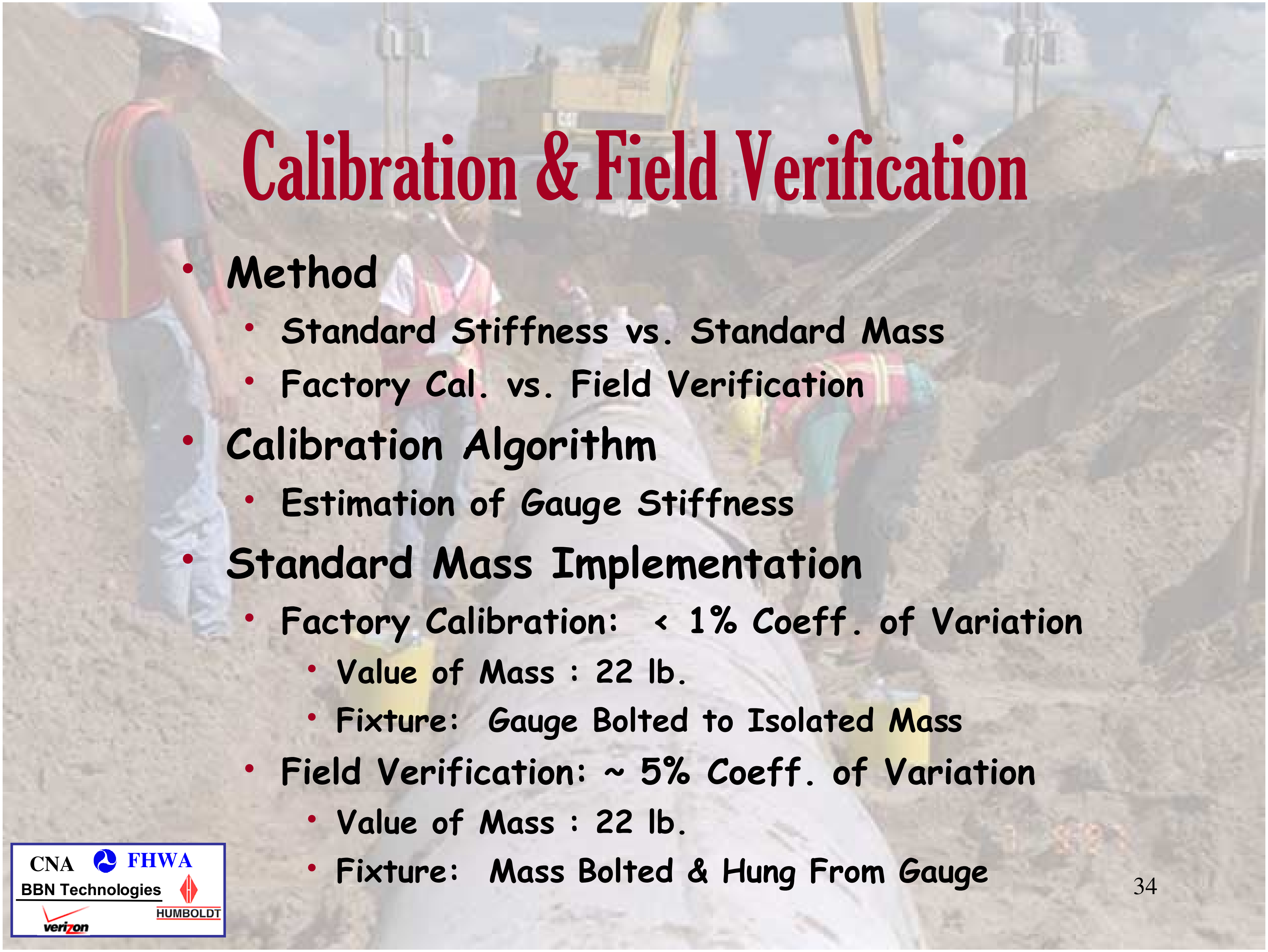
Mechanical Design & Packaging

- Structural Integrity
- Manufacturable, Testable, Repairable & Upgradeable
  - Modularity
- Consistency With Function
  - Stiffness & Mass
  - Frequency Response
- Survivability: Mechanical & Environmental



User Interface

- Cost
- Off-the-Shelf
- Presets vs. Operator Control
- Information: Displayed & Stored
- Engineering Units



Calibration & Field Verification

- Method
  - Standard Stiffness vs. Standard Mass
  - Factory Cal. vs. Field Verification
- Calibration Algorithm
  - Estimation of Gauge Stiffness
- Standard Mass Implementation
  - Factory Calibration: < 1% Coeff. of Variation
    - Value of Mass : 22 lb.
    - Fixture: Gauge Bolted to Isolated Mass
  - Field Verification: ~ 5% Coeff. of Variation
    - Value of Mass : 22 lb.
    - Fixture: Mass Bolted & Hung From Gauge

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Proof-of-Principle: ‘94

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Proof-of-Principle (1994)

- Partners (2 agencies, 2 contractors)
  - Minnesota DOT
  - Metropolitan (Mpls/St. Paul) Council Env. Services
  - Johnson Brothers Corporation
  - Lametti and Sons
- Technical
  - Does it work / What do we measure?
  - What are the “preferred” measurement features?
- Market Forces

1994 Technical Proof-of-Principle

- Ground coupling
- Foot design
- Reliability & repeatability
- Densification during testing
- Machine weight
- Soil moisture content
- Signal to noise ratio / drive level
- Depth of measurement
- Frequency range / frequency dependence

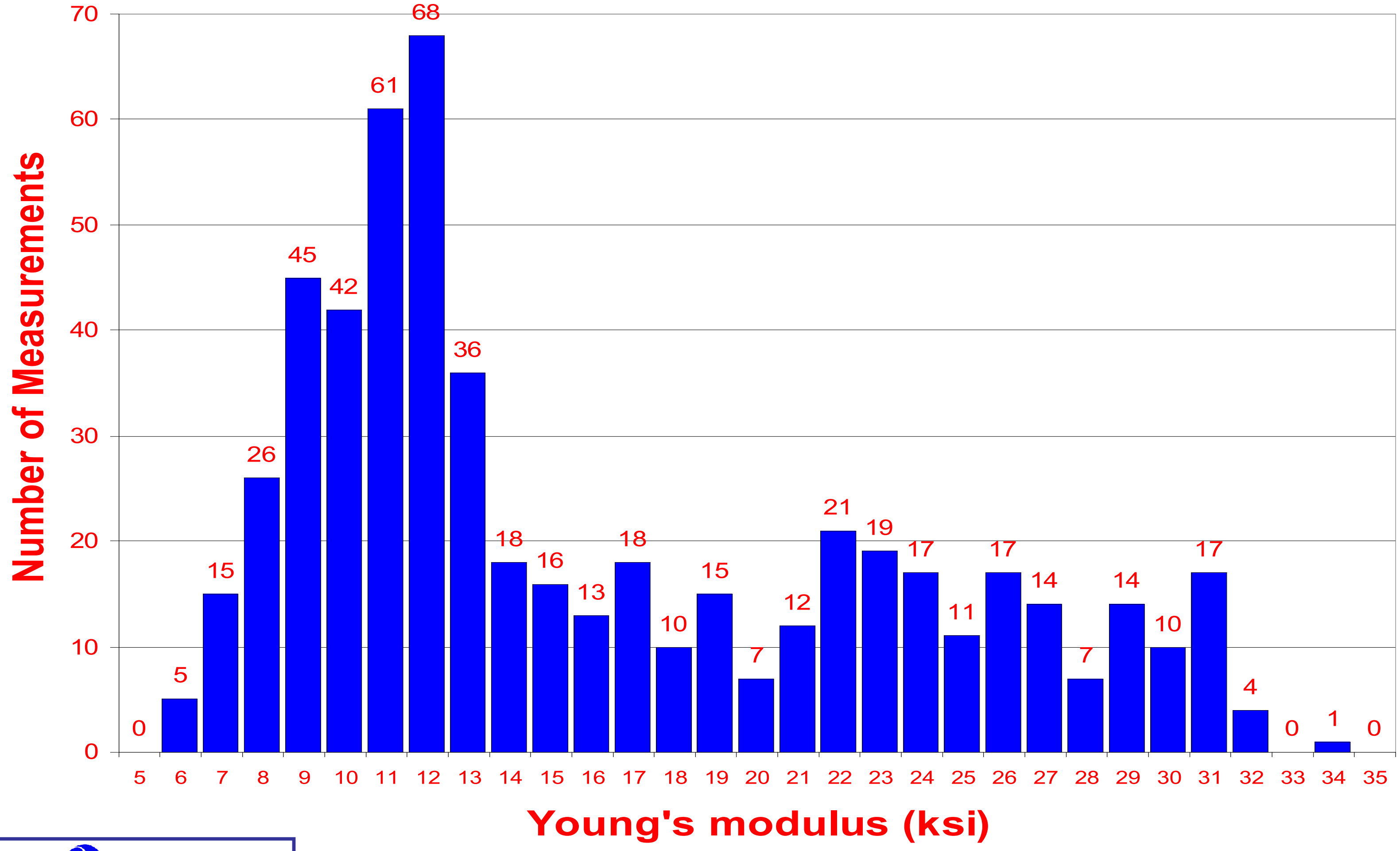
Summary of Minnesota Field Testing

Site	Description	Cooperative Partners	Soil Description
Blaine Interceptor	deep interceptor sewer, constructed by trench and fill	MCWWS	Recompacted trench backfill at surface; deep natural & recompacted soil
Mendota TH 110, 55 & 13	large highway project, testing done on or near eastbound TH 110 east of TH 55 crossover	MnDOT JBC	Roadway subgrade; dense natural soil
Inver Grove Heights TH 55 & 3	large highway project, testing done on an entrance ramp to westbound TH 55	MnDOT	Roadway subgrade

Summary of Field Testing

Site	Locations	Stiffness Measurements	Background Noise Datasets
Massachusetts	3	200	na
Blaine Interceptor	22	188	12
Mendota TH 110, 55 & 13	36	321	7
Inver Grove Heights TH 55 & 3	14	50	4

Distribution of Field Data



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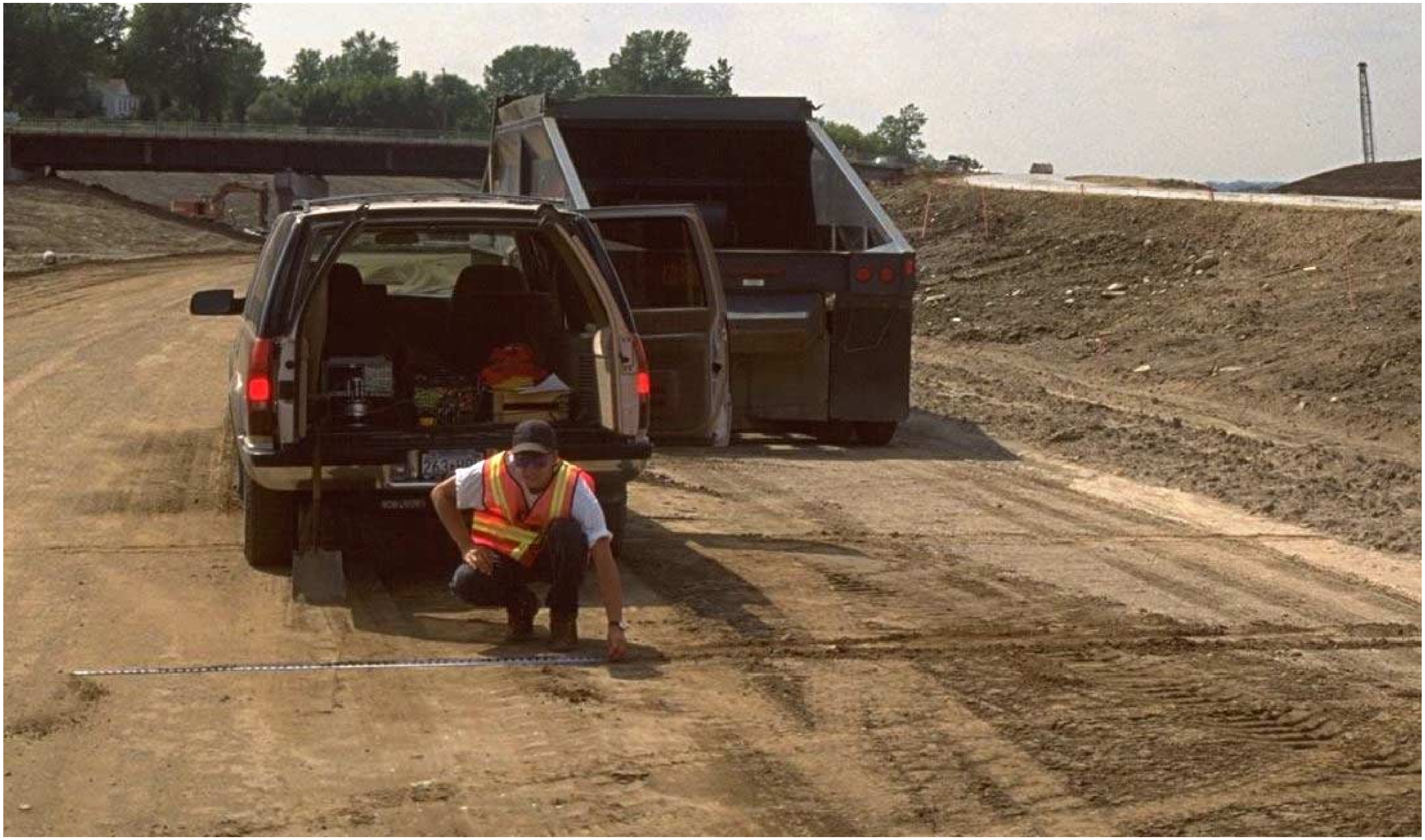
Proof-of-Principle Apparatus



Proof-of-Principle Apparatus (close-up)

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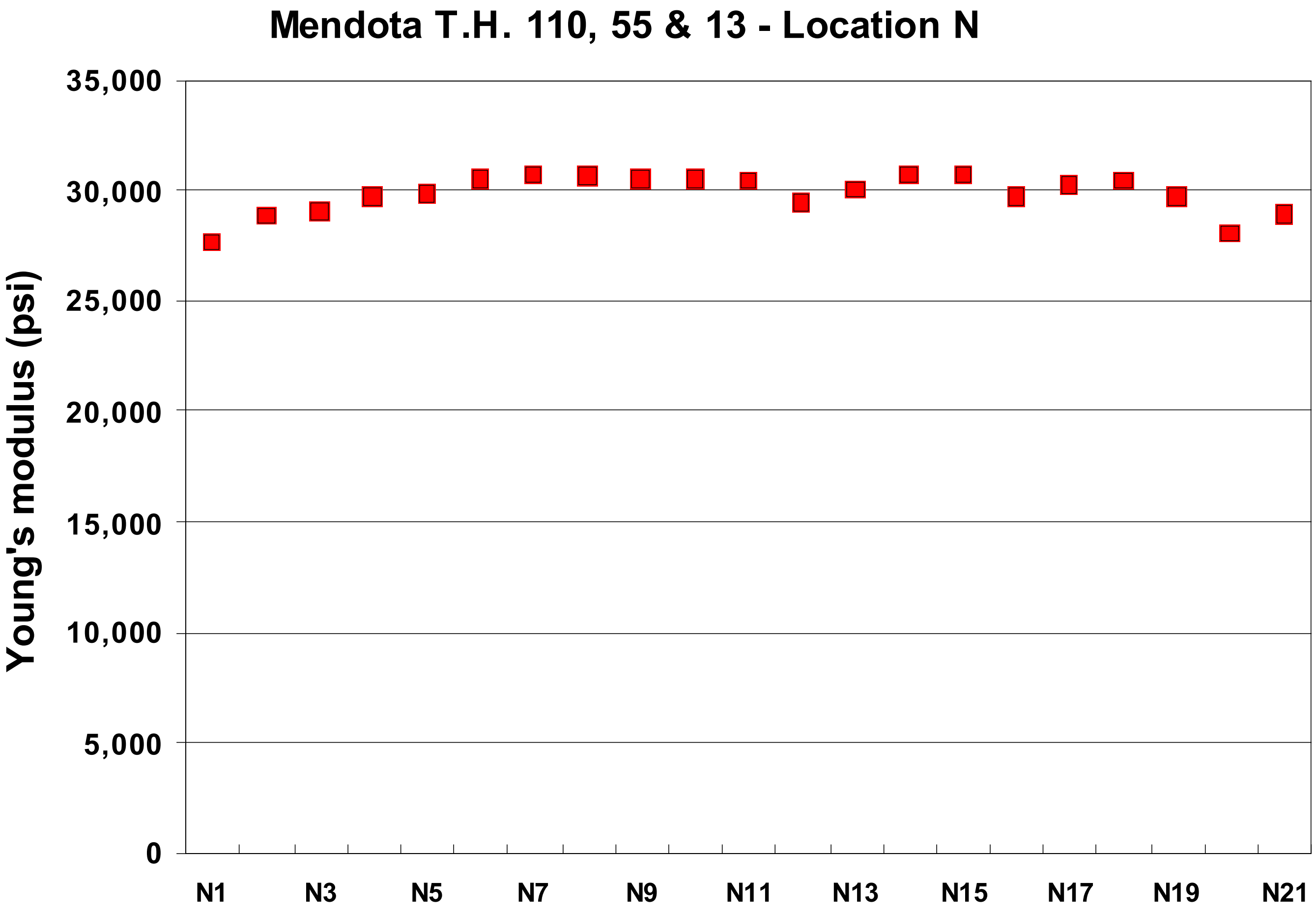
Ground Coupling & Foot Design

Repeatability, Densification, Coupling



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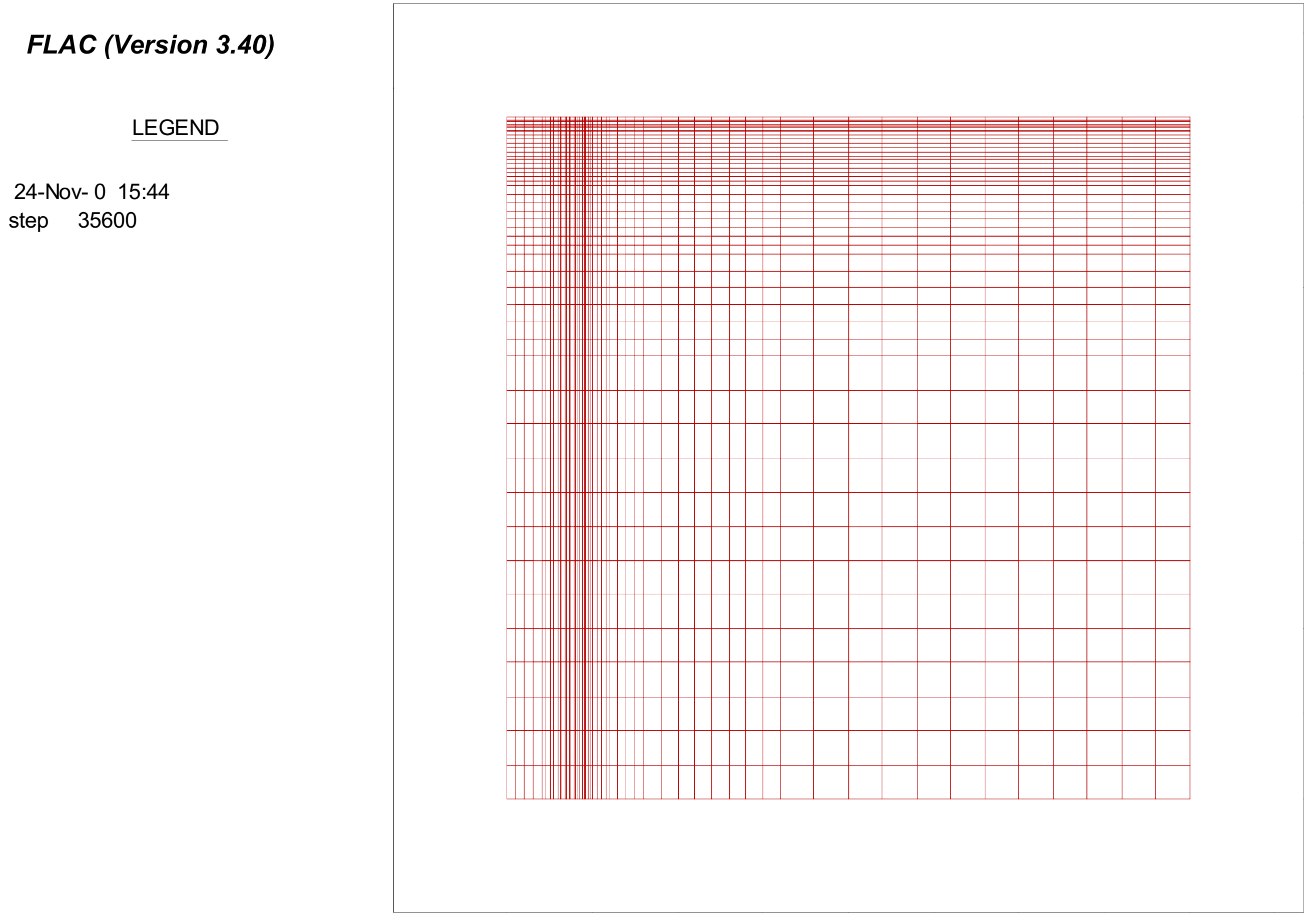
Modeling



FLAC (Version 3.40)

LEGEND

24-Nov- 0 15:44
step 35600

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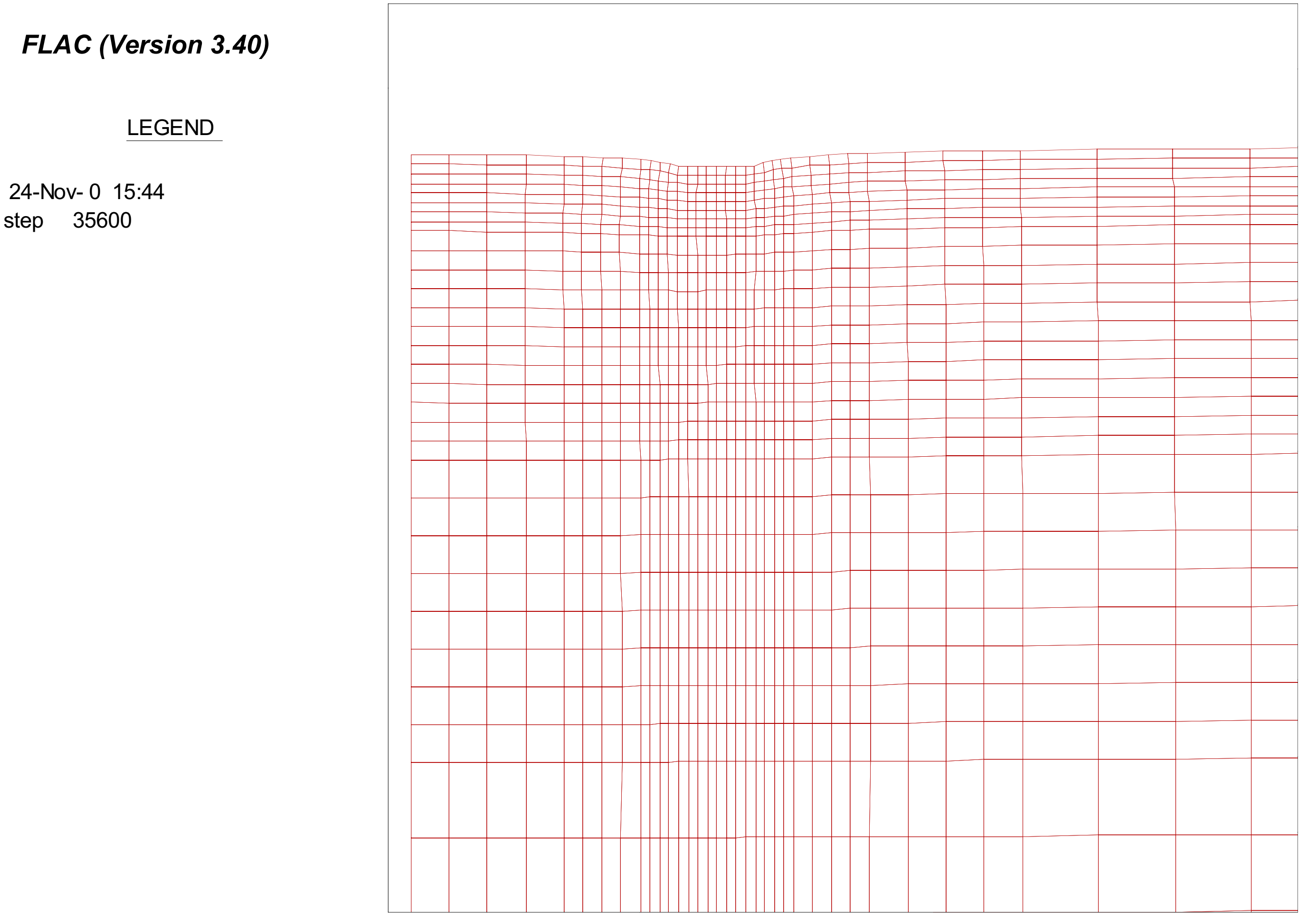
Displacements



Stresses

FLAC (Version 3.40)

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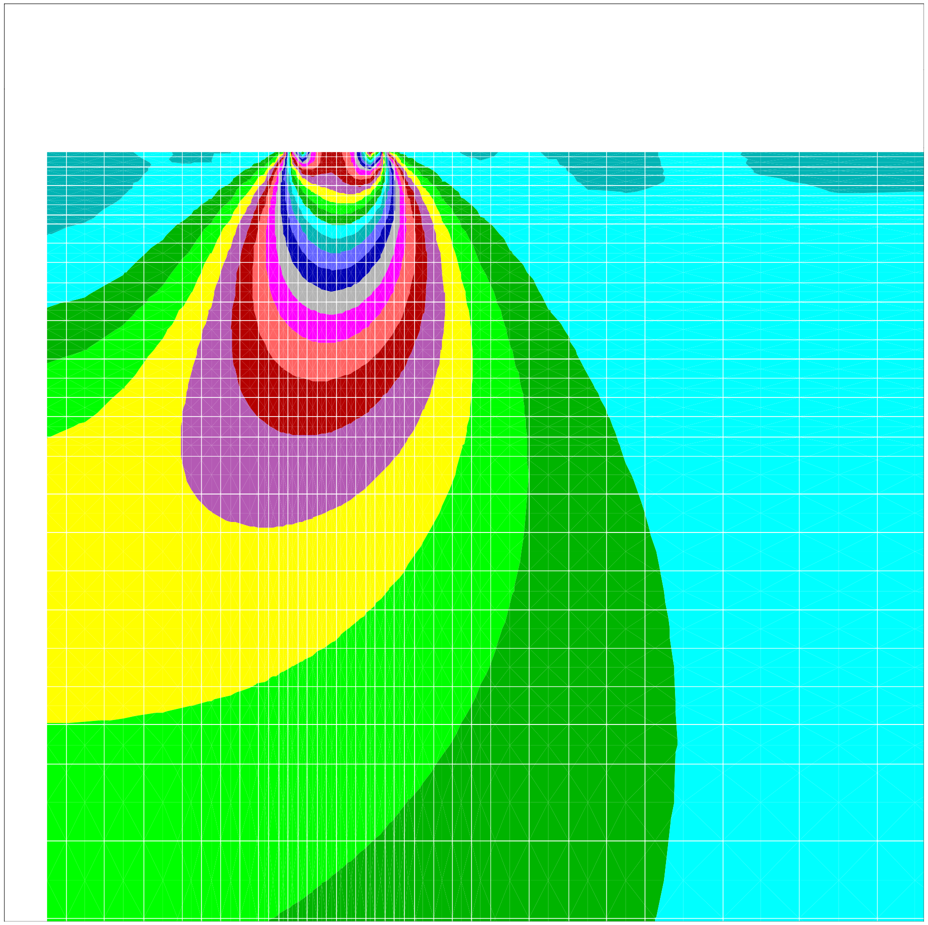

Stresses

FLAC (Version 3.40)

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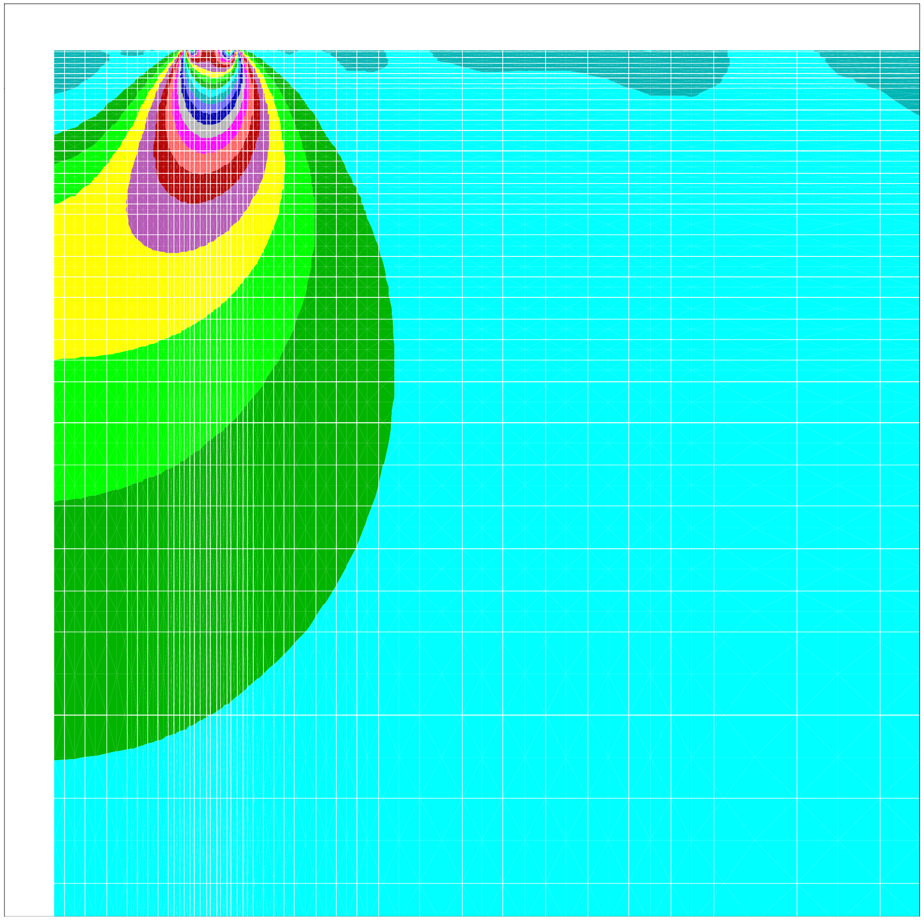

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Backfilled Trench Example

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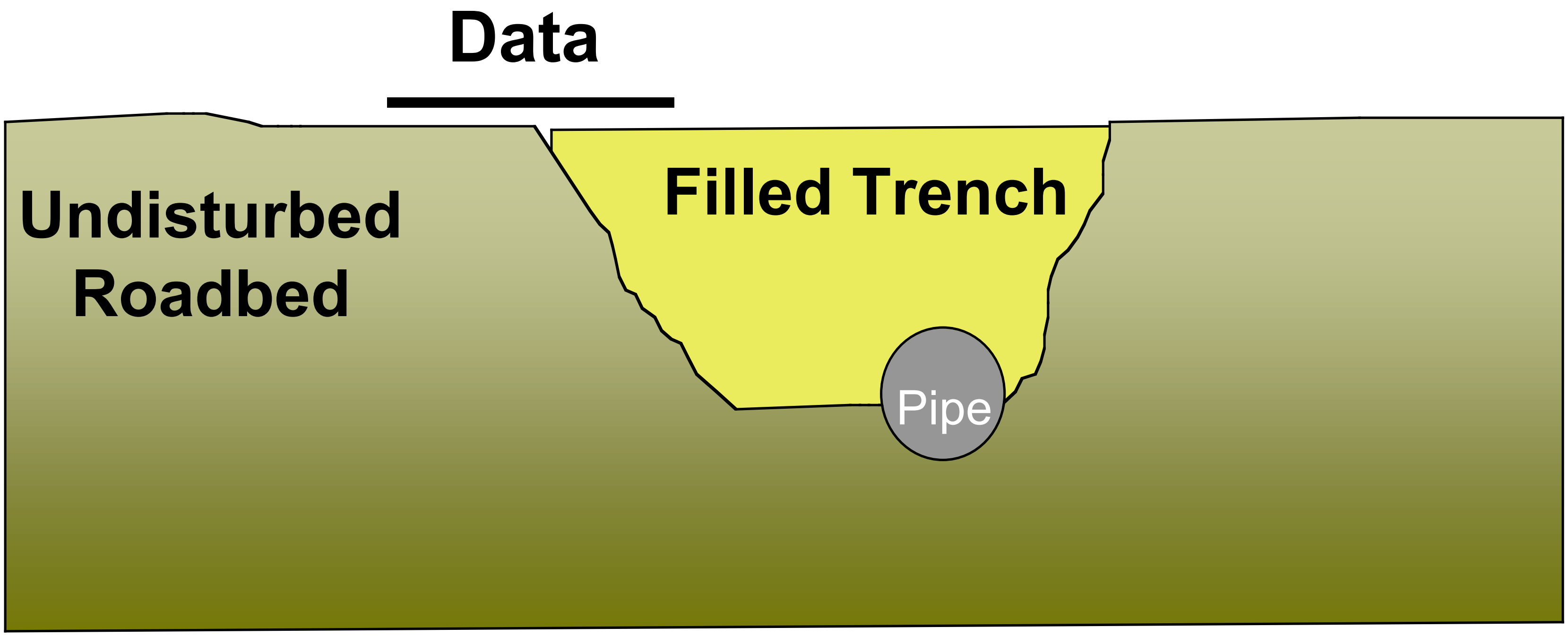
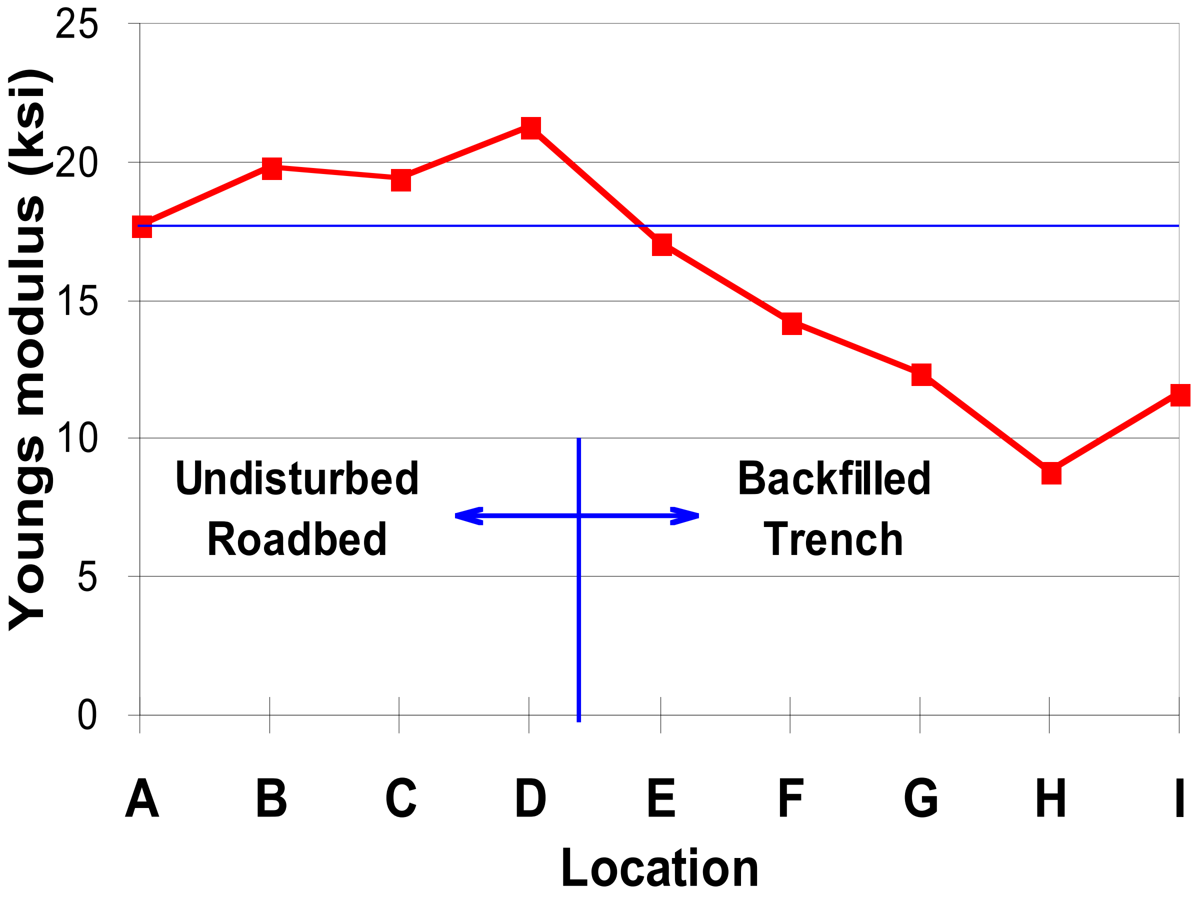
Backfilled Trench Example



Backfilled Trench Example



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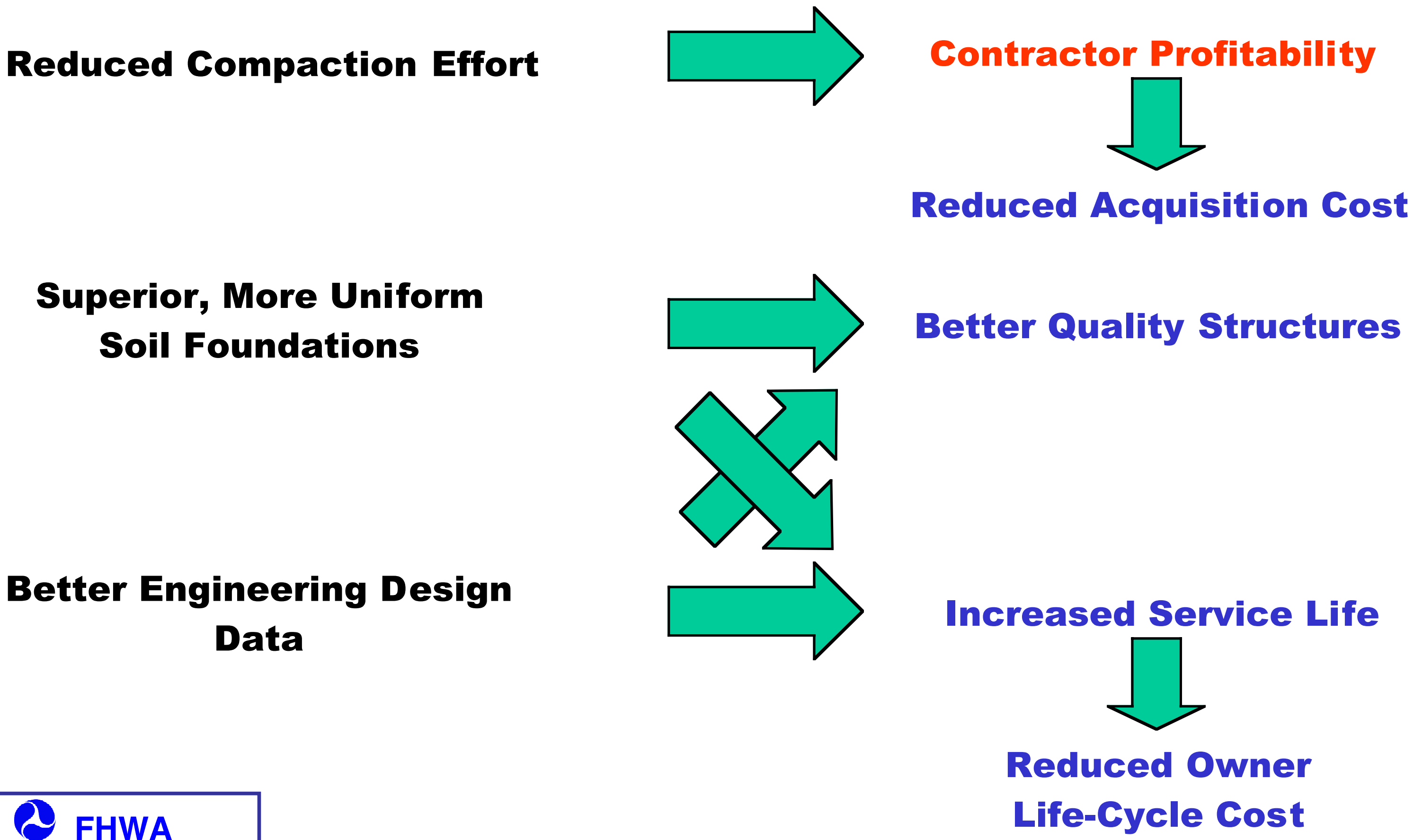
Market Driving Forces



Benefits

Outcomes

Reduced Compaction Effort

Contractor Profitability

Reduced Acquisition Cost

Superior, More Uniform Soil Foundations

Better Quality Structures

Better Engineering Design Data

Increased Service Life

Reduced Owner Life-Cycle Cost

Industry Feedback

- Overcompaction & undercompaction occur
- Uniform compaction is desirable
- Experienced inspectors vs. measurements
- Agency standards & acceptance
- Documented results
- Demonstration projects
- Process control concepts

Commercialization

Design Validation: '97 to '98

Marketing: '96 to '00

Production: '98 to '00

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Design Validation

- Alpha
  - Field Trials: MN, NY & TX
  - Construction Noise: Freq. Shift & Improved Filtering
  - Calibration: Soil vs. Elastomer vs. Mass
  - Relationship Between Density & Modulus
- Beta
  - Field Trials: MN, TX, NC, FL, OH, CA, NJ & MO
  - Usability & Reliability
  - Manufacturing & Test Methods Development
  - Establish Precision & Bias
- Standards Development

Marketing

- Market Survey
- Business Plan Development & Evolution
- Alpha & Beta Site Selection & Lessons Learned
- Education: The Value of Stiffness & Modulus
- Custom Solutions: Realizing Immediate Benefits
- Market Driven Product Improvements

Production

- Manufacturing Plan: 10s to 100s annually
- Design Manufacturability
- Material Sourcing
- Manufacturing, QA & QC Methods
- Training
- Facilities

Enabling the Benefits of Stiffness & Modulus Today

Control of the Compaction Process

Mitigating the Risk of Pavement Failure

Control of Stabilized Fill Quality

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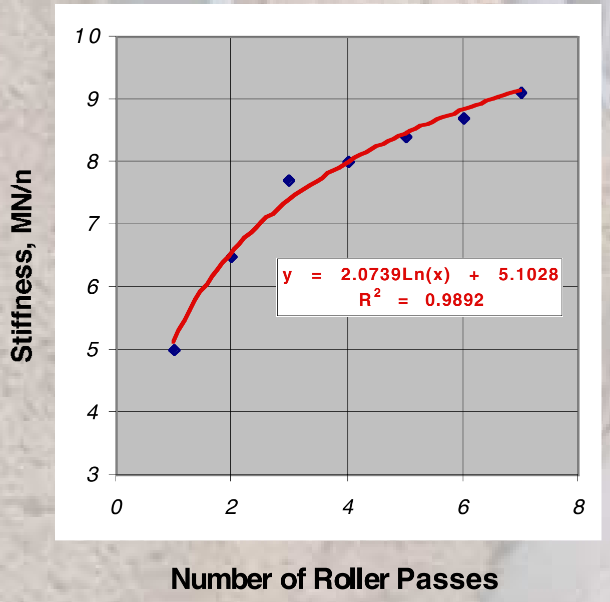
Control of the Compaction Process

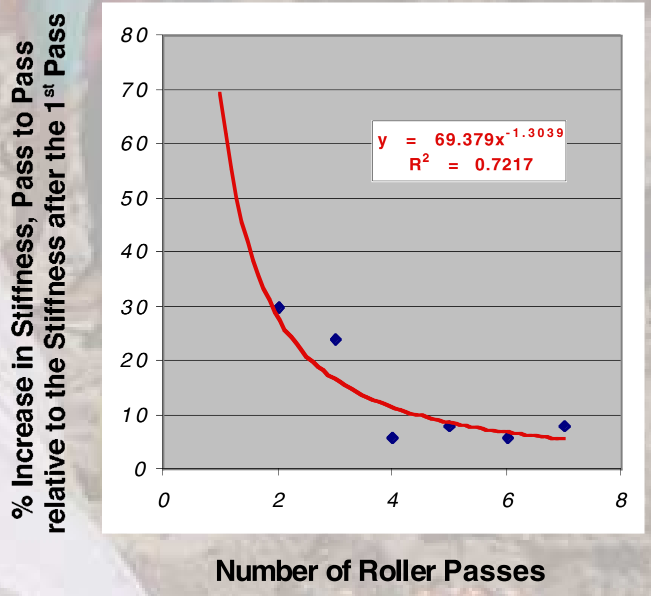
- Compaction of A Layer Is Only As Good As the Supporting Material Will Allow
- Directly Measure Compaction (Rate of Increase in Stiffness) As a Function of Effort
- When the Rate Is Approx. Constant, the Compaction Is Optimized
- ~ 30% Reduction in Compactive Effort Possible



COMPACTION OF 2" OF HMA

MANGUM ASPHALT, INC.

JUNE, 2000



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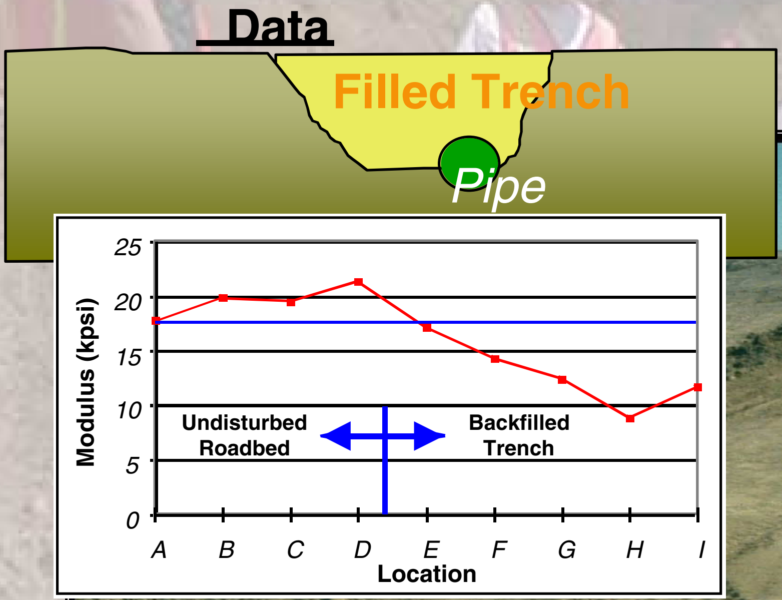
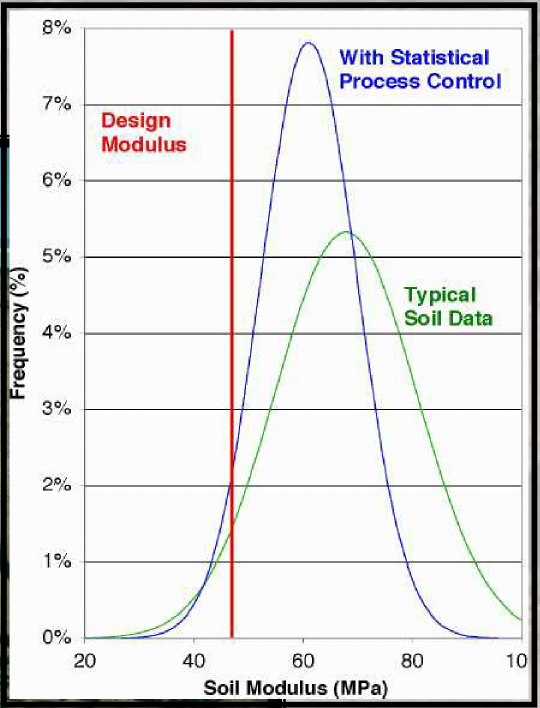
OPTIMUM COMPACTION WITH MINIMUM EFFORT

Mitigating the Risk of Pavement Failure

More Uniform Stiffness = More Time Between Failures





- Sharp Stiffness Changes = Near Term Failures
- Experience Is Indicating:
  - ± 50% Stiffness Tolerance, Fewer Near Term Failures
  - ± 25% Stiffness Tolerance, Fewer Long Term Failures

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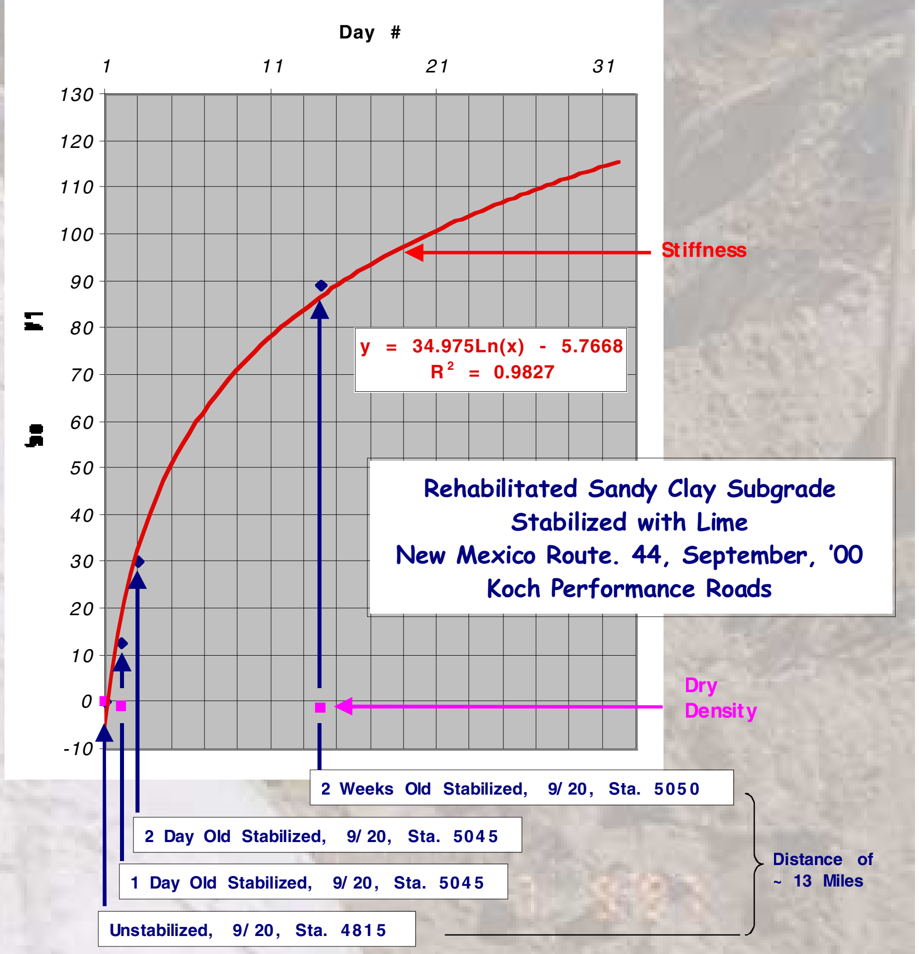
Control of Stabilized Fill Quality

- "Is the Fill Hard Enough?"
- "Has Rain Inhibited Stabilization?"
- "Can I Customize Stabilization?"
- GeoGauge Can Enable:
  - Monitoring of Material Cure Rate
  - Direct Measurement of Material Modulus
  - Laboratory Design of Custom Mixes & Determination of Indexes for Evaluating Construction
- GeoGauge Specified By USAF for Runway Infield Stabilization
  - Used to Estimate Increases in CBR

Evaluation of Stabilization



y = 34.975Ln(x) - 5.7668
R^2 = 0.9827

Rehabilitated Sandy Clay Subgrade
Stabilized with Lime
New Mexico Route. 44, September, '00
Koch Performance Roads

2 Weeks Old Stabilized, 9/20, Sta. 5050
2 Day Old Stabilized, 9/20, Sta. 5045
1 Day Old Stabilized, 9/20, Sta. 5045
Unstabilized, 9/20, Sta. 4815

Distance of ~ 13 Miles

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Some Other Applications

- Specification Development
- Mechanistic Design Validation
- Buried Structures QC
- Utility Back-Fills QC
- Determination of HMA “Tender Zone”
- Evaluation of Controlled Low Strength Materials
- Quantification of Soil-Cement Micro-Cracking
- Cold Mix Asphalt QC