Intelligent Compaction
Mn/DOT Demonstrations 2005

Iowa Geotechnical Workshop

December 13, 2005

Ames, IA

John Siekmeier, PE

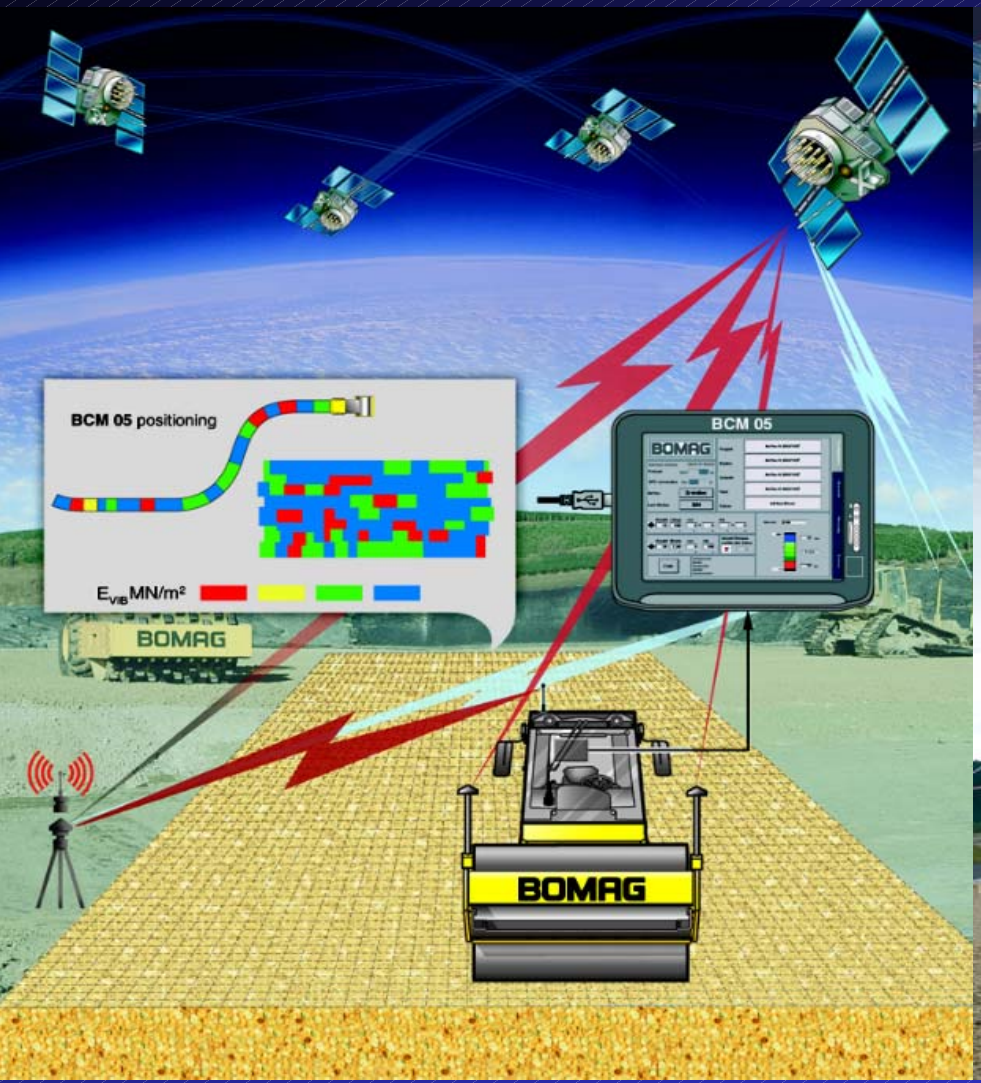
Mn/DOT

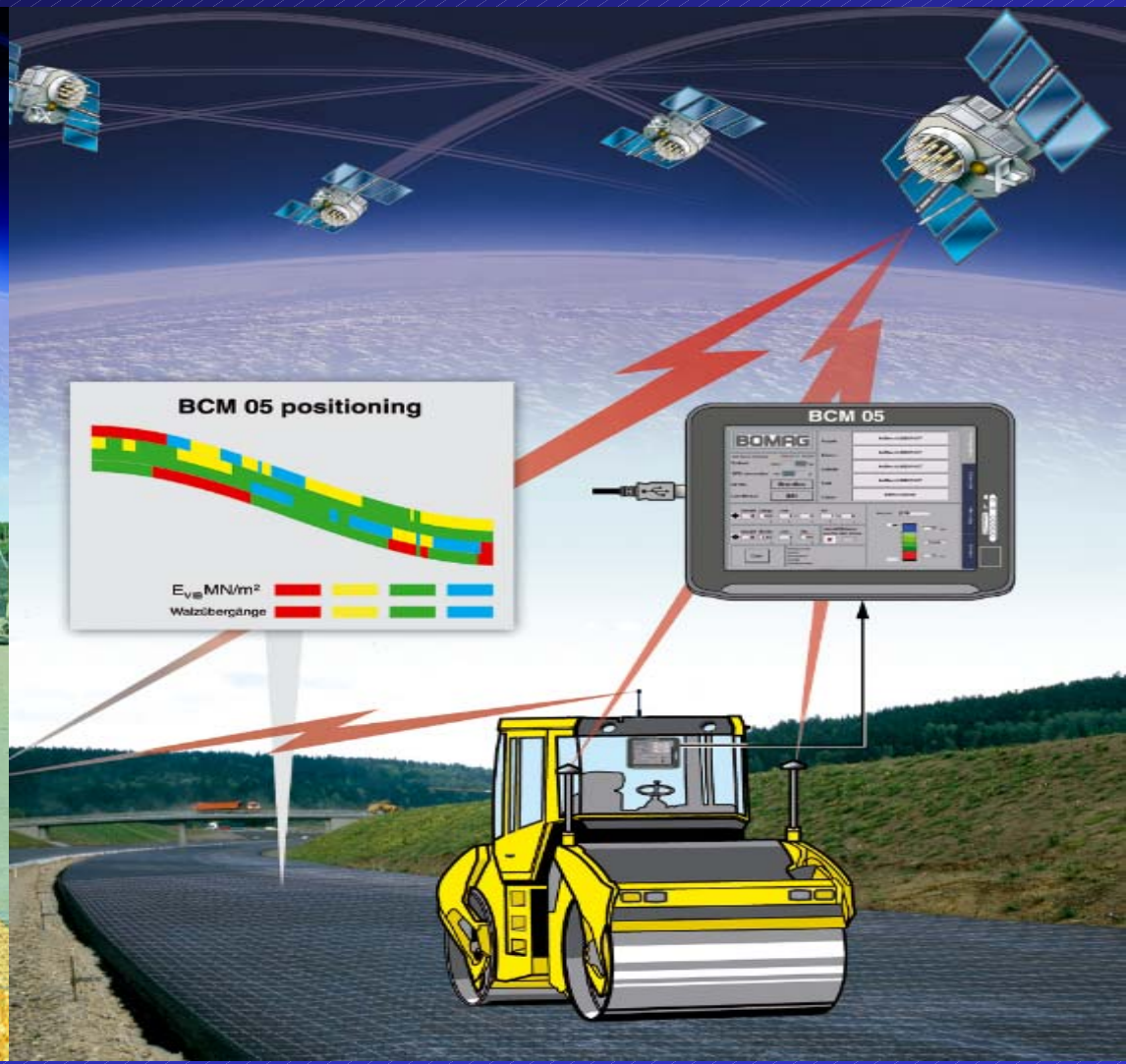
Office of Materials and Road Research

Definition

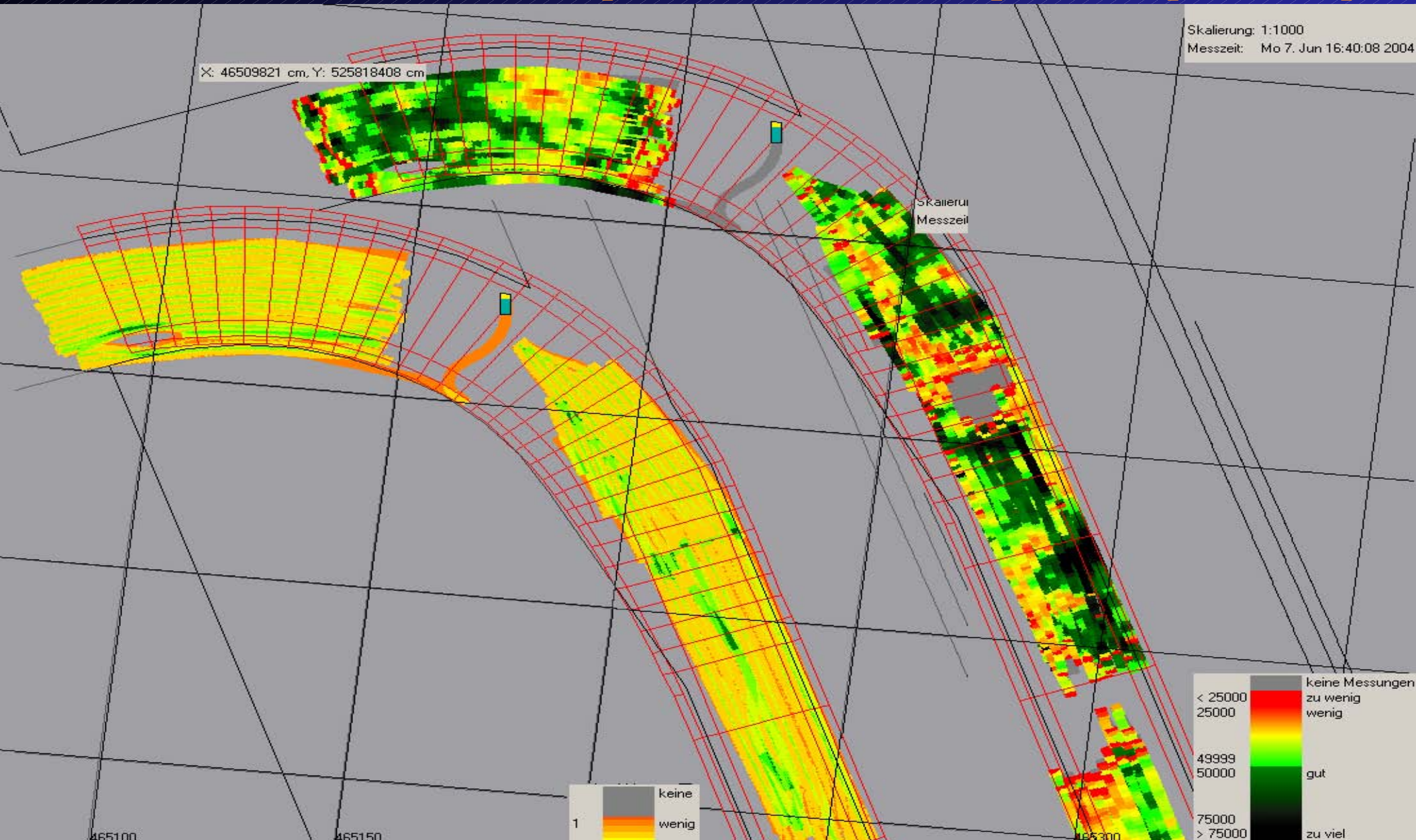
- Intelligent compaction equipment measures and records the quality of compaction during the compaction process. The compactor's force changes in real time to increase compaction where needed, while preventing over compaction. The equipment uses a global positioning system to create a map that shows the quality of compaction across the entire surface of each lift.

Bomag Soil and Asphalt IC Systems



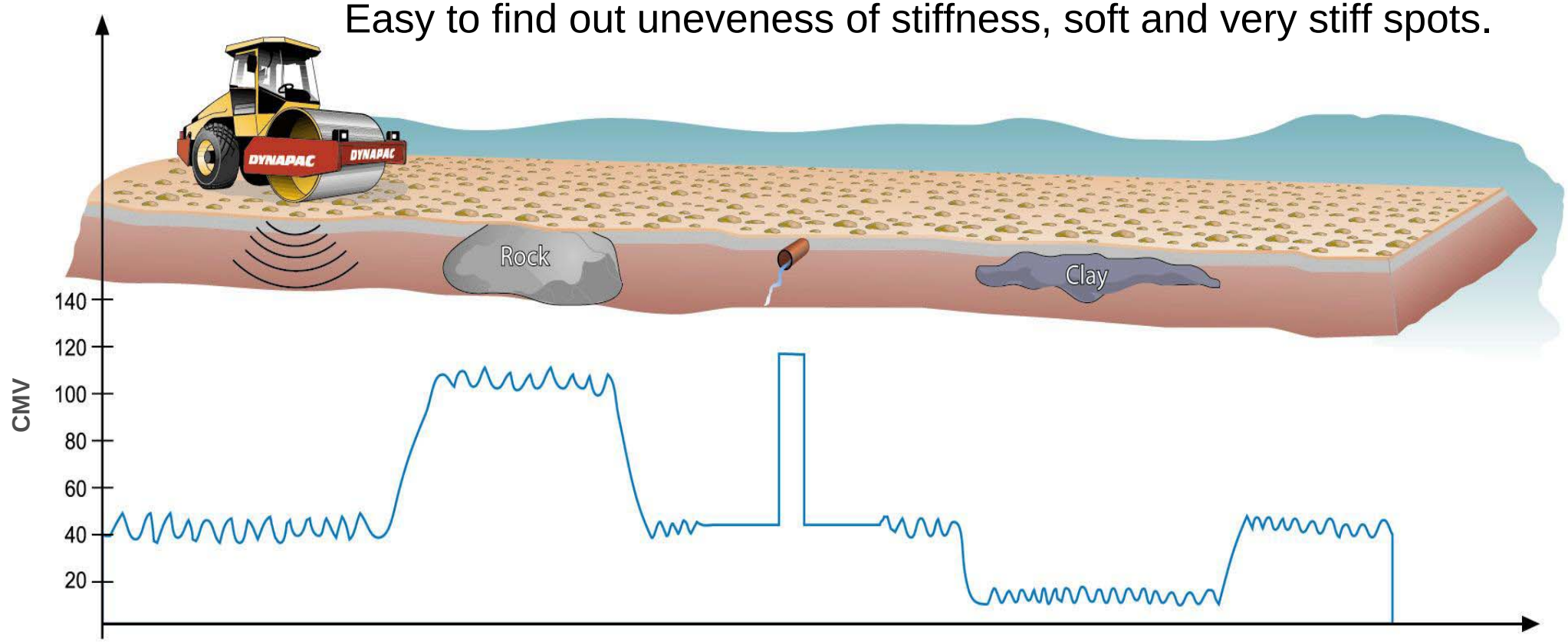


AMMANN Compaction Expert (ACE)



Dynapac Continuous Compaction Control

Easy to find out uneveness of stiffness, soft and very stiff spots.



Intelligent Compaction Task Force

- District 1
- District 7
- District 8
- Office of Construction
- Office of Investment Management
- Office of Materials
- Office of Technical Support
- Federal Highway Administration

Task Force Objective

- Begin the process of determining whether to change the Mn/DOT compaction acceptance criteria and quality control / quality assurance (QC / QA) procedures for soils and aggregate bases from density to modulus by using emerging technologies that include intelligent compaction.

Benefits to Mn/DOT

- Increased Compaction Uniformity
- Complete Documentation of Every Lift
- Better Record Keeping and Reporting
- Automation and Higher Productivity
- Improved Inspector Safety
- No More Sand Cone Testing


217.5


BOMAG

QA During Bomag Dam Construction

Testing for Compaction

- **Uniformity is the Priority**
- **Currently (Empirical Pavement Design, R-Value)**
  - Specify Relative Density (Proctor Test)
  - Specify Moisture Limits (Proctor Test)
  - Test Rolling (optional)
- **Future (Mechanistic Pavement Design, Modulus)**
  - QC: Intelligent Compaction Equipment
  - QC/QA: Continue to Specify Moisture
  - QA: Specify Modulus and Strength

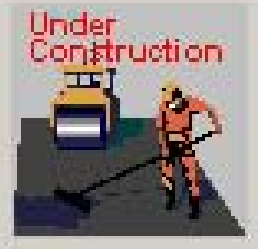
In-Situ Non-Destructive Tests Exist

- Achieve agreement between construction quality assurance and pavement design.
- Quantify alternative materials and construction practices. Show economic benefit of improved materials. Reward good construction.
- This requires new specifications and new tools. Tools must be quantitative, portable, and accurate in the field.

Cell33Demo.mpv

Structure

Basic | Intermediate | Advanced



Check box to enter test data.
Uncheck to use Basic defaults.

HMA Modulus

Edit HMA Properties

Agg. Test Type

- (•) Modulus, psi
- ( ) R-Value
- ( ) DCP,mm/blow
- ( ) CBR

Soil Test Type

- ( ) Modulus, psi
- (•) R-Value
- ( ) DCP,mm/blow
- ( ) CBR

Other

All others require Modulus, psi

PG 58-28 Select

[✓] 25000 M

[✓] 12

Edit Structure

Layers	Material	Thickness (in.)
( ) 1	HMA	4
( ) 2	AggBase	12
(•) 3	EngSoil	infinite
( ) 4		
( ) 5		

Design Mode: Intermediate

Units

- (•) English
- ( ) SI

Finished Structure
Go to
Control Panel

Agg. Base Moisture Condition

- (•) Optimum
- ( ) Wet

Soil Moisture Condition

- (•) Optimum
- ( ) Wet

Optimum = Fall conditions, Wet = Late Spring conditions

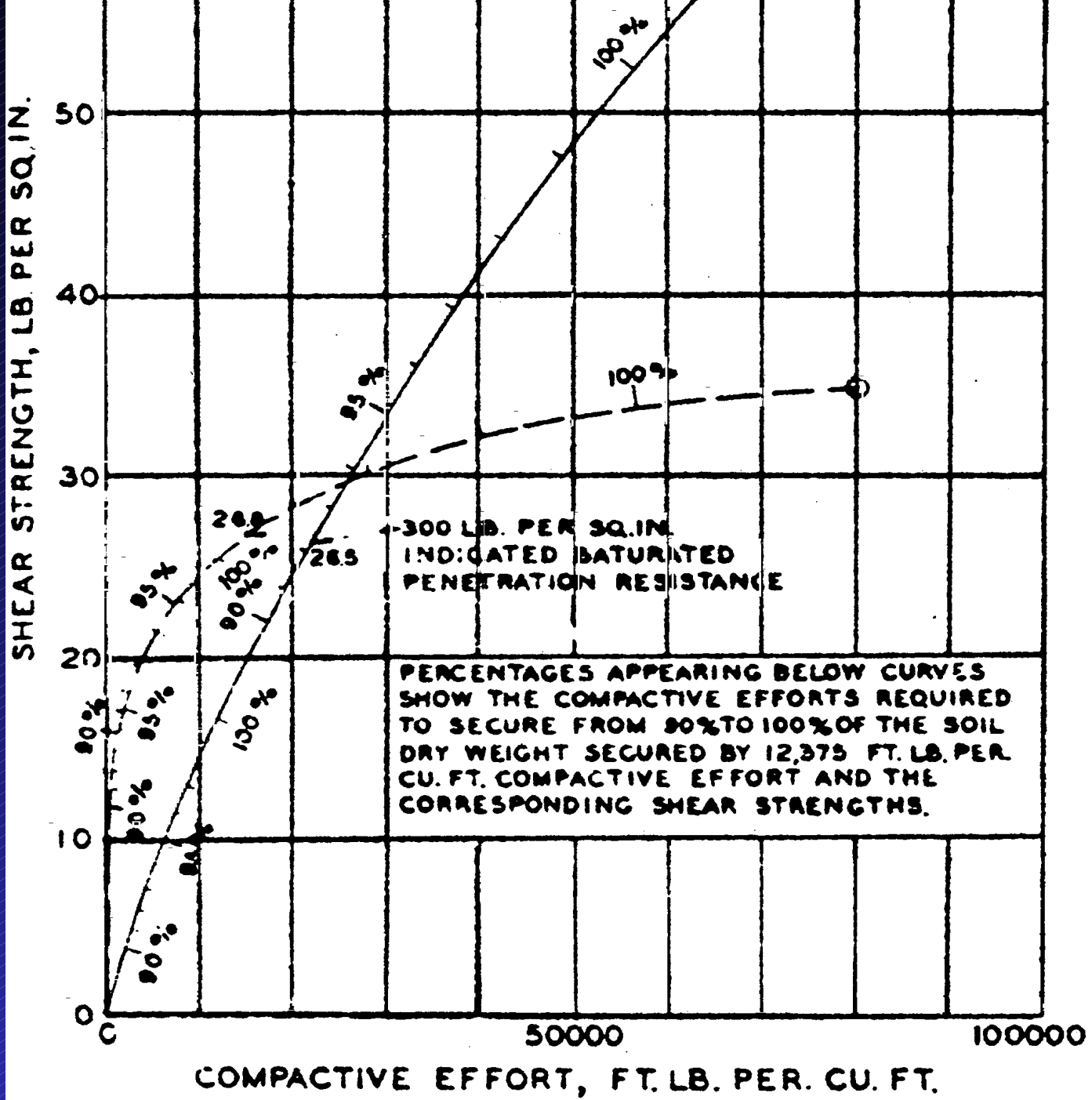
Density Testing Issues

- Proctor had a Different Idea
- Optimum Moisture for Compaction
- Strength May Not be Achieved
- Rutting Due to Moisture and Construction Traffic
- Is Not Necessarily Consistent with the Moisture and Density of the R-Value Test Specimens

Proctor 1948

- "Originally published objective of compaction in earth fills was a saturated penetration resistance of 300 lb per sq in."

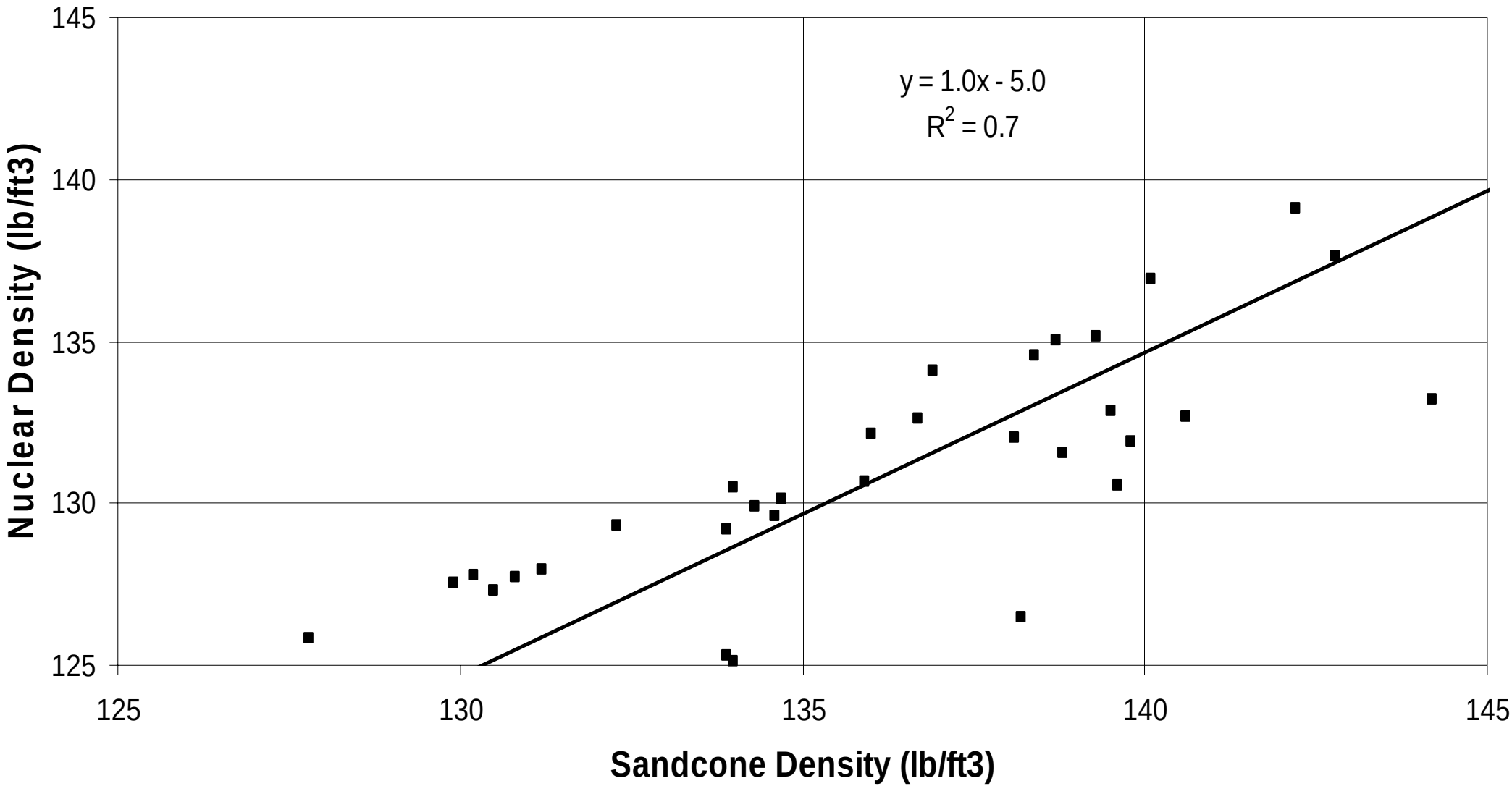
- "Soil would then have twice the penetration resistance required to permit loaded truck travel when fully saturated."


SHEAR STRENGTH, LB. PER SQ. IN.
0
10
20
30
40
50
0
50000
100000
COMPACTIVE EFFORT, FT. LB. PER. CU. FT.
100%
95%
90%
85%
80%
26.8
26.5
300 LB. PER SQ. IN. INDICATED SATURATED PENETRATION RESISTANCE
PERCENTAGES APPEARING BELOW CURVES SHOW THE COMPACTIVE EFFORTS REQUIRED TO SECURE FROM 80% TO 100% OF THE SOIL DRY WEIGHT SECURED BY 12,375 FT. LB. PER CU. FT. COMPACTIVE EFFORT AND THE CORRESPONDING SHEAR STRENGTHS.

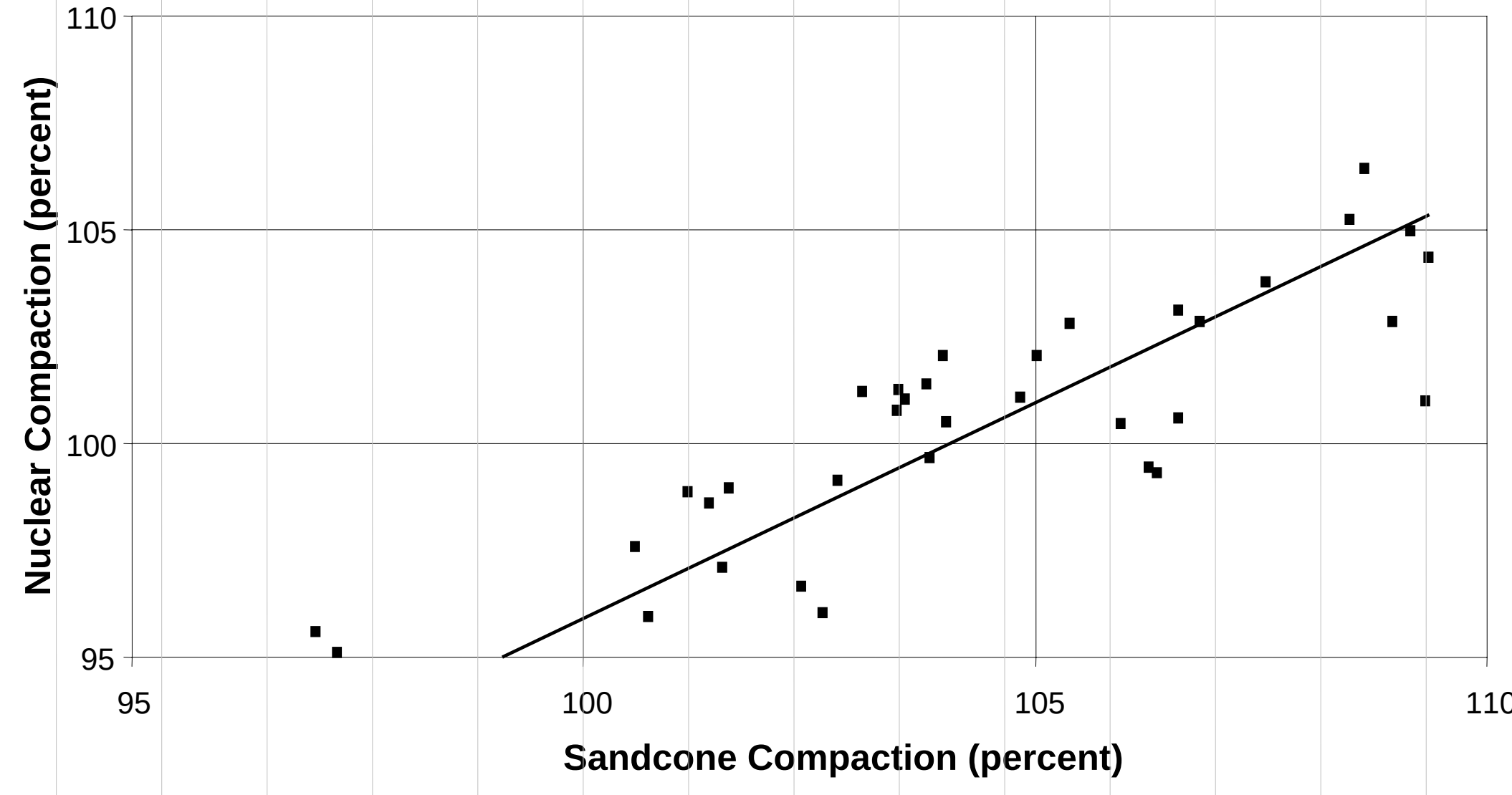
Nuclear vs Sandcone Densities

- Investigation 622, U of M, LRRB, Mn/DOT, 1966
- Sandcone results have appreciable errors
- Greatest errors in high density granular soils
- More than 5 lbs per cubic foot
- Due to inherent errors in the sandcone procedure

Nuclear Density vs Sandcone Density
Mn/ROAD Aggregate Base
1998, 1999, 2000, 2001, and 2004

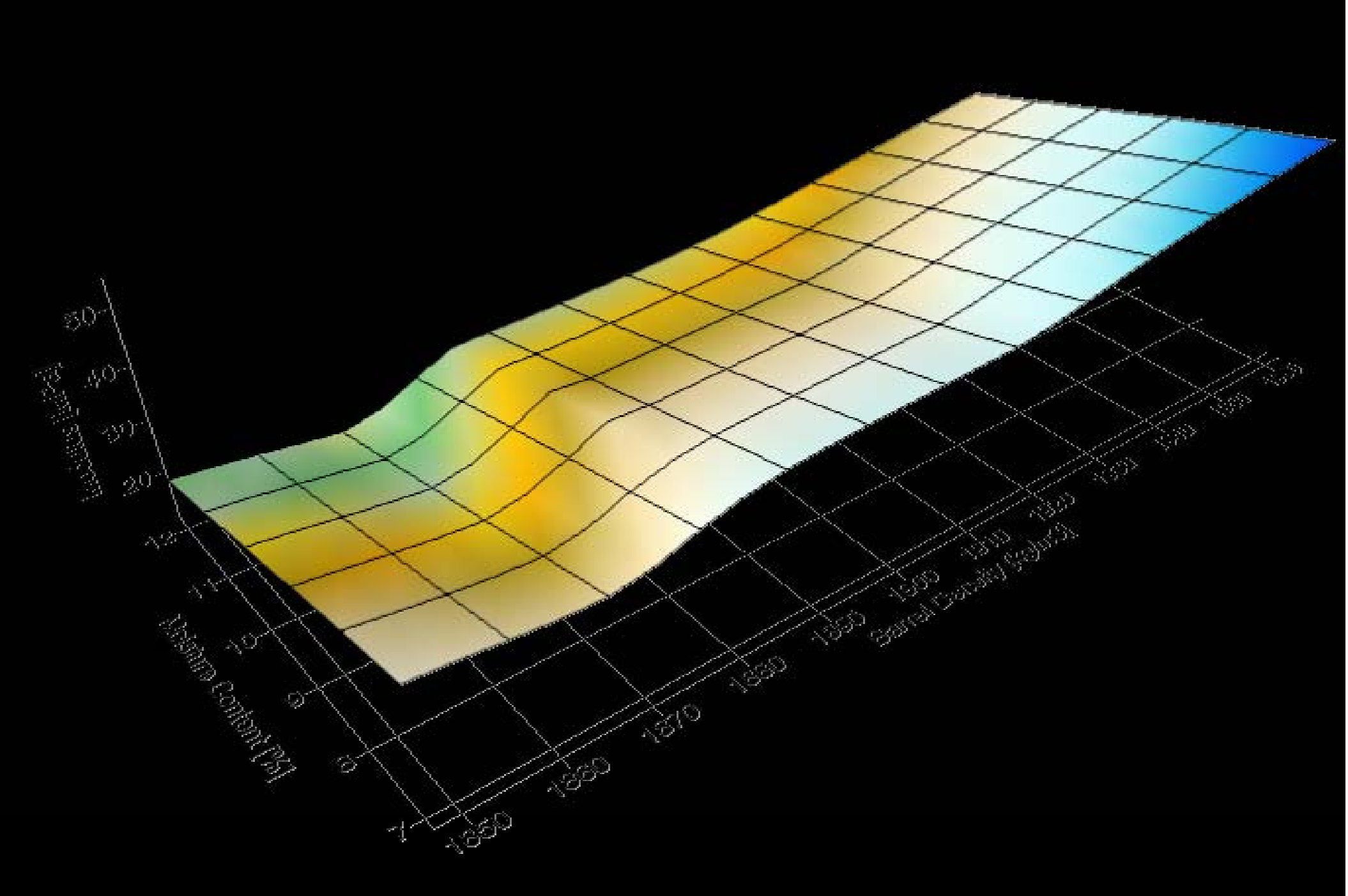


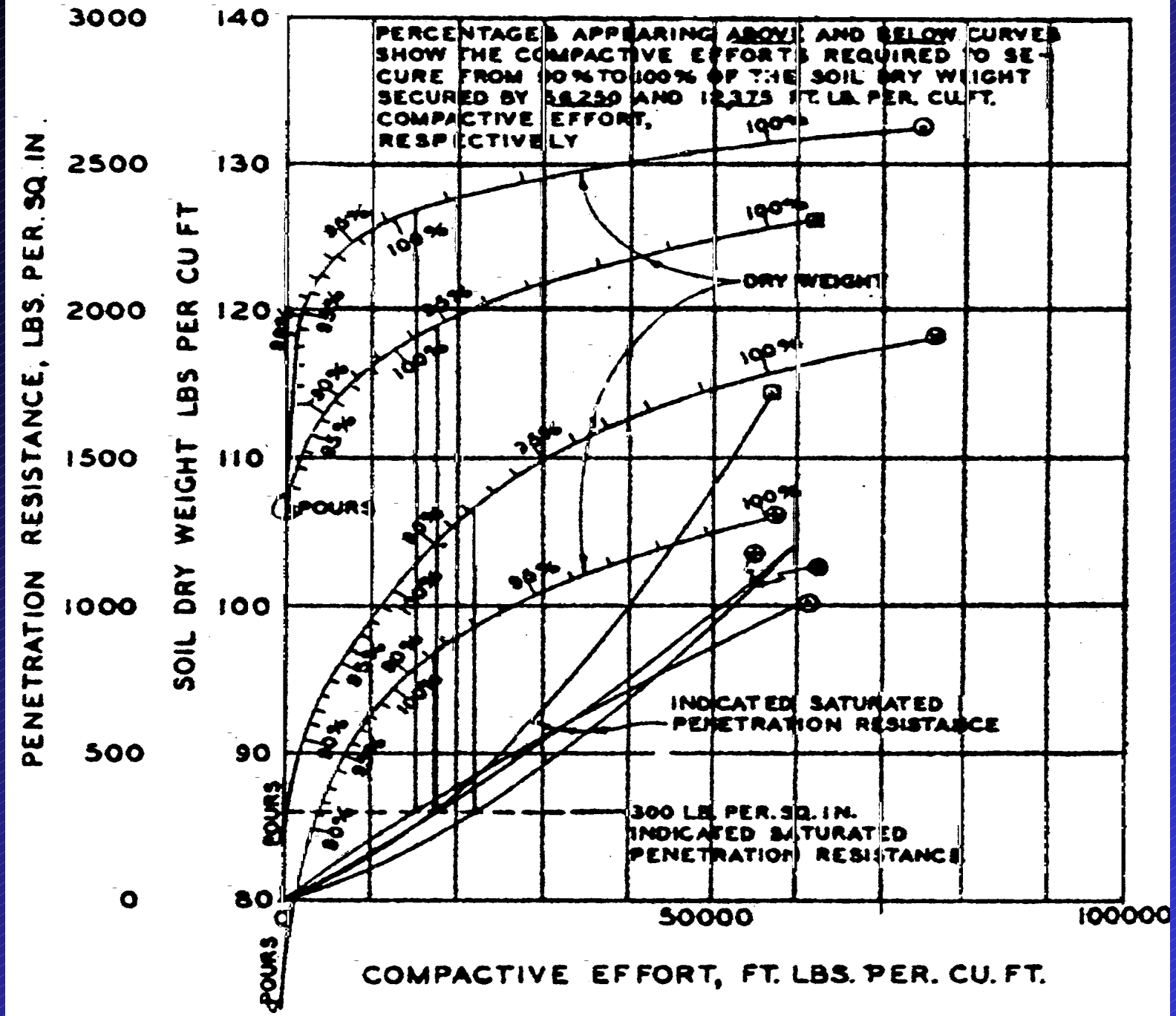
Nuclear Compaction vs Sandcone Compaction
Mn/ROAD Aggregate Base
1998, 1999, 2000, 2001, and 2004



Changing from Density to Modulus

- **We Still Need Moisture Control**
- **Density**
  - Mass / Volume
  - Proctor Test is NOT the Maximum
- **Modulus (Stiffness or Strength)**
  - All Are Mechanical Properties
- **We Just Need Two of the Three**
  - Moisture and Modulus


50
40
30
20
1.2
1.1
1.0
0.9
0.8
Alumina Content [%]
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
1850
1860
1870
1880
1890
1900
1910
1920
1930
1940
1950
Spinel Density [kg/m3]


PERCENTAGES APPEARING ABOVE AND BELOW CURVES SHOW THE COMPACTIVE EFFORTS REQUIRED TO SECURE FROM 90% TO 100% OF THE SOIL DRY WEIGHT SECURED BY 56,250 AND 12,375 FT. LBS. PER. CU. FT. COMPACTIVE EFFORT, RESPECTIVELY
100%
100%
100%
DRY WEIGHT
90%
80%
POURS
POURS
POURS
INDICATED SATURATED PENETRATION RESISTANCE
300 LBS. PER. SQ. IN. INDICATED SATURATED PENETRATION RESISTANCE
PENETRATION RESISTANCE, LBS. PER. SQ. IN.
SOIL DRY WEIGHT LBS PER CU FT
COMPACTIVE EFFORT, FT. LBS. PER. CU. FT.
3000
2500
2000
1500
1000
500
0
140
130
120
110
100
90
80
50000
100000

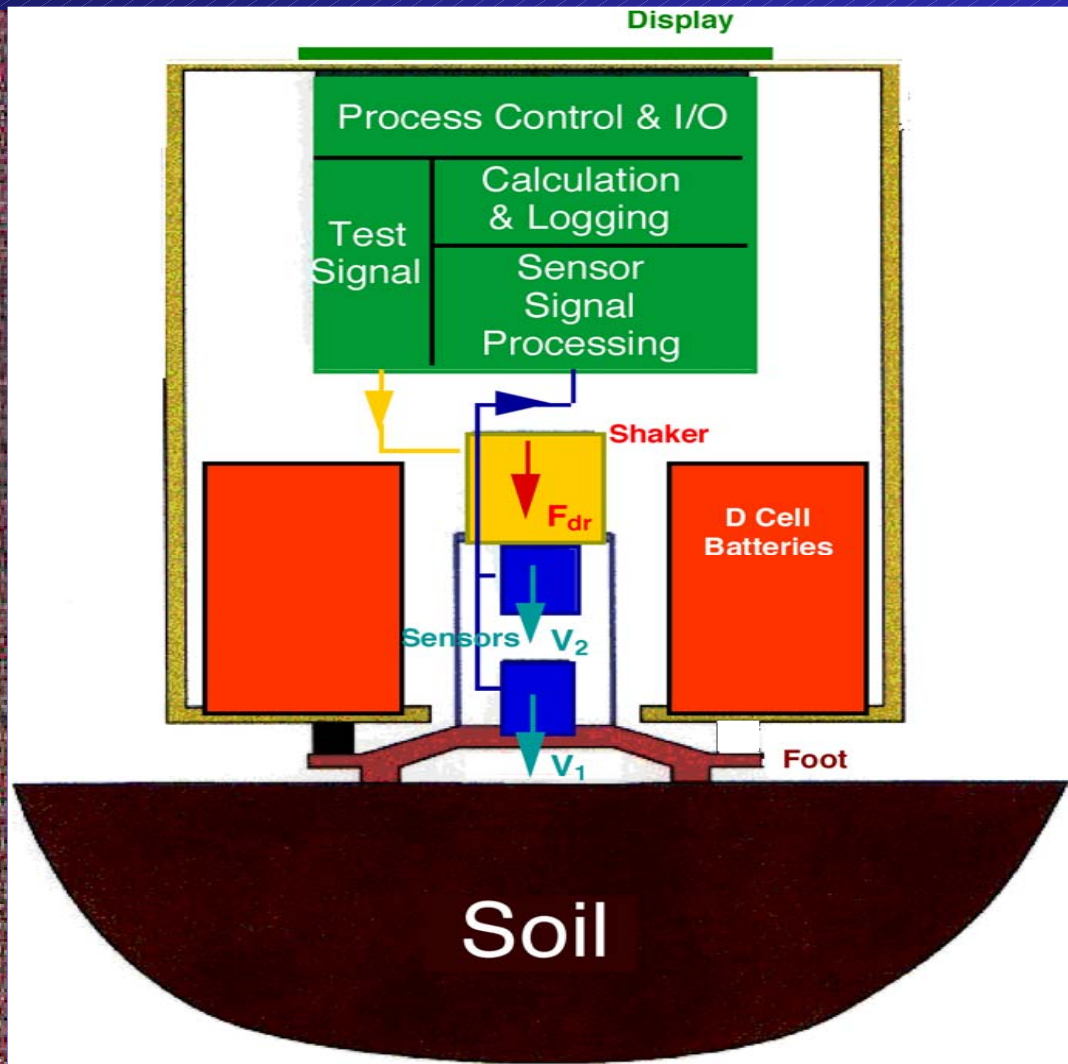
Test Type and Equipment

- **Elastic Modulus**
  - Intelligent Compactor (IC)
  - Falling Weight Deflectometer (FWD)
  - Light Weight Deflectometer (LWD)
  - Soil Stiffness Gauge
  - Quasi-static Plate Load Test
- **Shear Strength**
  - Dynamic Cone Penetrometer (DCP)
- **Density**
  - Sand Cone, Nuclear Gauge
- **Moisture**
  - Sand Cone, Nuclear Gauge
  - Camp Stove with Scale, Kessler FMO
  - Trident and Percometer

Field Testing Equipment


Keros

Humboldt GeoGauge



Materials QC/QA Compliance

Materials database

- Test requirements known
- Field samples taken
- Field test results recorded
- Pass / fail in real time

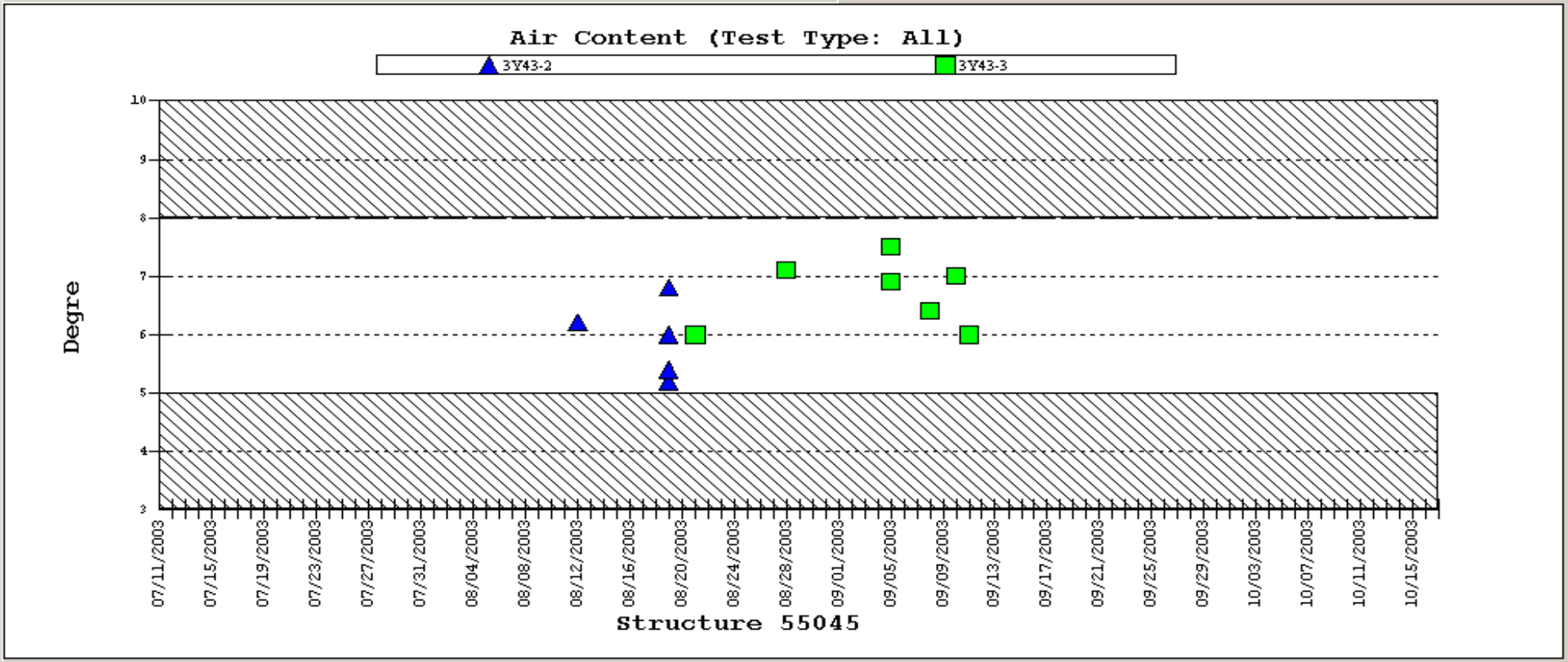
MT Application

File Edit Reports Tools Window Help

Work Order Graphics

Materials Testing/Tracking System (MTS)
Minnesota Department of Transportation
Test Result Graph Criteria

Page1 | Graph



Print Graph

Return

Start 4:05 PM

2005 Intelligent Compaction Projects

- **District 8**
  - TH12 near Atwater
  - June 2005
  - 1 mile of bridge approaches
  - 10” HMA, 6” Class 5, 14” Select Granular, 6” R-Value 12
- **District 7**
  - TH14 near Janesville
  - July and October 2005
  - Length 12.4 miles
  - 8.5” PCC, 4” Open-graded Base, 4” Class 5, 42” Select Grading Material
- **District 1**
  - TH53 near Duluth
  - September 2005
  - Length 2.25 miles
  - 8” HMA, 6” Class 6, 36” Select Granular

TH12 District 8 Atwater

- June 22 to June 28
- Bomag Intelligent Compaction Equipment
- Mn/DOT Materials Testing and Report


BOMAG


BW213 DH

TH14 District 7 Janesville

- July 18 to July 22
- CAT Intelligent Compaction Equipment
- Iowa State University Testing
- FHWA Funding


CATERPILLAR


1058

Back to TH14 at Janesville

- October 27 to November 11
- Ammann Intelligent Compaction Equipment
- Iowa State University, Mn/DOT FHWA Funding
- Colorado School of Mines, NSF Funding


IOWA STATE UNIVERSITY
LAB SPONSORS
MN-Anirnch.
IOWA STATE UNIVERSITY
GEOTECHNICAL MOBILE LAB


AMMANN
ACE

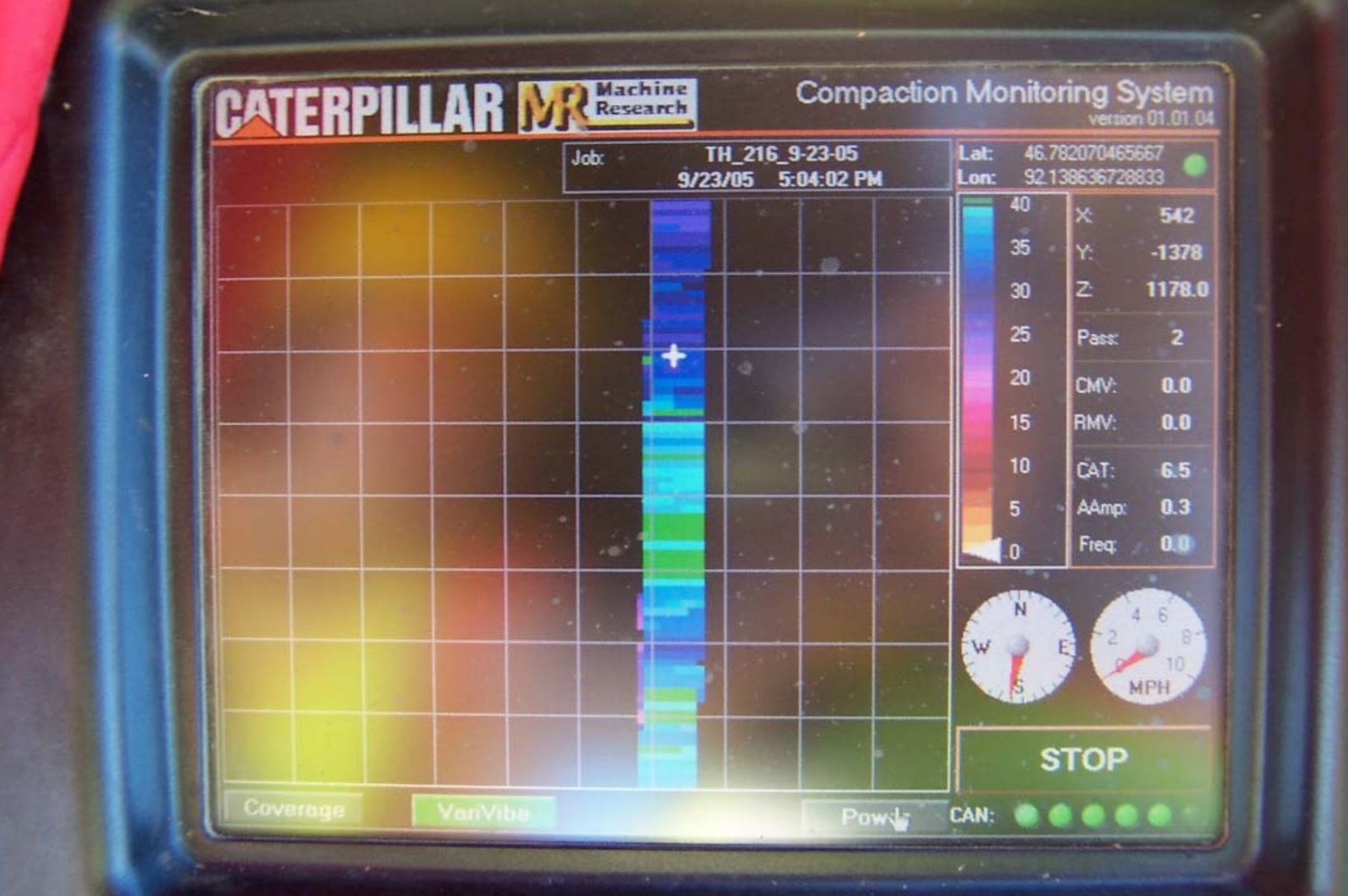

TRACK
PRINT


ACE
AC110

TH53 District 1 Duluth

- September 19 to October 6
- CAT Intelligent Compaction Equipment
- CNA Consulting Engineers Testing and Report
- Mn/DOT Implementation Funding
- Mn/DOT Materials Testing and Conference Paper


CATERPILLAR


CATERPILLAR
Machine Research
Compaction Monitoring System
version 01.01.04
Job: TH_216_9-23-05
9/23/05 5:04:02 PM
Lat: 46.782070465667
Lon: 92.138636728833
40
35
30
25
20
15
10
5
0
X: 542
Y: -1378
Z: 1178.0
Pass: 2
CMV: 0.0
RMV: 0.0
CAT: 6.5
AAmp: 0.3
Freq: 0.0
N
W
E
S
MPH
STOP
Coverage
VanVibe
CAN:


Keros

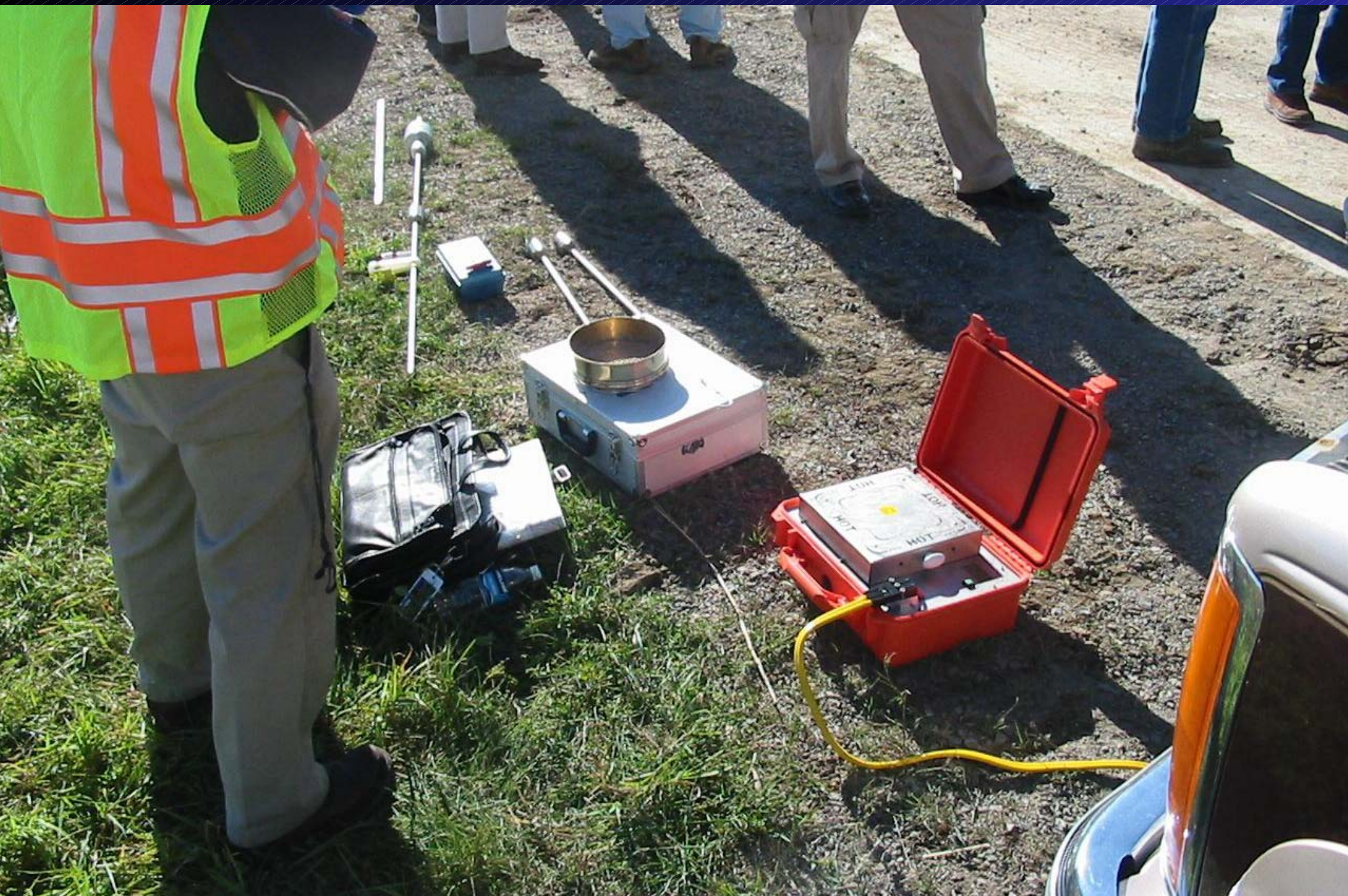
Trident T-90 Moisture Meter

- **Volumetric Moisture Meter**
  - Utilizes Frequency Domain Reflectometry to estimate volumetric moisture content
  - The calibration procedure for the instrument allows for estimation of the gravimetric moisture content
  - Calibration is required for each different soil type

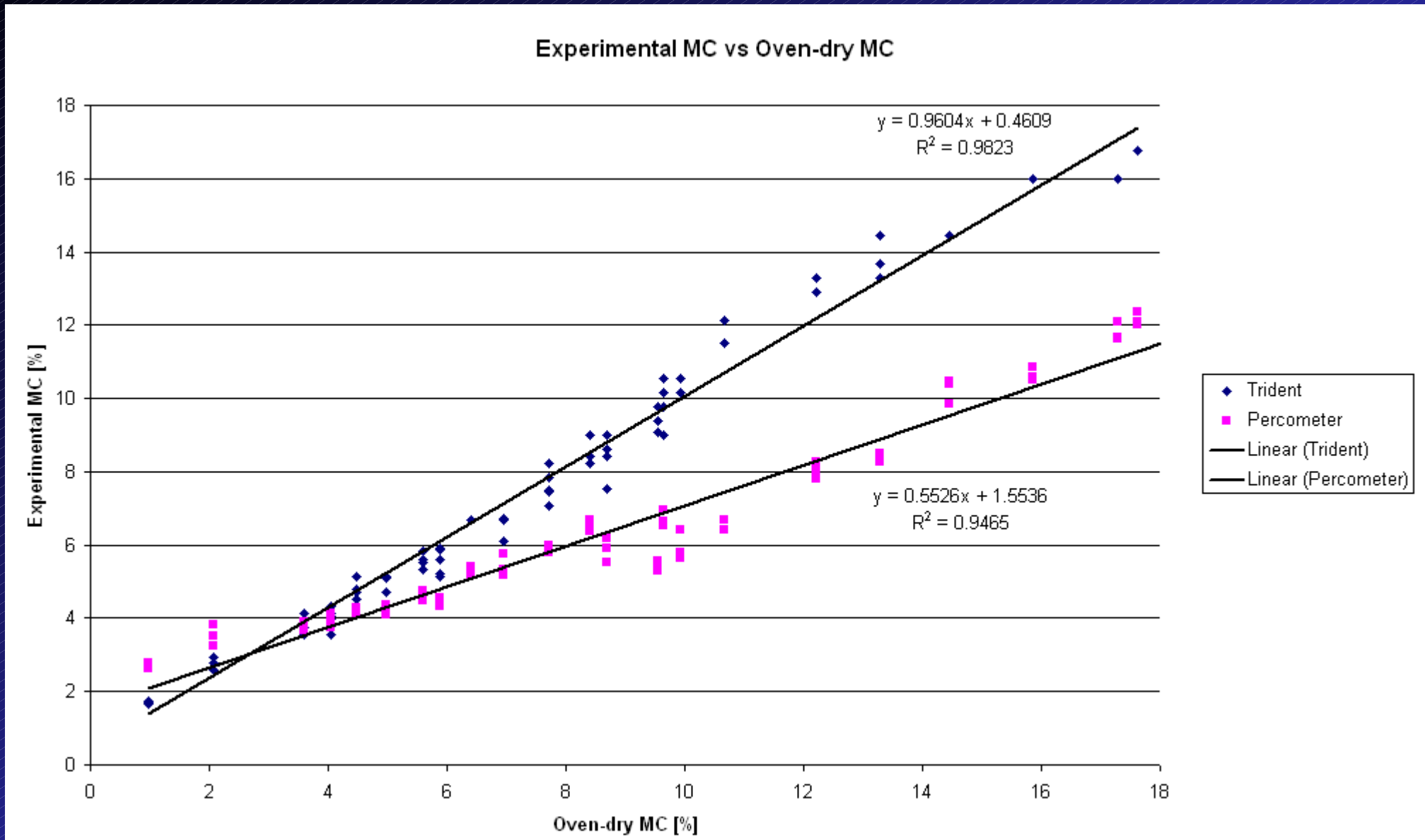

RADONEER
ON/OFF

Field Moisture Oven

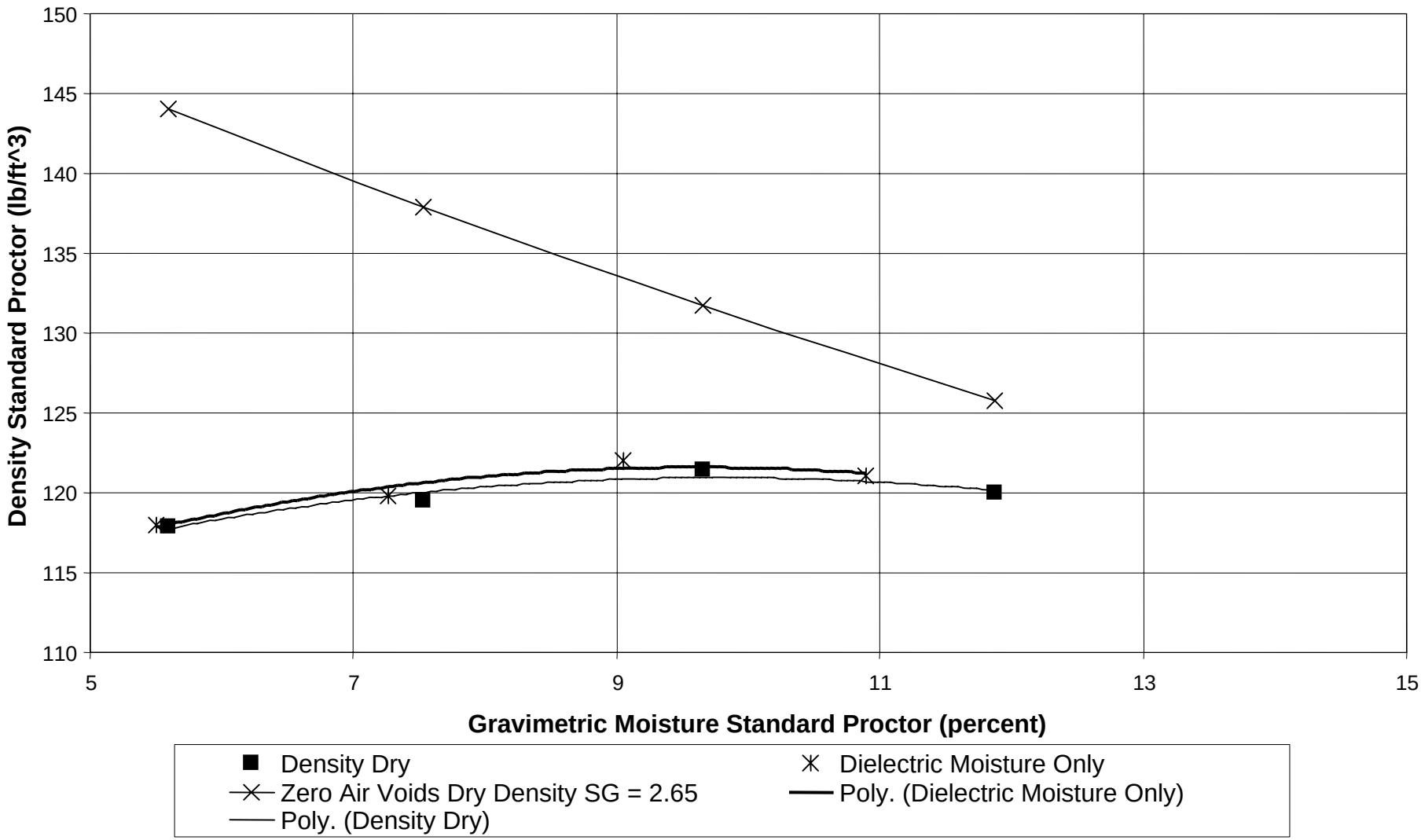
- **Gravimetric Moisture Meter**
  - Heats 200-250g soil sample on dual thermostatically controlled platens at 200 C°
  - Tests take approximately 8-12 minutes for granular samples
  - Best suited for:
    - Fine and coarse grained soils
    - Fine gravels


HOT
HOT
HOT

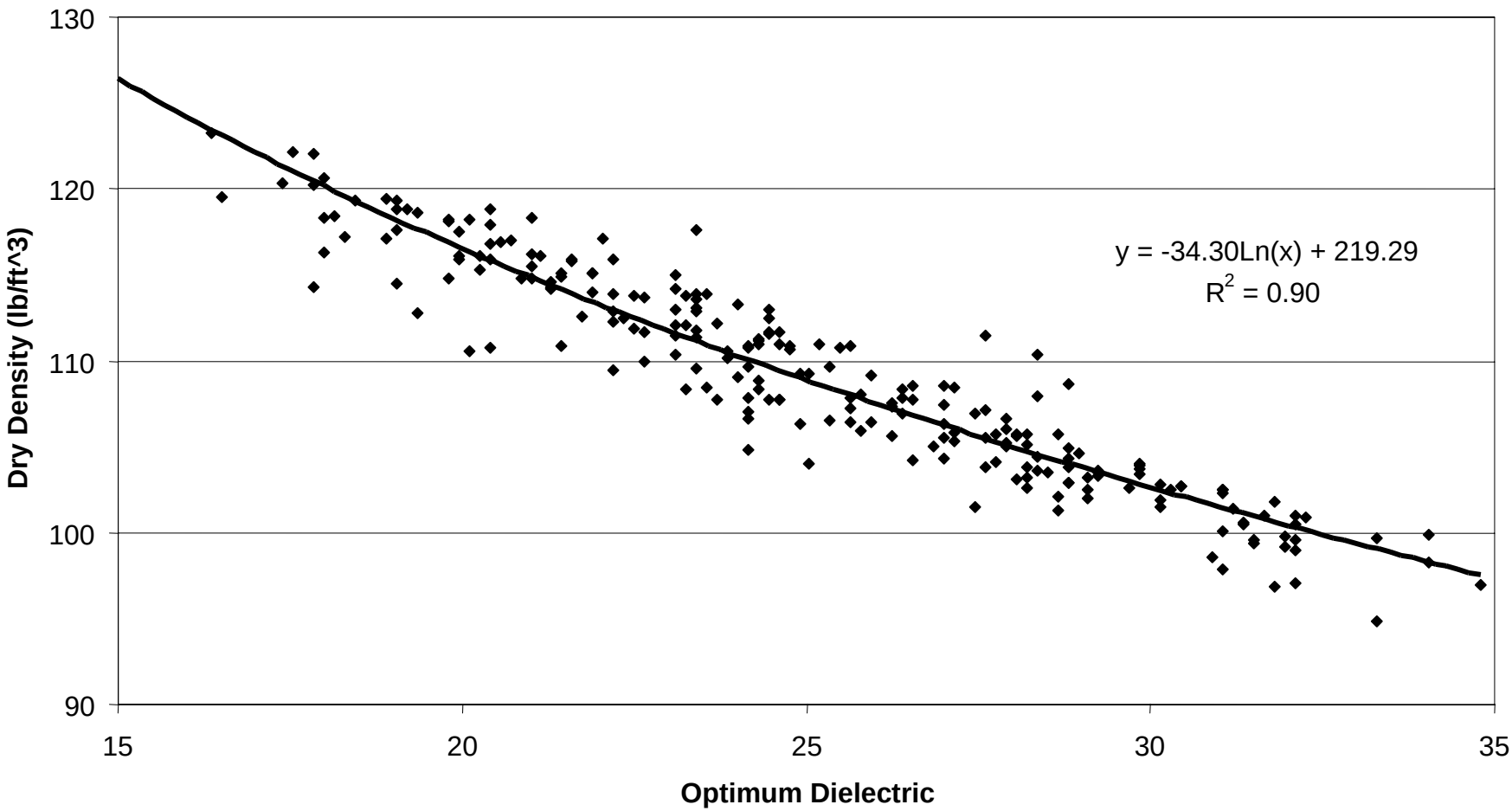

BRAUN


Experimental MC vs Oven-dry MC
y = 0.9604x + 0.4609
R2 = 0.9823
y = 0.5526x + 1.5536
R2 = 0.9465
Experimental MC [%]
Oven-dry MC [%]
0
2
4
6
8
10
12
14
16
18
Trident
Percometer
Linear (Trident)
Linear (Percometer)

Density vs Moisture
Median of Dielectric Repetitions Taken Near Edge and Center
Sample SS02263



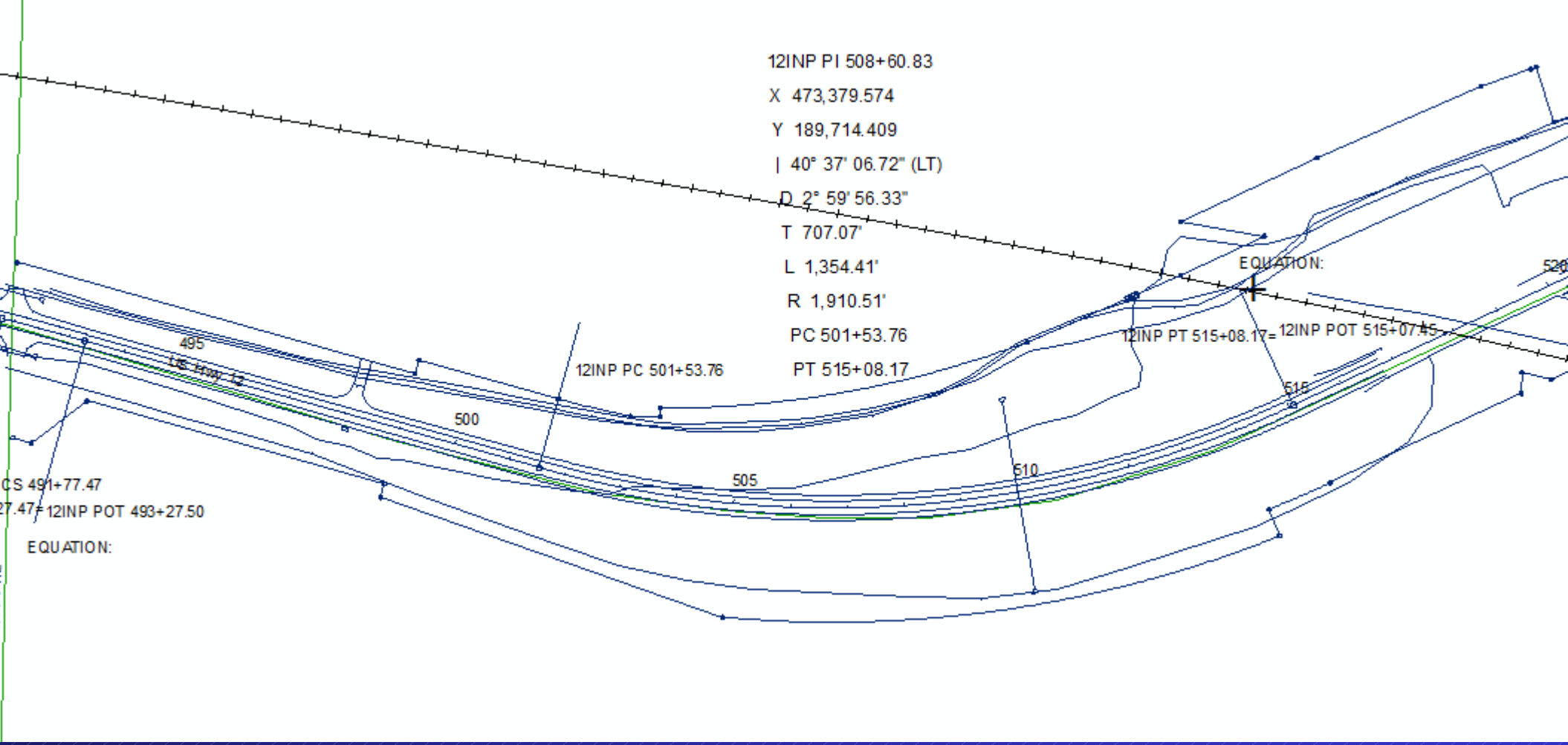
Standard Proctor Density vs Optimum Dielectric
Mn/DOT Textural "Clay Loam" Classification
Minnesota Statewide (not Mn/ROAD)



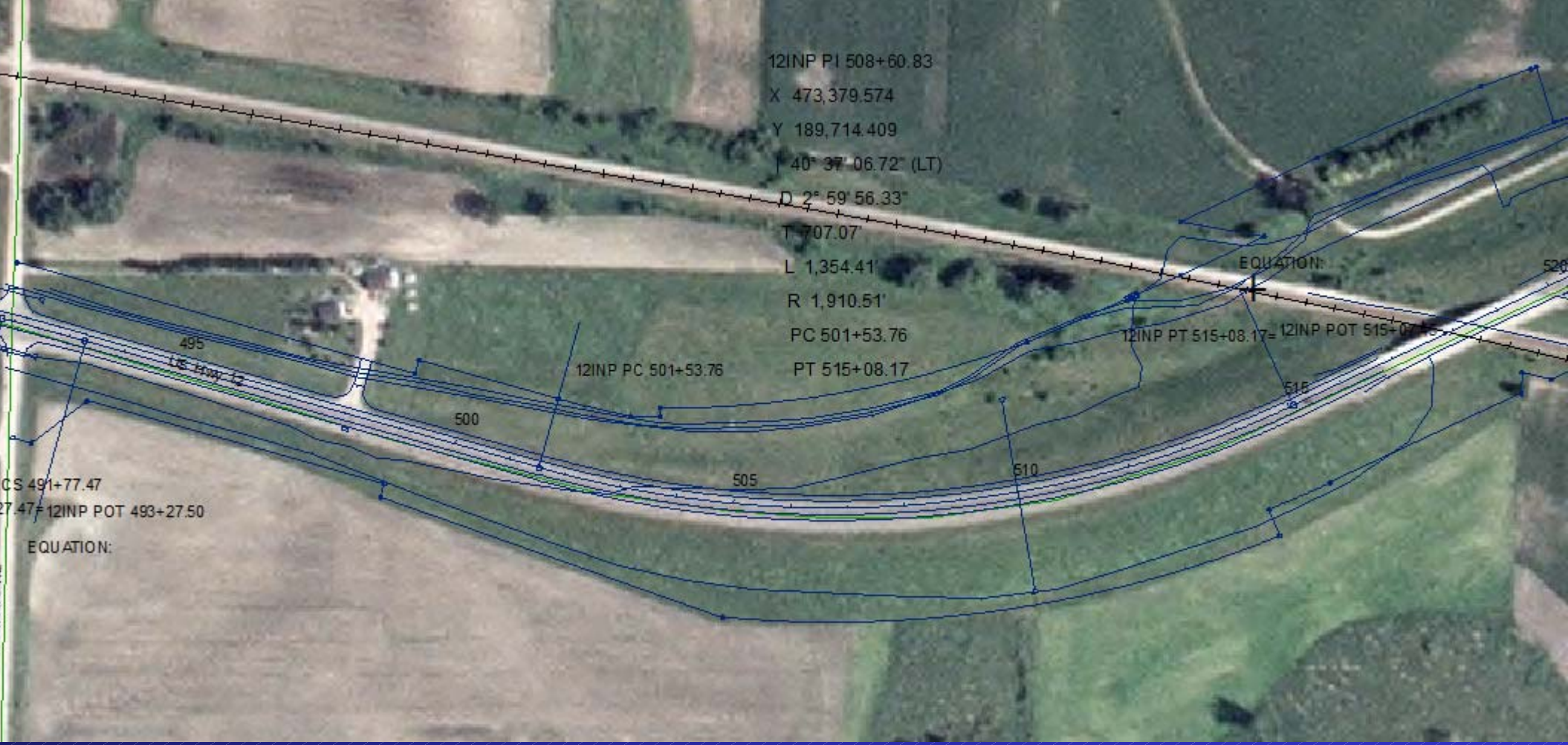
How We Handle the IC Roller Data

ICTGI Team

- Ruth Roberson
- Bruce Chadbourn
- John Siekmeier
- Felipe Camargo
- Brett Larsen
- Cassie O'Neal
- Peter Davich
- Agueda Guerra



MINNESOTA DEPARTMENT OF TRANSPORTATION

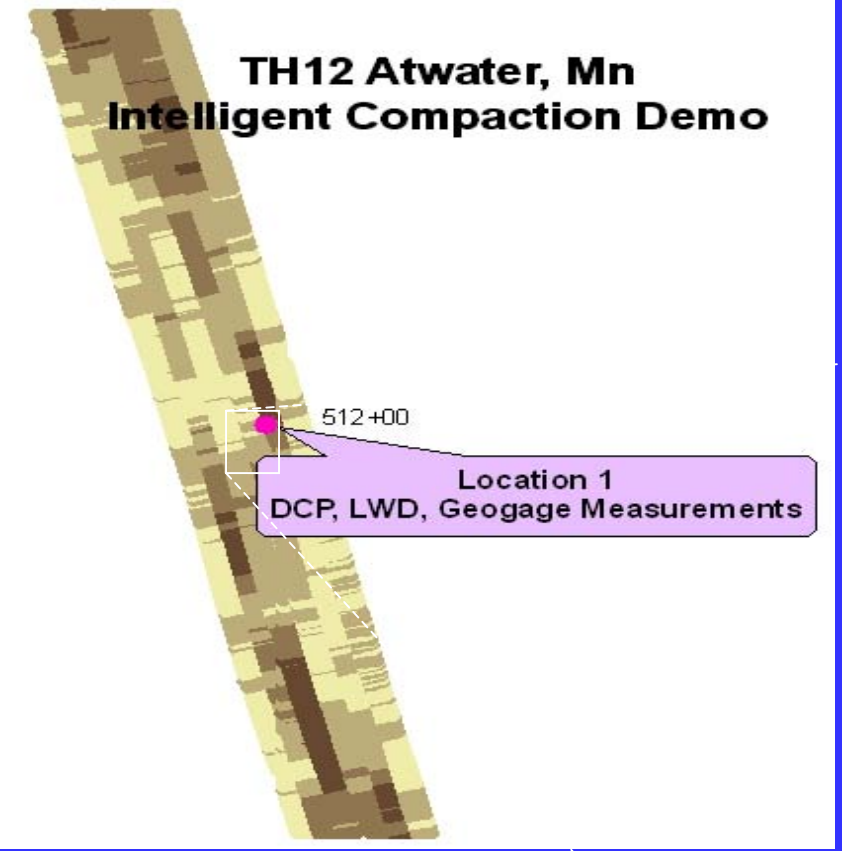


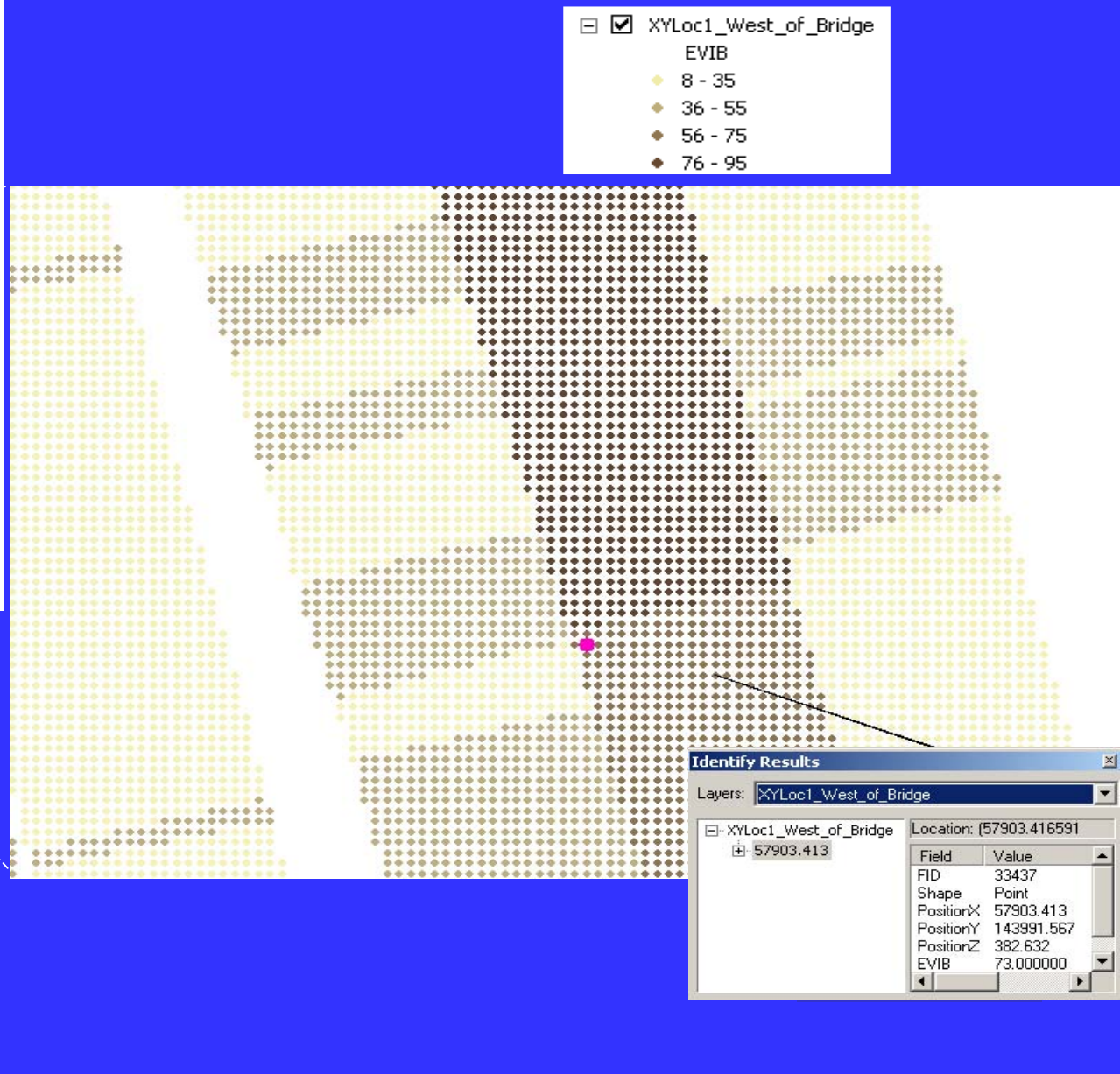
MINNESOTA DEPARTMENT OF TRANSPORTATION

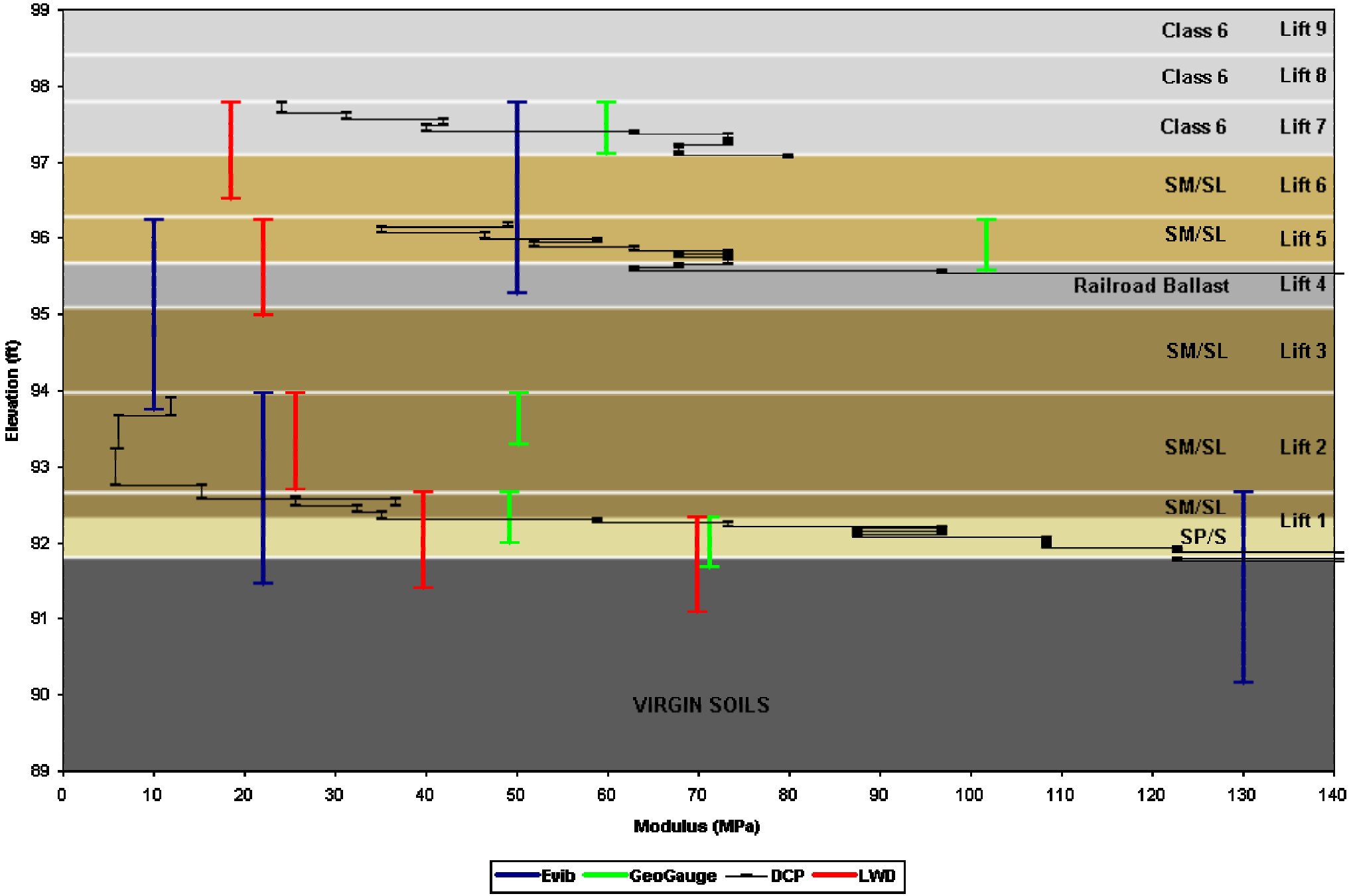

12INP PI 508+60.83
X 473,379.574
Y 189,714.409
Δ 40° 37' 06.72" (LT)
D 2° 59' 56.33"
T 707.07'
L 1,354.41'
R 1,910.51'
PC 501+53.76
PT 515+08.17
12INP PC 501+53.76
12INP PT 515+08.17=
EQUATION:
495
500
505
510
515
CS 491+77.47
27.47=12INP POT 493+27.50
EQUATION:

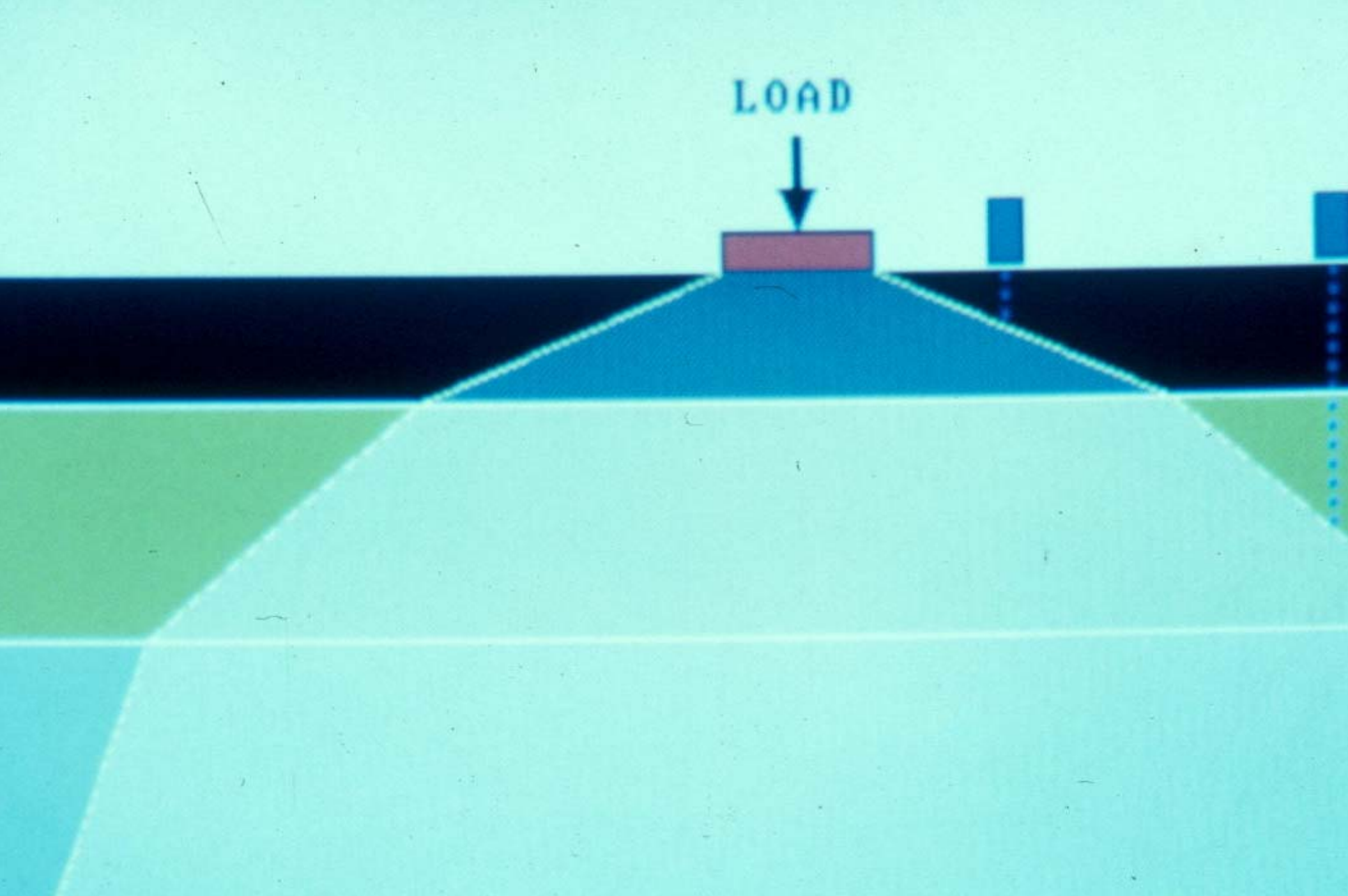

12INP POT 515+07.45
12INP PT 515+08.17=
515
US HWY 12
BOMAG Output
8 - 30
30 - 40
40 - 50
50 - 66
66 - 129

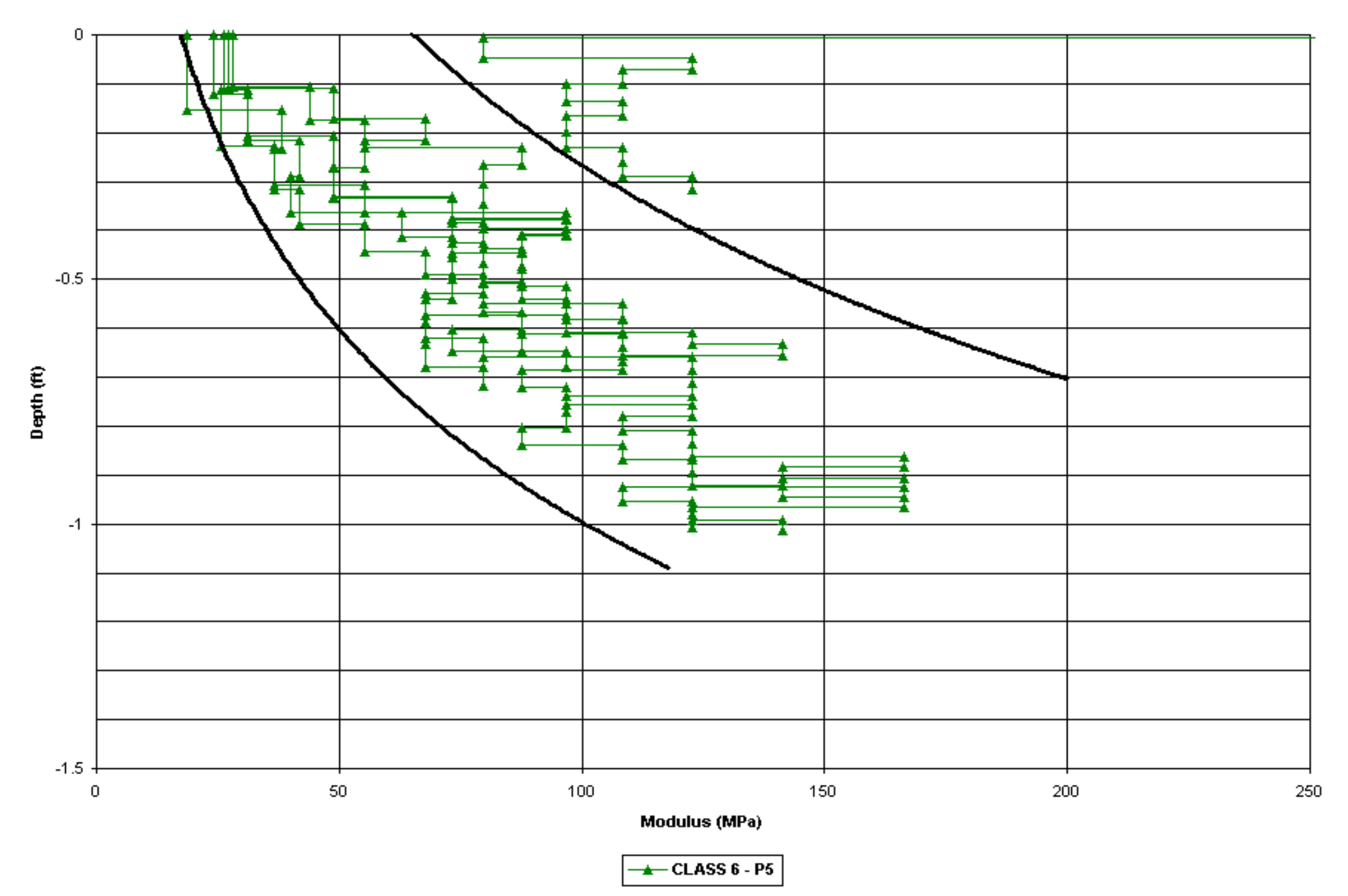
TH12 Atwater, Mn
Intelligent Compaction Demo

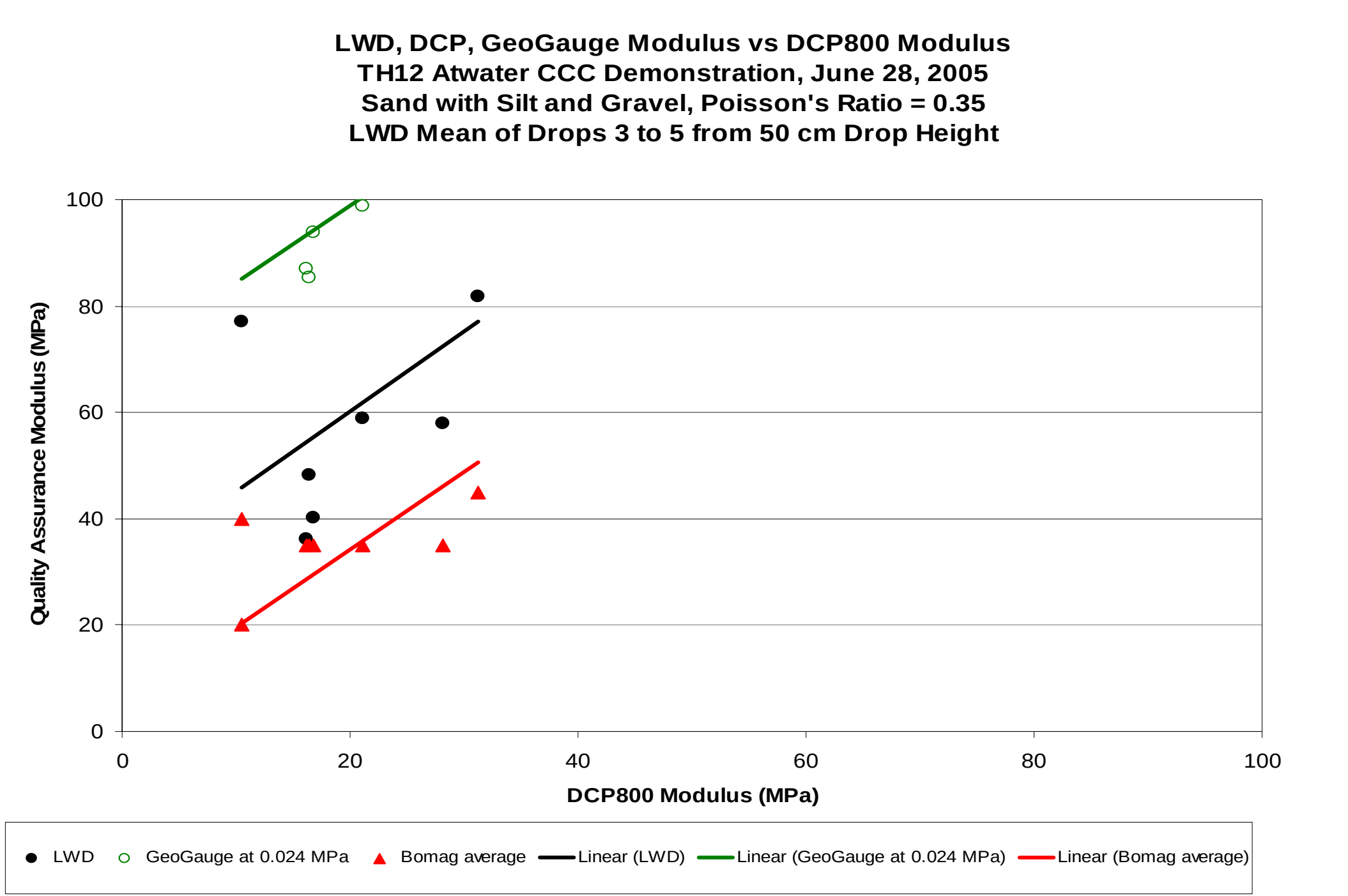




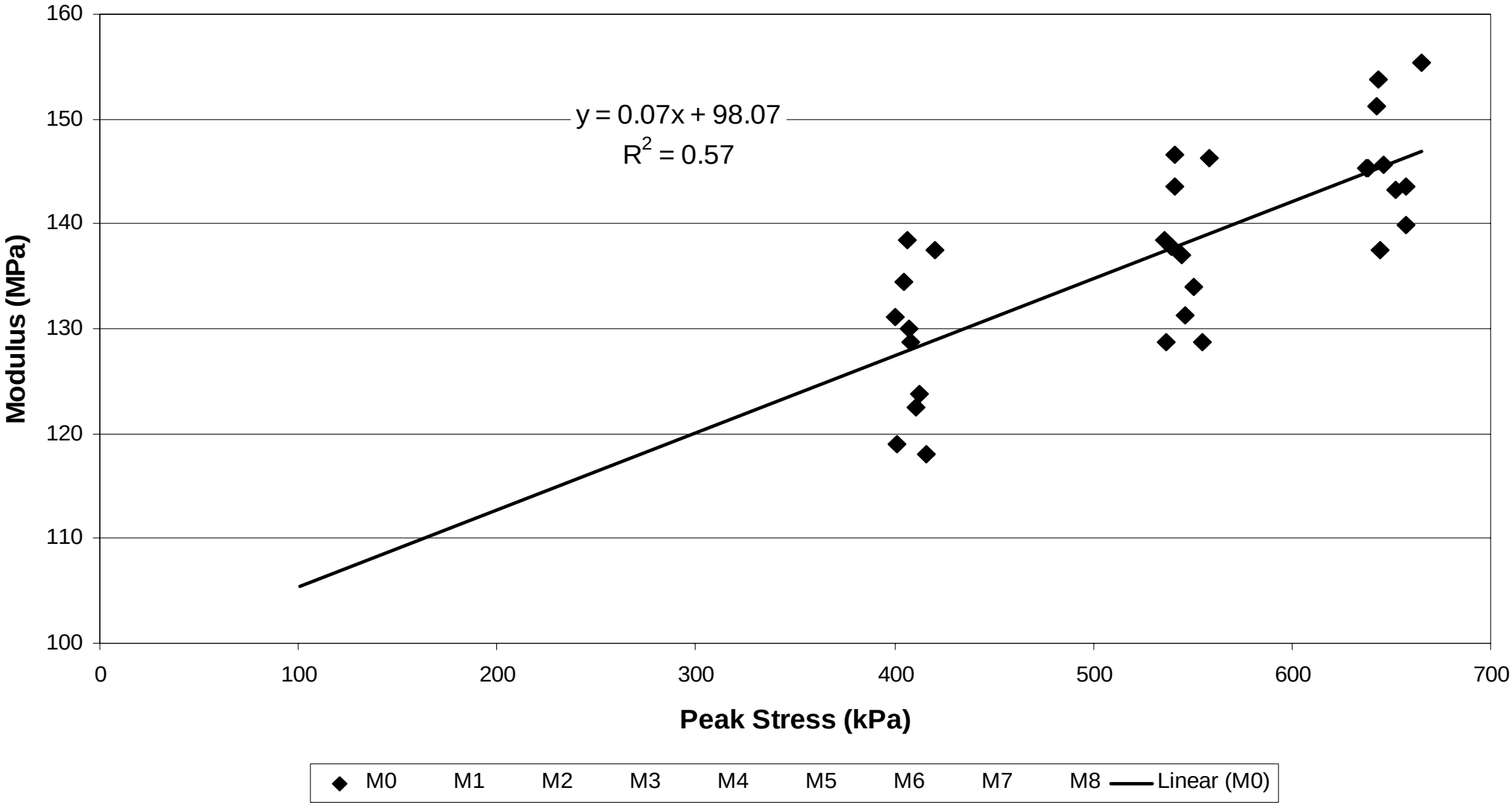

Class 6
Lift 9
Class 6
Lift 8
Class 6
Lift 7
SM/SL
Lift 6
SM/SL
Lift 5
Railroad Ballast
Lift 4
SM/SL
Lift 3
SM/SL
Lift 2
SM/SL
SP/S
Lift 1
VIRGIN SOILS
Elevation (ft)
99
98
97
96
95
94
93
92
91
90
89
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Modulus (MPa)
Evib
GeoGauge
DCP
LWD


LOAD

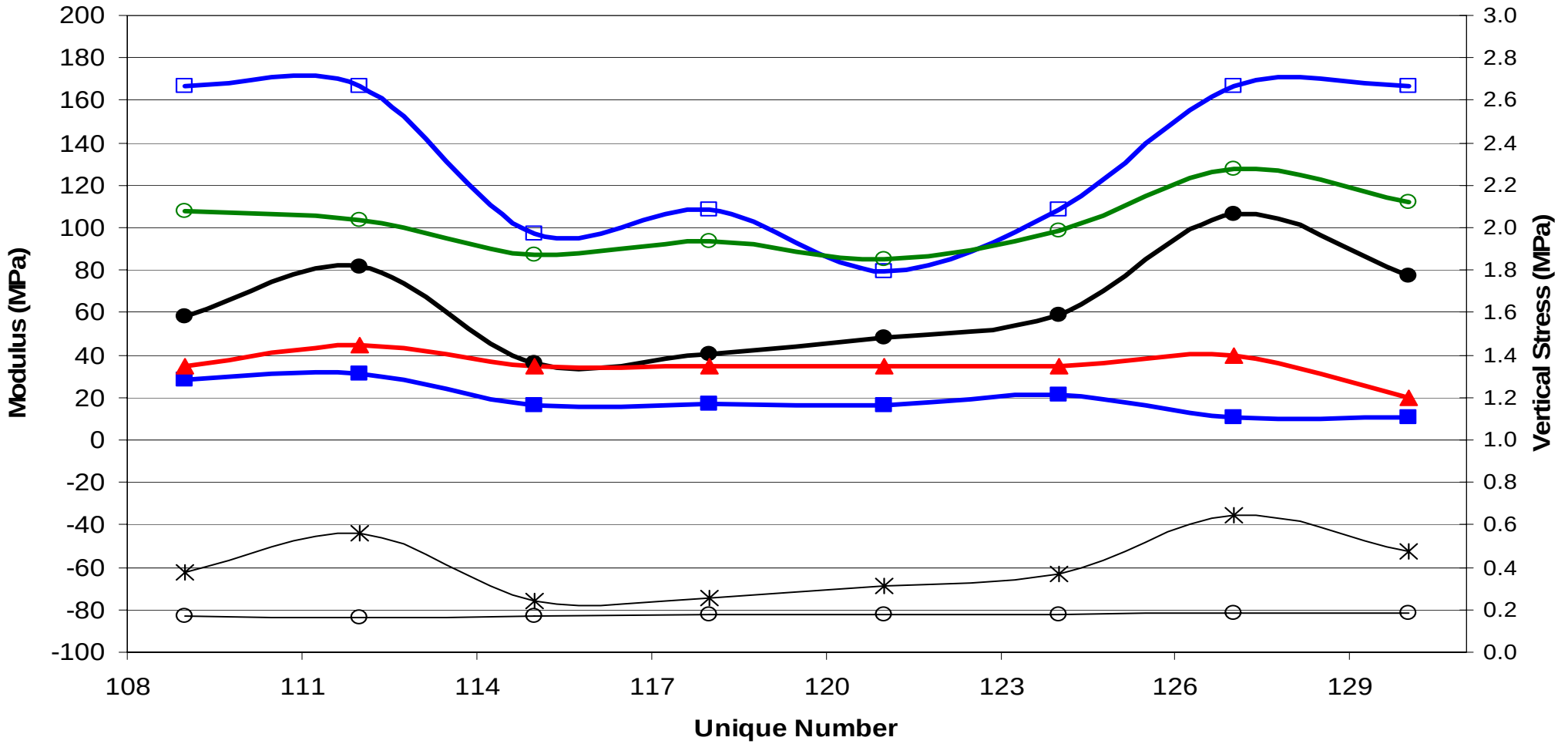

0
-0.5
-1
-1.5
Depth (ft)
0
50
100
150
200
250
Modulus (MPa)
CLASS 6 - P5


LWD, DCP, GeoGauge Modulus vs DCP800 Modulus
TH12 Atwater CCC Demonstration, June 28, 2005
Sand with Silt and Gravel, Poisson's Ratio = 0.35
LWD Mean of Drops 3 to 5 from 50 cm Drop Height
Quality Assurance Modulus (MPa)
DCP800 Modulus (MPa)
0
20
40
60
80
100
LWD
GeoGauge at 0.024 MPa
Bomag average
Linear (LWD)
Linear (GeoGauge at 0.024 MPa)
Linear (Bomag average)

FWD Moduli vs Peak Stress
MnROAD CCC Demonstration, October 21, 2004
Class 6 Prior to Paving, Three Drop Heights Shown, Mean of Three Repetitions Shown
Poisson's Ratio = 0.35, Plate Radius = 150 mm, Rigid Plate Factor = 0.79



LWD and DCP Modulus and Vertical Stress vs Unique Number
TH12 Atwater CCC Demonstration, June 28, 2005
Sand with Silt and Gravel, Poisson's Ratio = 0.35
Mean of Drops 3 to 5, EnAdj = 0.5, a=2, b=-0.6



What We Learned

- The compactors were well made and easy to operate.
- Intelligent compactors can measure the stiffness of the ground and adjust their compactive force as needed.
- Surface covering documentation can be produced.
- Data transfer was functional.

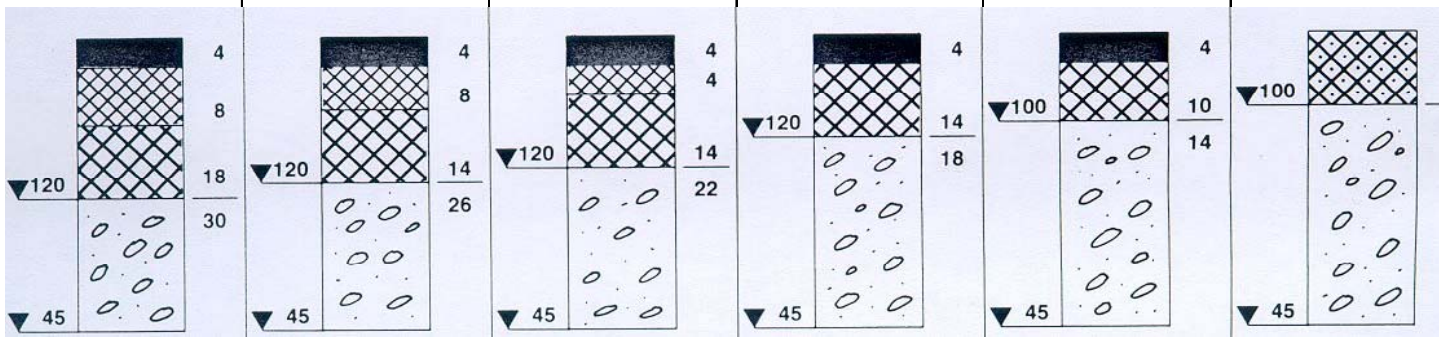
Conclusions

- Density testing has been useful, but is not time efficient, does not verify design properties, and should be replaced.
- Construction equipment and field tests are now available that can measure the mechanistic properties used to design pavements.
- Field data acquisition and materials reporting using global positioning systems (GPS) and geographic information systems (GIS) are available.

Current/Future Standards

- EU Performance Related Specifications
- Mn/DOT DCP Specifications Aggregate and Granular
- ASTM DCP Test Method
- ASTM LWD Test Method
- ASTM GeoGauge Test Method
- FHWA GeoGauge Pooled Fund
- FHWA CRREL Subgrade Performance Pooled Fund
- NCHRP 10-65 NDT QC/QA for Flexible Pavements
- NCHRP 21-09 Intelligent Compaction Specifications
- FHWA-led Intelligent Compaction Pooled Fund
- AASHTO M-E Pavement Design

German Design Standards

Road classification	I				II				III				IV				V				VI			
Equiv.10 t axle loads	> 10--32				>3–10				<0,8--3				>0,3–0,8				0,1– 0,3				<0,1			
Thickn. of frostres. pavement	50	60	70	80	50	60	70	80	50	60	70	80	50	60	70	80	40	50	60	70	40	50	60	7
Asphalt base on subbase																								
Surface course Binder course Asphalt base Subbase (frost resistant material)																								
Thickness of subbase	-	30	40	50	-	34	44	54	28	38	48	58	32	42	52	62	26	36	46	56	30	40	50	6

Thickness in cm, modulus of deformation EV_2 in MN/m²

Equivalent 10axle loads on one lane during road (according to German specifications)

NCHRP 21-09

- Determine the Reliability of IC Equipment
- Develop Construction Specifications
- Soils and Aggregate Base Materials
- Five States
- Three IC Roller Types

FWHA-led Pooled Fund 954

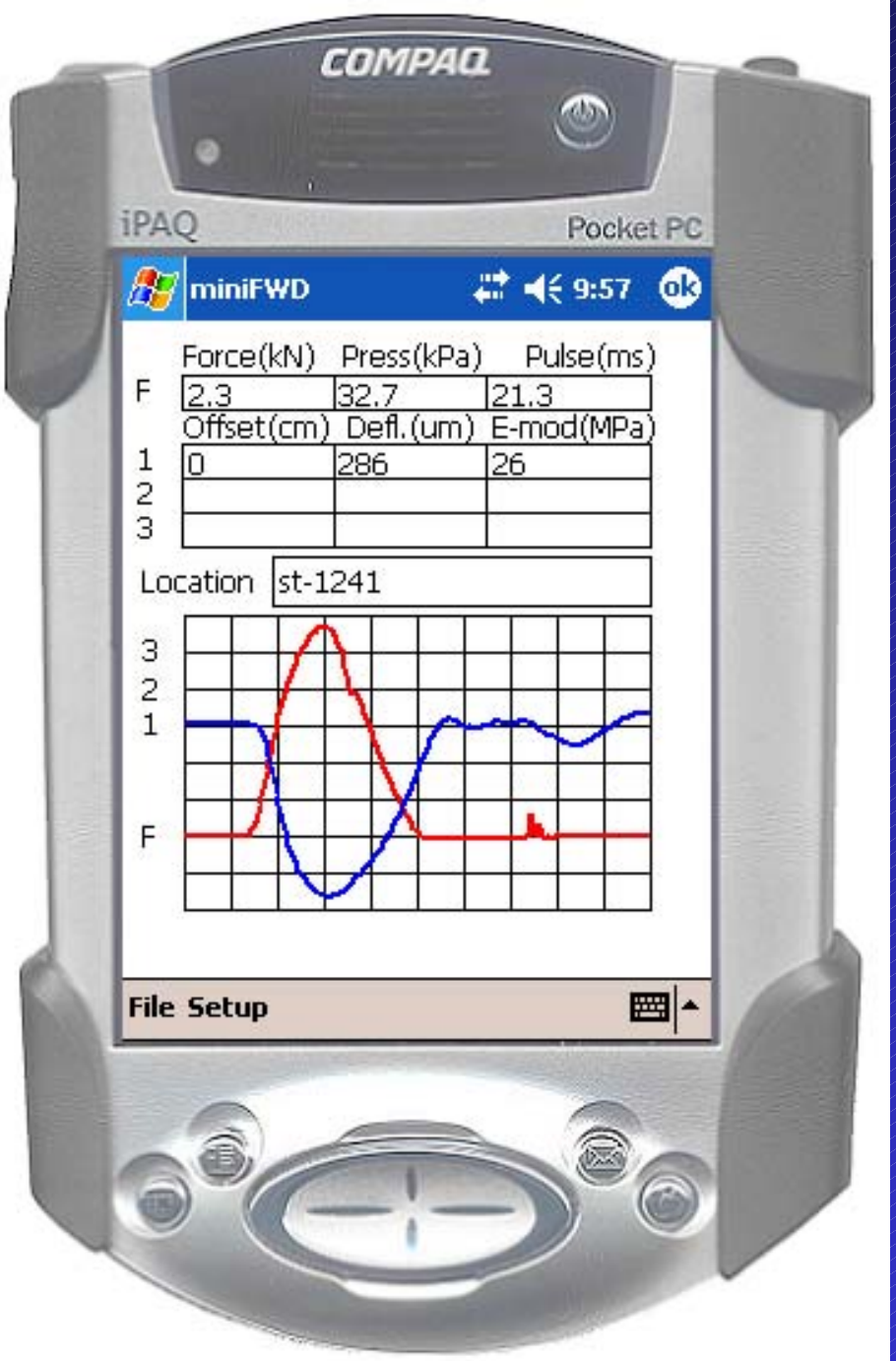
- Develop Construction Specifications
- Soils, Aggregate Base, HMA Materials
- More States Will Have Projects Included
- Increase DOT Experience Though Participation
- Identify and Prioritize Improvements
  - IC Equipment
  - In Situ Test Equipment Used for QC/QA

Mn/DOT Research Projects

Mechanistic Empirical Design	1999
Seasonal Properties	2000
Dynamic Analysis of FWD	2001
MnROAD TDR Data Analysis	2002
LWD Enhancement and Verification	2003
Moisture Retention Characteristics	2004
Modulus of Select Granular	2004
Moisture Effects on DCP/LWD	2005
Unsaturated Material Resistance Factors	2005
Implementation of LWD Dynamic Analysis	2006
Implementation of Intelligent Compaction	2006

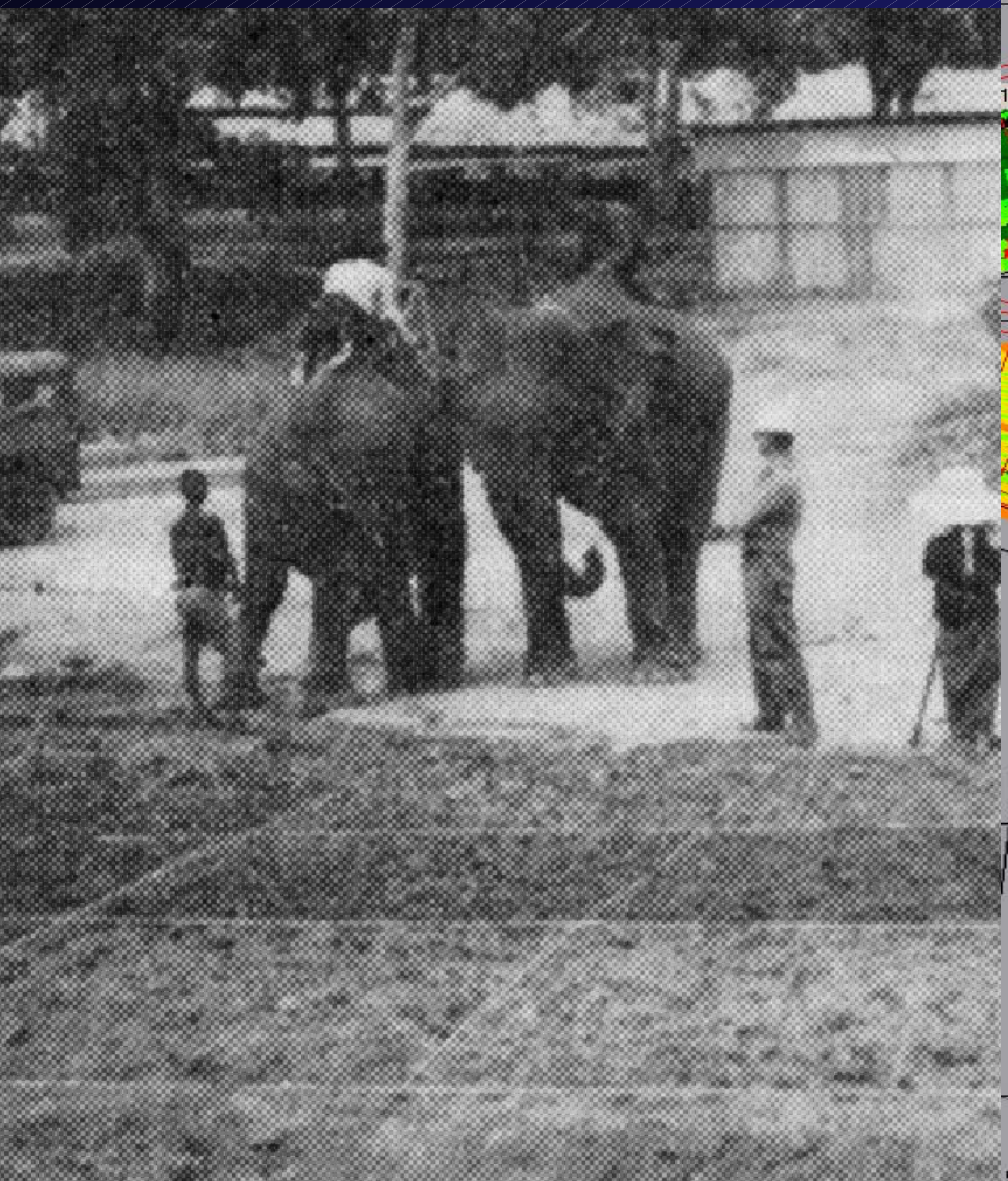
What's Next in Minnesota 2006

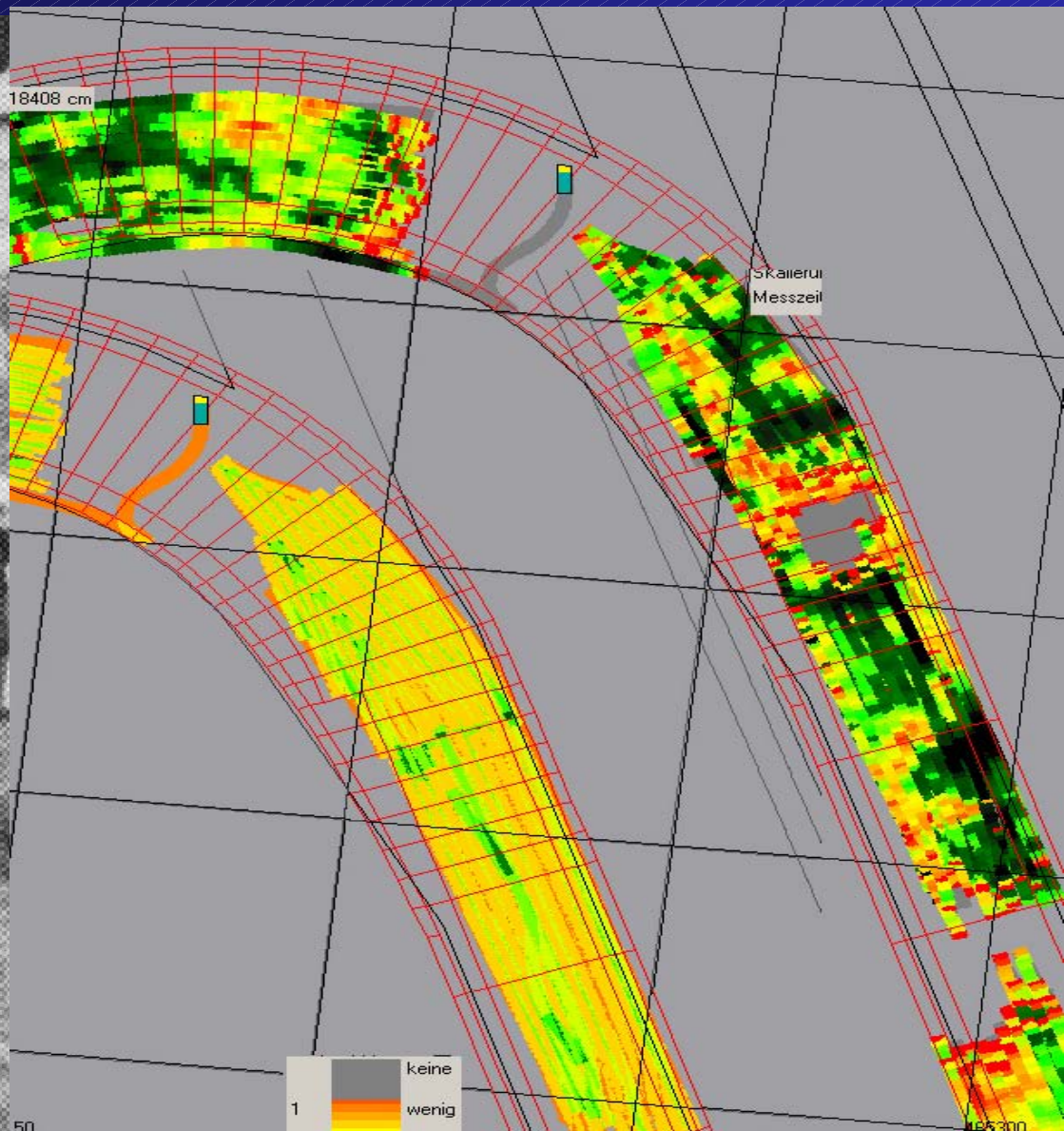
- **Intelligent Compaction in Several TH Contracts**
  - Grading Projects with Resident Engineer Interest Identified
  - TH212 Meeting with Contractor and IC Manufacturers
  - HMA Projects are also Possible with Iowa State Testing
- **Open House/Demonstration at MnROAD TS 27-28**
- **Continued Technology Transfer at Conferences**
- **Mn/DOT Participation with Other DOTs**
  - FHWA-led Intelligent Compaction Pooled Fund
  - NCHRP 21-09 Intelligent Compaction Specifications


COMPAQ
iPAQ
Pocket PC
miniFWD
9:57
ok
Force(kN) Press(kPa) Pulse(ms)
F
2.3
32.7
21.3
Offset(cm) Defl.(um) E-mod(MPa)
1
0
286
26
2
3
Location
st-1241
3
2
1
F
File Setup


MINN
HIGHWAY
DEPT
61029

Elephant vs Intelligent Compaction





Thank you.

- Questions?

- http://mnroad.dot.state.mn.us
  - Research Products
  - Mechanistic Empirical Resources