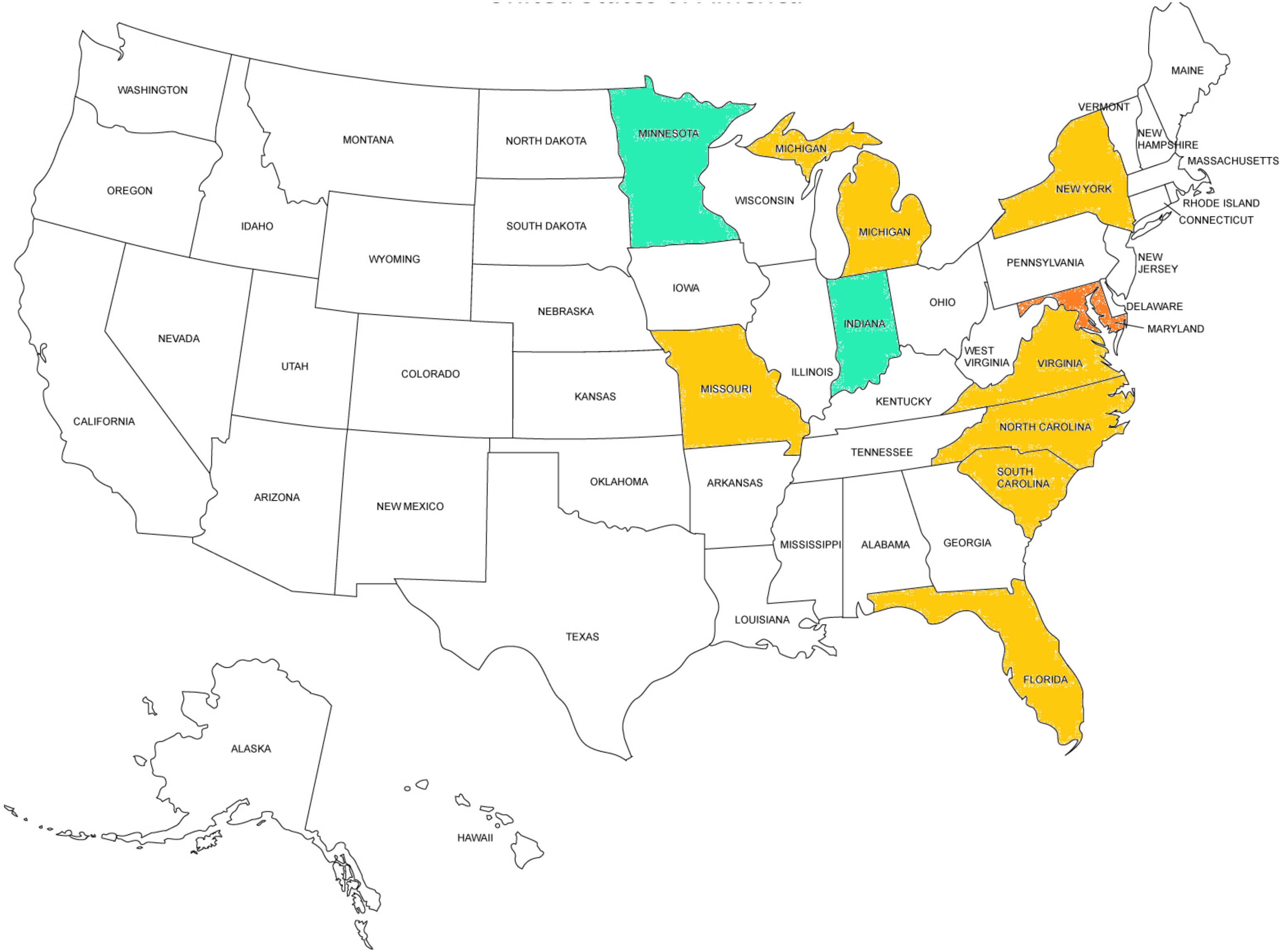
Standardizing Lightweight Deflectometer (LWD) Modulus Measurements for Compaction Quality Assurance

LWD study TPF-5(285)

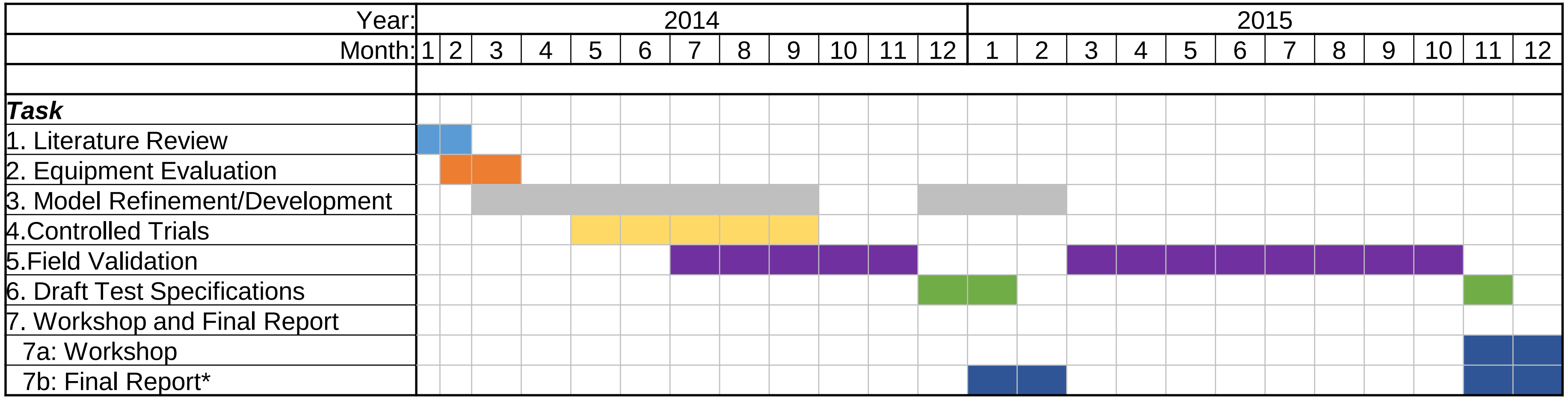
Charles W. Schwartz
University of Maryland – College Park

Project Status Meeting
July-01-2014

Participating Agencies



Schedule



Project Milestones: Q Q Q Q Q Q Q F

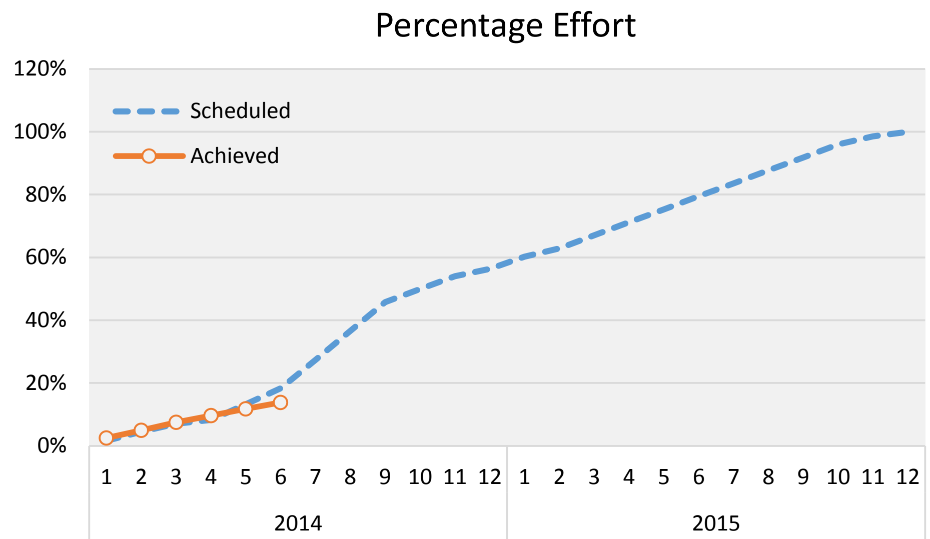
K = Kick-off/Coordination Meeting K P1 P2 P3 W

Q = Quarterly Progress Report

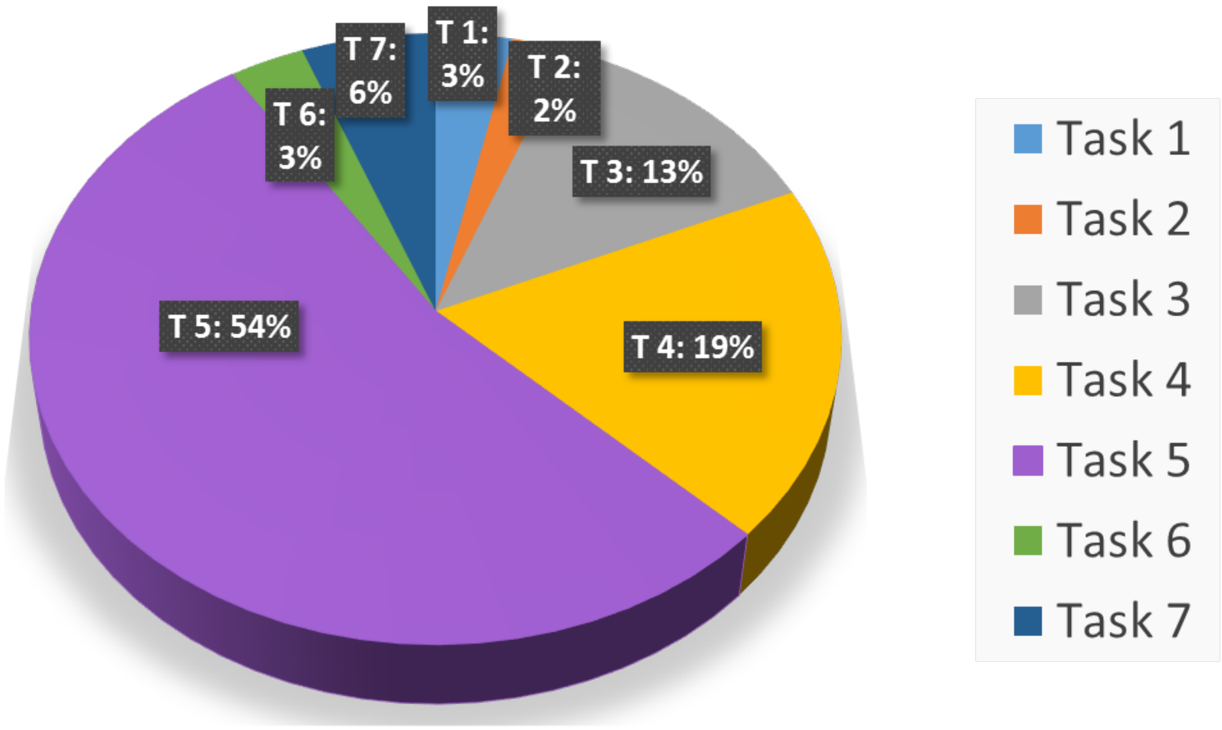
F = Final Project Report

Pi = Project Progress Meeting

W = Final Project Workshop



Schedule



: Literature Review
: Equipment Evaluation
: Refine/Develop Model
: Controlled Trials
: Field Validation
: Draft Test Specifications
: Workshop&Final Report

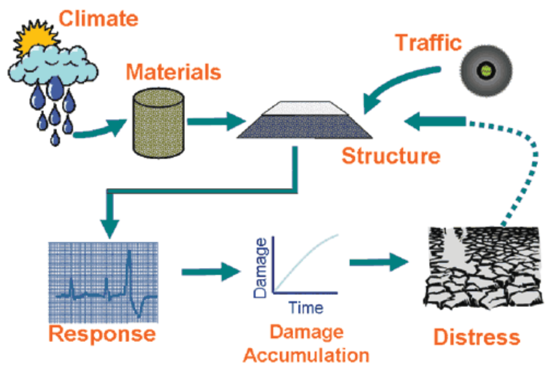
Research Objective

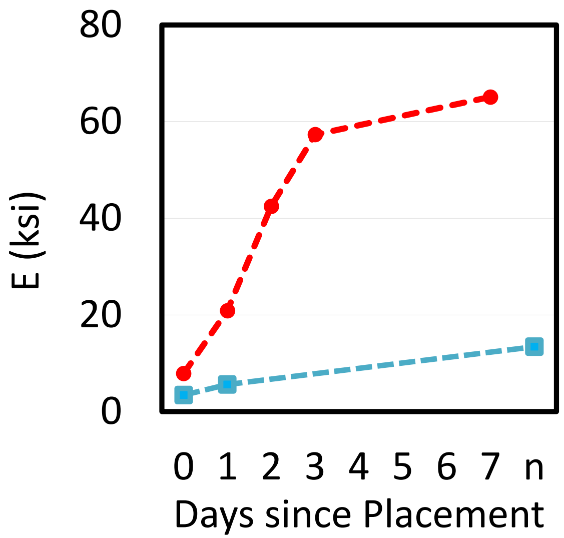
To provide a straightforward procedure for using LWD for modulus/stiffness-based compaction control that is suitable for practical implementation by field inspection personnel.

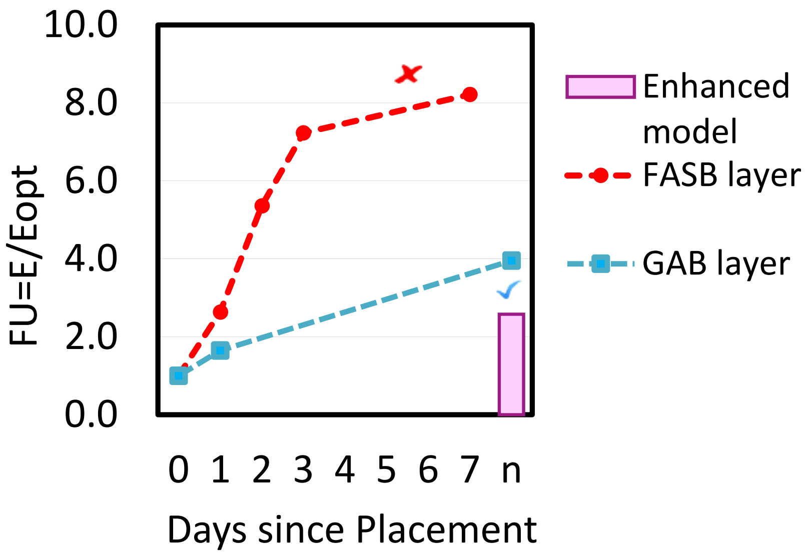
Significance of the Project

Why advantageous to go to stiffness measurement?

- Move away from nuclear quality control methods
- Better testing of unconventional materials
- Reflect the engineering properties of material
- Provide criteria for stiffness based design







Key Issues?

- Factors affecting soil modulus: Compaction moisture content, energy, density, void ratio, degree of saturation

- Factors affecting LWD raw measurements
- Factors affecting LWD modulus calculation/back calculation (nonlinear structure)
- LWD device variability
- Moisture measurement device variability
- Mr of soil as a function of stress and moisture
- Spatial Variability of soil

Prediction of modulus changes due to changes in moisture from compaction to time of testing

Properties @ Time of Field Compaction

Reference Condition

Properties @ Time of Field Testing

Design Target Properties

Target LWD stiffness value based on lab M_r and tolerable variability

Work Plan

Task 1: Review Literature

Task 2: Equipment Evaluation

Task 3: Model Refinement/Development

Task 4: Controlled Trials: Calibration of Proposed Procedure

Task 5: Field Trials: Validation of Proposed Procedure

Task 6: Specification Development

Task 7: Final Report

Task 1: Literature Review

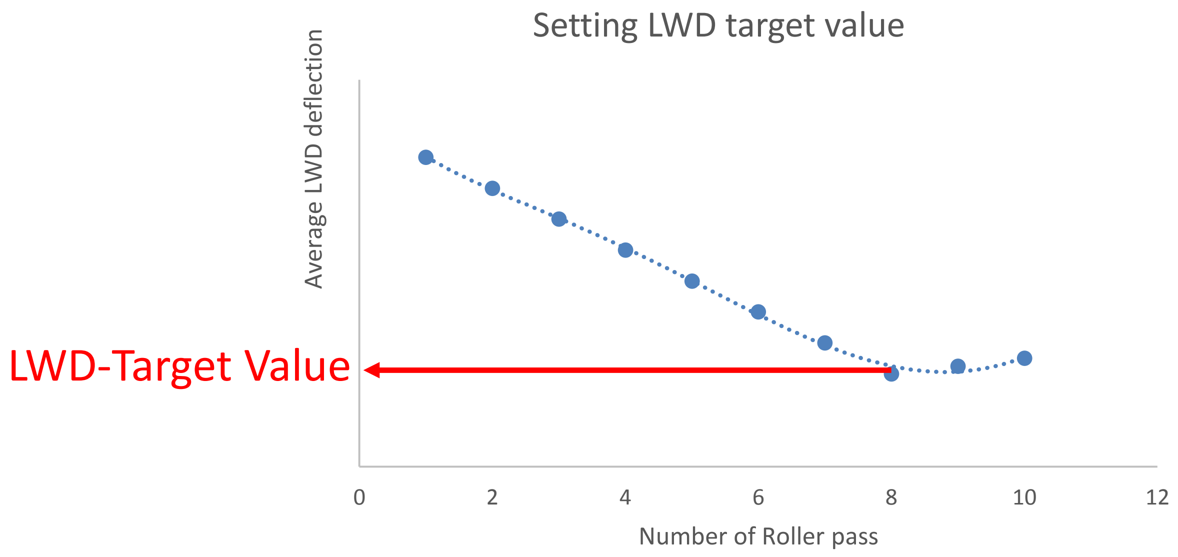
Current state of practice

- Minnesota
- Indiana
- Europe

Task 1: Literature Review

Minnesota

1. The control strip method



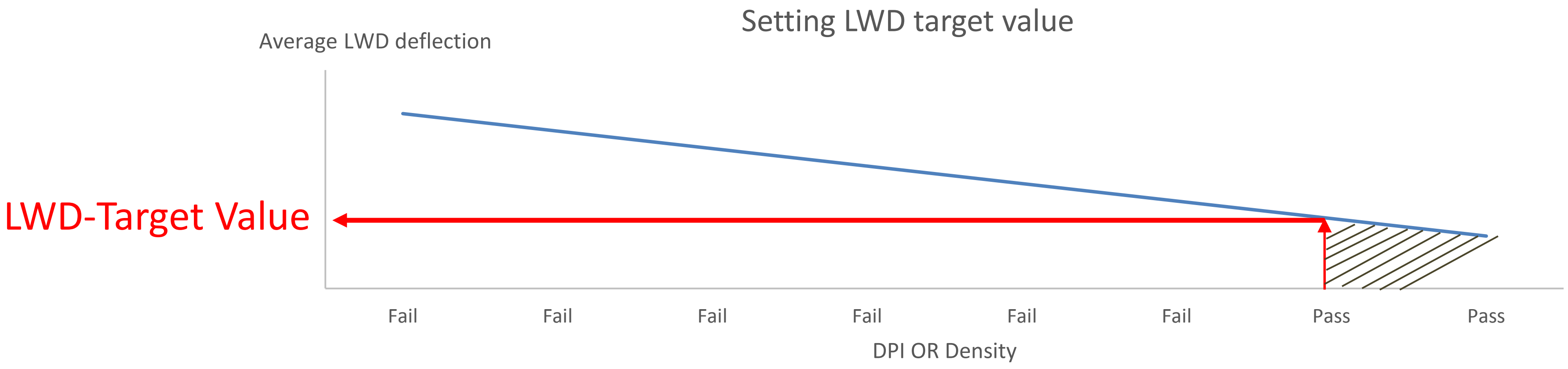
✓ average of all LWD tests < (1.1 * LWD-Target Value)

Task 1: Literature Review

Minnesota

2. Comparison test method

- Dynamic Penetration Index (for granular and base)
- Minnesota DOT-specified density method (for non-granular)
- ➢ LWD-TV = deflection where DPI or density values are passing



✓ LWD deflection value < LWD-TV

Task 1: Literature Review

Minnesota

(Siekmeier et al., 2009)

3. Recommended LWD target values

Based on Grading Number and MC (course)

Based on Plasticity Index and MC(fine)

Grading Number GN	Moisture Content (%)	Target LWD Modulus		Target LWD Deflection Zorn (mm)
		Keros/Dynatest (MPa)	Zorn (MPa)	
3.1 – 3.5	5 -7	120	80	0.38
	100	100	67	0.45
	75	75	50	0.6
3.6 – 4.0	5 -7	120	80	0.38
	80	80	53	0.56
	63	63	42	0.71
4.1 – 4.5	5 -7	92	62	0.49
	71	71	47	0.64
	57	57	38	0.79
4.6 – 5.0	5 -7	80	53	0.56
	63	63	42	0.71
	52	52	35	0.86
5.1 – 5.5	5 -7	71	47	0.64
	57	57	38	0.79
	48	48	32	0.94
5.6 – 6.0	5 -7	63	42	0.71
	50	50	33	0.9
	43	43	29	1.05

Plastic Limit	Estimated Optimum Moisture	Field Moisture as a Percent of Optimum Moisture	Zorn Deflection Target at Field Moisture minimum	Zorn Deflection Target at Field Moisture maximum
[%]	[%]	[%]	[mm]	[mm]
non-plastic	10-14	70-74	0.5	1.1
		75-79	0.6	1.2
		80-84	0.7	1.3
		85-89	0.8	1.4
		90-94	1	1.6
15-19	10-14	70-74	0.5	1.1
		75-79	0.6	1.2
		80-84	0.7	1.3
		85-89	0.8	1.4
		90-94	1	1.6
20-24	15-19	70-74	0.8	1.4
		75-79	0.9	1.6
		80-84	1	1.7
		85-89	1.2	1.9
		90-94	1.4	2.1
25-29	20-24	70-74	1	1.7
		75-79	1.2	1.9
		80-84	1.4	2.1
		85-89	1.6	2.3
		90-94	1.8	2.6
30-34	25-29	70-74	1.3	2
		75-79	1.5	2.2
		80-84	1.7	2.4
		85-89	1.9	2.7
		90-94	2.2	3

Task 1: Literature Review

Minnesota

LWD properties and test requirements

- plate diameter = 200 mm (7.9 inch)
- falling mass = 10 kg (22.1 lb)
- height of fall = 500 mm (19.7 inch)
- MC maintained from 65% to 95% of the target moisture content
- force applied = 6.28 kN (1539.9 lbf)
- stress = 0.2 MPa (29 psi)
- tests -> **immediately after compaction**

Task 1: Literature Review

Indiana

- To asses:
  - granular soils with aggregate sizes greater than 19mm (¾ inch)
  - coarse aggregate sizes No. 43, No. 53, and No. 73
  - structural backfill sizes 2 inches and 1.5 inches
- ➢ OMC - 6% < MC of aggregate < OMC
- ➢ LWD target value via control strip:
  1. Only LWD tests on the test section. 10 random places. After 4th and 5th roller pass; or until the difference between average LWD deflection is less than 0.01mm
  2. LWD and nuclear density gauge tests concurrently

average {maximum deflection in three LWD tests} ≤ maximum allowable deflection from control strip

LWD properties

- Metal plate diameter = 300 mm (11.8 inch)
- falling mass = 10 kg (22.1 lb)
- accelerometer attached to the center of the loading plate
- force applied = 7.07 kN (1589.4 lbf)
- Additional compaction of the tested material is required if the change in deflection for **any two consecutive LWD drops is 10% or greater**

Task 1: Literature Review

Europe

- Standard: CEN ICS 93.020: "Measuring Method for Dynamic Compactness & Bearing Capacity with Small-Plate Light Falling Weight Deflectometer"

Technical Requirements (CEN ICS 93.020)

• mass of the falling weight (including handle)	10,5 kg ± 0.5 kg
• total mass of guide rod (including the spring consisting of spring elements, transportation protection of the falling weight, triggering structure and tilting protection)	max. 5 ± 0.5 kg
• dynamic loading	0.35 MPa
• loading time	18 ± 2ms
Design requirements of the loading plate :	
• diameter of the loading plate	163 ± 2 mm
• thickness of the loading plate	min.20 mm
• total mass of the loading plate complete masse (including measuring cell for the sensor and handles)	15 ± 1.0 kg
Fixed technical data of acceleration gauge applied for deformation measurement:	
• measurement range of in-built acceleration gauge	0 – 50 g
In case of applying other strain gauge and the acceleration gauge:	
• measurement time	18 ± 2ms min. signals/18 ms
• processed measurement signal	min. 0.01 mm
• reading accuracy of deformation	maximum ± 1.5 s per
• reading accuracy of deformation	minimum 0.01 mm

Task 1: Literature Review

Europe

1. Dynamic modulus
2. Dynamic compactness rate

- Boussinesq method:

$$E = \frac{c\,(1-\mu^2)\rho_{dyn} r}{s_{1a}} = \frac{C\mu}{s_{1a}}$$

c	Boussinesq plate multiplier (considering π/2 rigid plate)
$s_{1a}-$	Average vertical travel of the center of the plate
μ	Poisson's ratio (according to MSZ 2509-3 standard)
r	Radius of the loading disc, mm
ρ_{dyn}	F_{dyn}/A theoretical pressure applied to soil
A	Loading plate area , mm²

$F_{dyn} = \sqrt{2.m.g.h.K}$

m	Mass of falling body,
g	Acceleration of gravity m/s²
h	Drop height, m
K	spring constant, N/m

Task 1: Literature Review

Europe

- Relative compactness rate (T_{rE}) at the field moisture content :

$$T_{rE}\%=100-\varnothing_0*D_m$$

  - $\varnothing_0$: a linear coefficient calculated from the Proctor-test results, in general, it is taken to be 0.365 ± 0.025
  - D_m: deformation index, it is calculated from the sum of the elements of the data line formed from the difference of the subsequent deflections up to the drop.
- Adjust to the optimal moisture content :

$$T_{rd} = T_{rE} .T_{rw}$$

  - TrE : site relative compaction at a given water content
  - Trw: is the moisture correction coefficient to adjust for differences between the measured moisture content and optimum moisture content:
    - based on the results of a modified Proctor test:

$$T_{rw} = \frac{\rho_{di}}{\rho_{d\max}}$$

    - ρdmax : is maximum dry density value obtained in the modified Proctor test
    - ρdi : is dry density value on compaction curve of the modified Proctor tests corresponding to the in situ moisture -content

Task 1: Literature Review

Target stiffness/deflection values

New England Transportation Consortium Study:

Target modulus at the optimum moisture for a base course material

(Steinart et al., 2005)

Relative Compaction based on AASHTO T-180 (%)	Equivalent LWD Composite Modulus (MPa) at Optimum Water Content
90	92
95	115
98	130
100	139

Correction factor

(Steinart et al., 2005)

Water Content Relative to Optimum		Correction Factor to be Added to Composite Modulus (MPa) Measured at Field Moisture Content
Dry of OMC	-4%	-31
	-3%	-23
	-2%	-15
	-1%	-8
At OMC		0
Wet of OMC	+1%	8
	+2%	15
	+3%	23
	+4%	31

Task 1: Literature Review

Target stiffness/deflection values

United Kingdom Highway Agency specifications:

Foundation surface modulus
measured using the standard FWD
✓ correlation between LWD and FWD measurements
(Highway Agency, 2009)

		Surface Modulus (MPa)			
		Class 1	Class 2	Class 3	Class 4
Long-Term In-service Surface Modulus		≥50	≥100	≥200	≥400
Mean Foundation Surface Modulus	Unbound Mixture Types	40	80	*	*
	Fast-setting Mixture Types	50	100	300	600
	Slow-setting Mixture Types	40	80	150	300
Minimum Foundation Surface Modulus	Unbound Mixture Types:	25	50	*	*
	Fast-setting Mixture Types:	25	50	150	300
	Slow-setting Mixture Types:	25	50	75	150

**Unbound materials are unlikely to achieve the requirements for Class 3 & 4*

Task 1: Literature Review

EFFECT OF MOISTURE CONTENT AT TIME OF COMPACTION AT CONSTANT DENSITY (Pacheco and Nazarian, 2011)

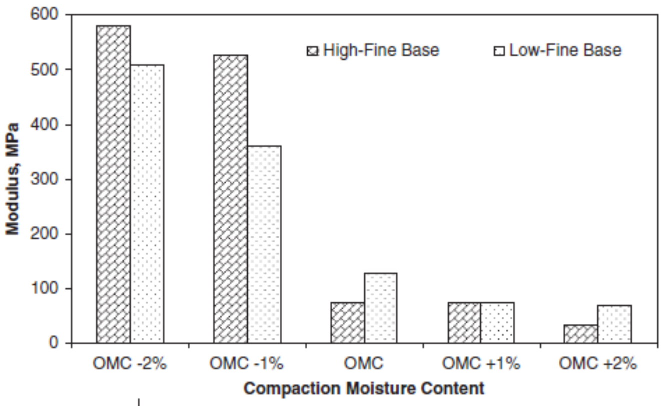
High-PI Clay

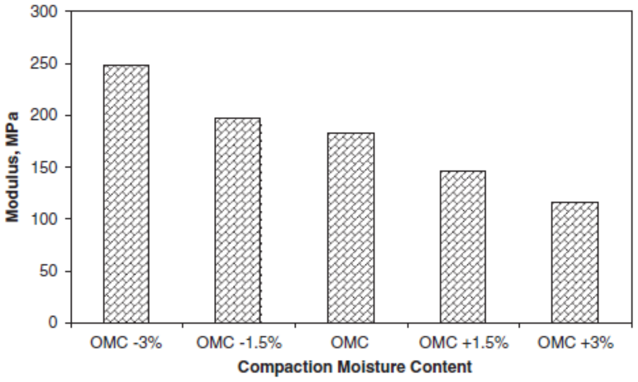
- OMC + 3%
- OMC+1.5%
- OMC
- OMC-1.5%
- OMC - 3%

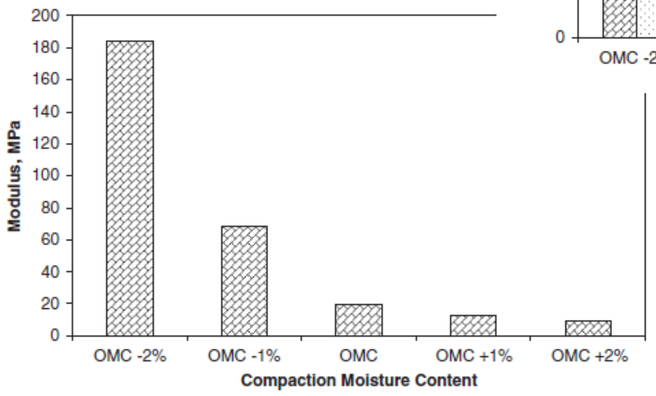
Clayey Sand
HF granular base
LF granular base

- OMC + 2%
- OMC + 1%
- OMC
- OMC - 1%
- OMC – 2%

Adjust the compaction energy → Corresponding target MDD

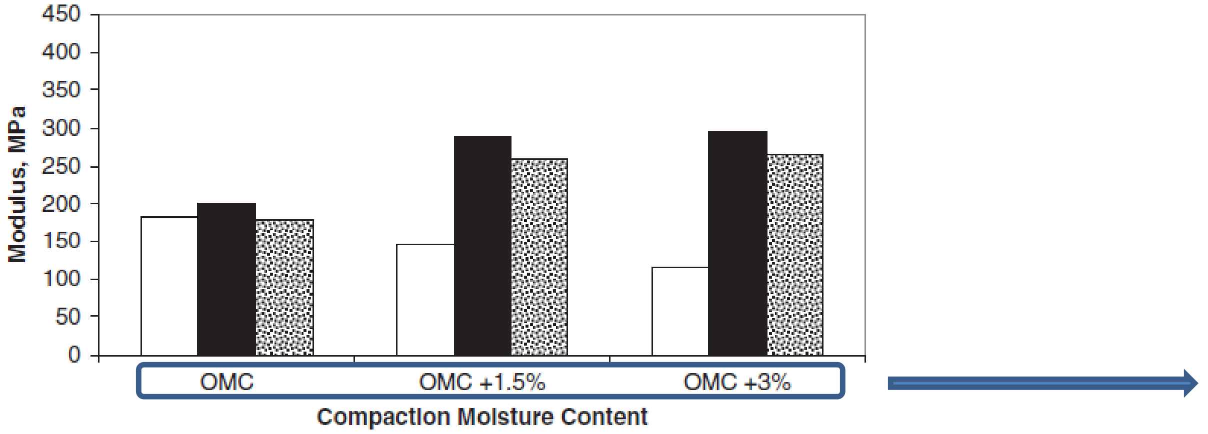




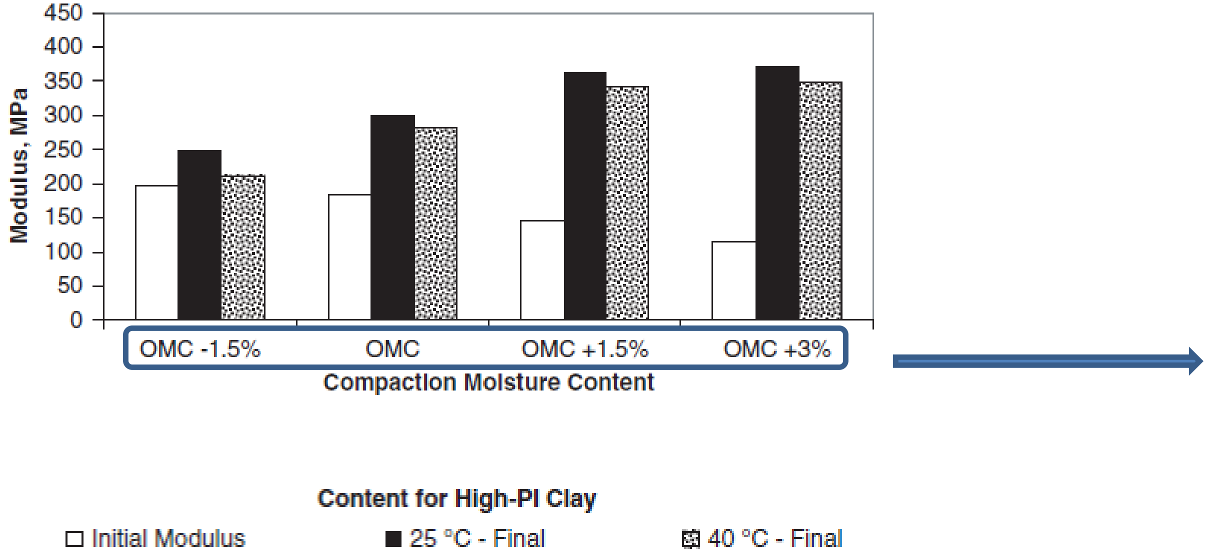


Task 1: Literature Review

EFFECT OF MOISTURE CONTENT AT TESTING (Pacheco and Nazarian, 2011)



Dried to OMC-1.5%



Dried to OMC-3%

Task 1: Literature Review

EFFECT OF DIFFERENCE BETWEEN COMPACTION AND TESTING MOISTURE CONTENT (Pacheco and Nazarian, 2011)

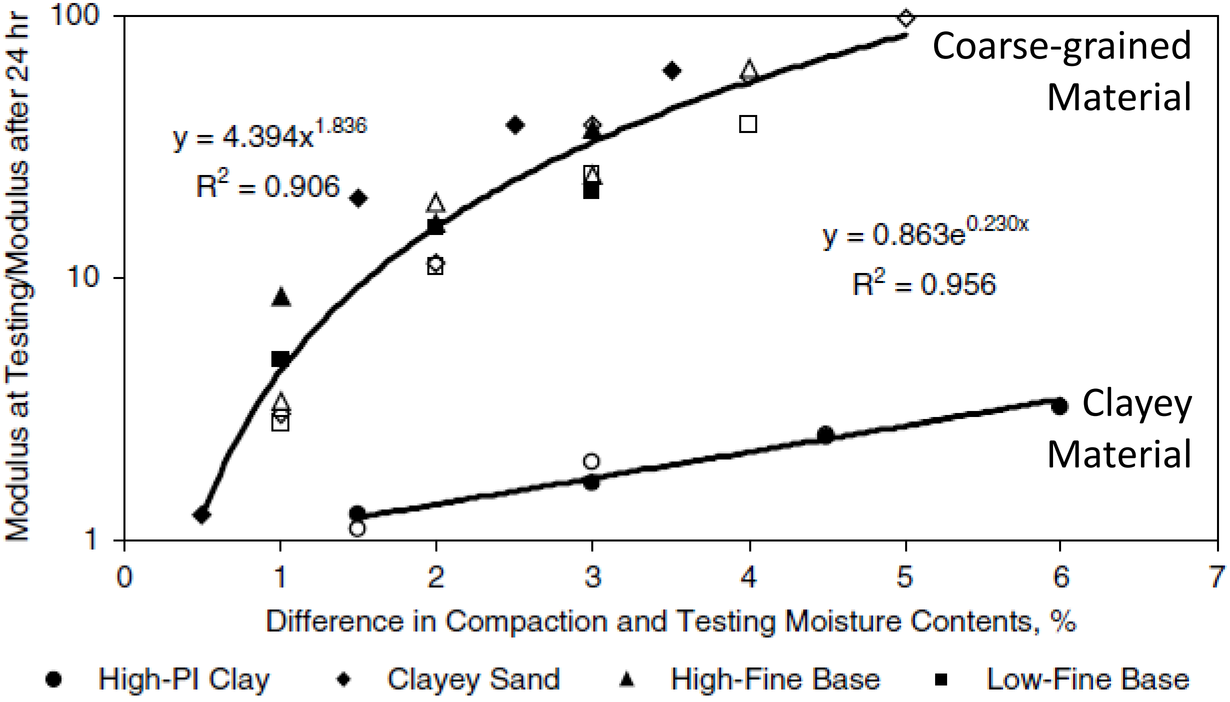
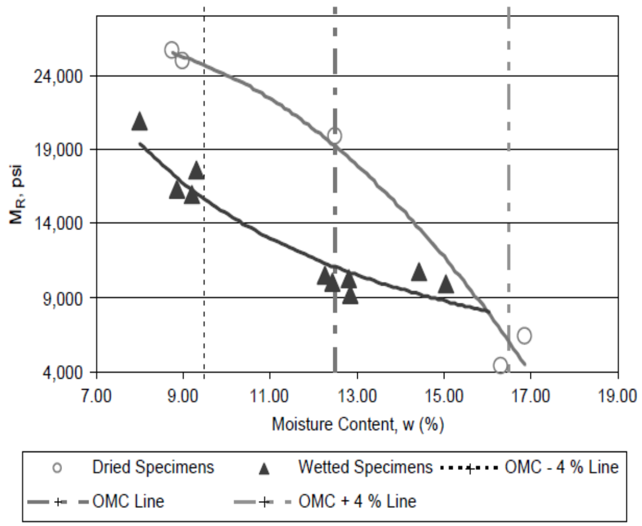


FIGURE 8 Effect of differences between compaction and testing moisture contents on modulus (closed and open markers indicate specimens dried to OMC − 1.5% and OMC − 3%, respectively).

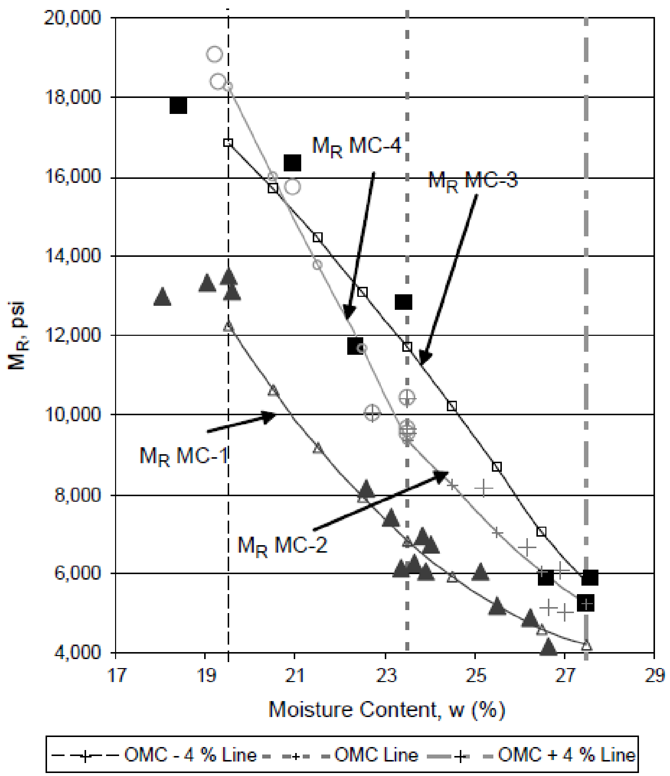
Task 1: Literature Review

EFFECT OF DIFFERENCE BETWEEN COMPACTION AND TESTING MOISTURE CONTENT (Khoury and Zaman, 2004)

- Sandy and a clayey subgrade soil in Oklahoma
- Differences in Mr of specimen compacted less/more than OMC and then subjected to wetting/drying
- MR–moisture content relationships for C-Soil exhibit a hysteretic behavior due to wetting and drying



S-soil Variation of M_R of S-Soil with moisture content.



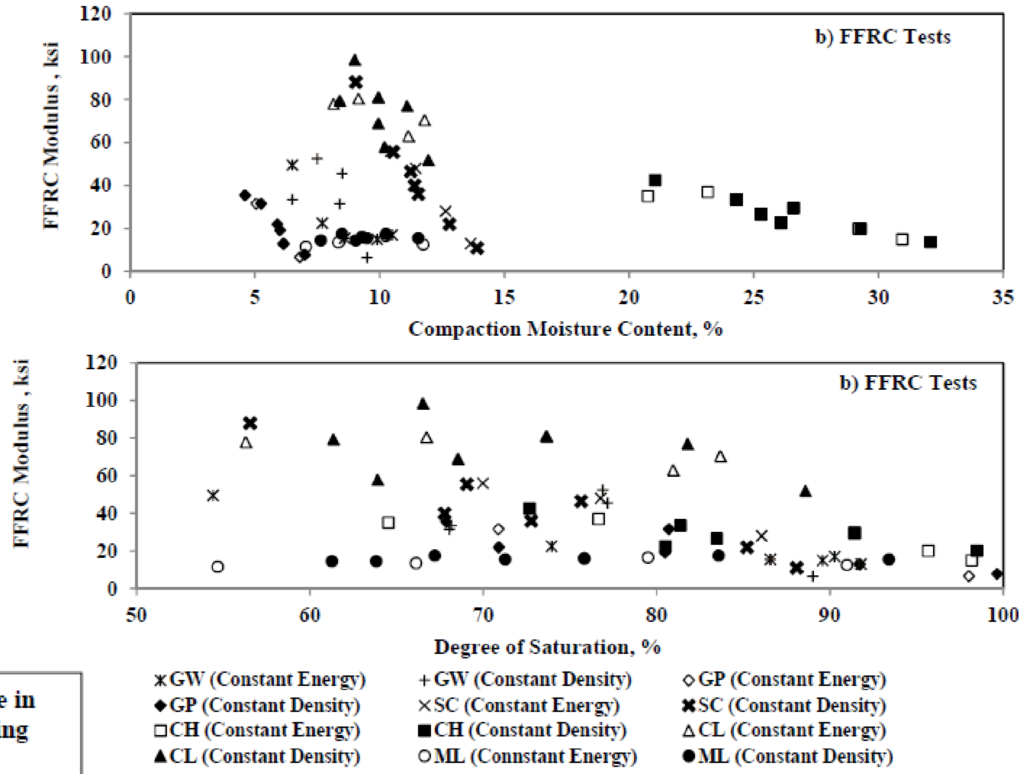
C-soil Variation of M_R with moisture content.

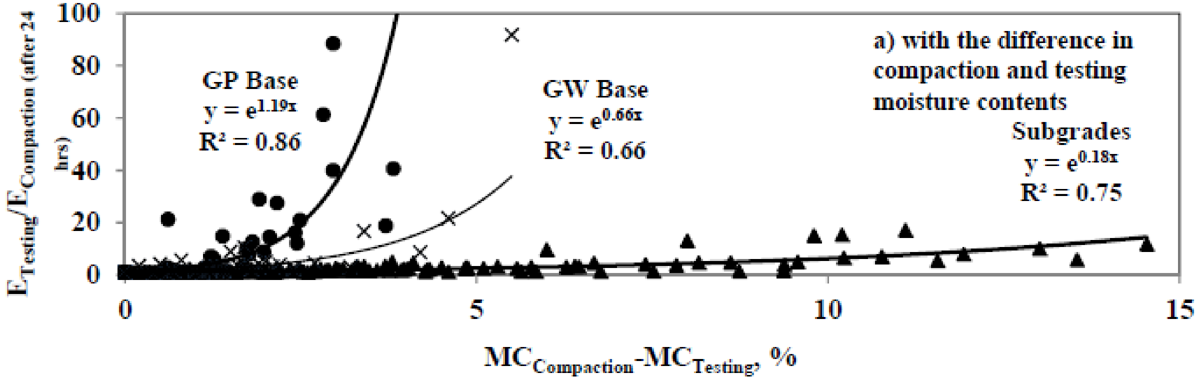
Task 1: Literature Review

EFFECT OF DIFFERENCE BETWEEN COMPACTION AND TESTING MOISTURE CONTENT (Nazarian et al. 2013)

- capture the effect of compaction MC, testing MC, and density on modulus
- Free-free resonant column (FFRC) tests

✓ the higher the difference between the MC at compaction and testing, the higher will be the seismic modulus -> correlated with resilient modulus

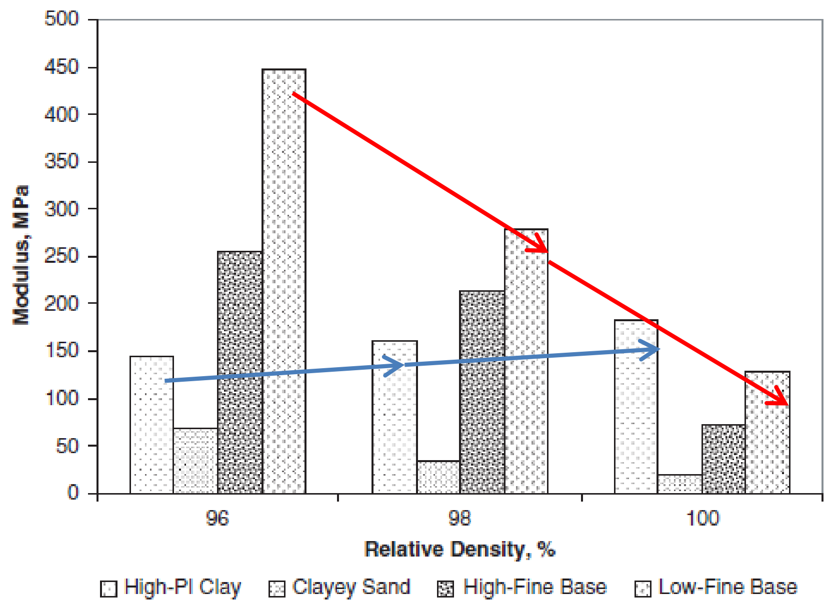




Task 1: Literature Review

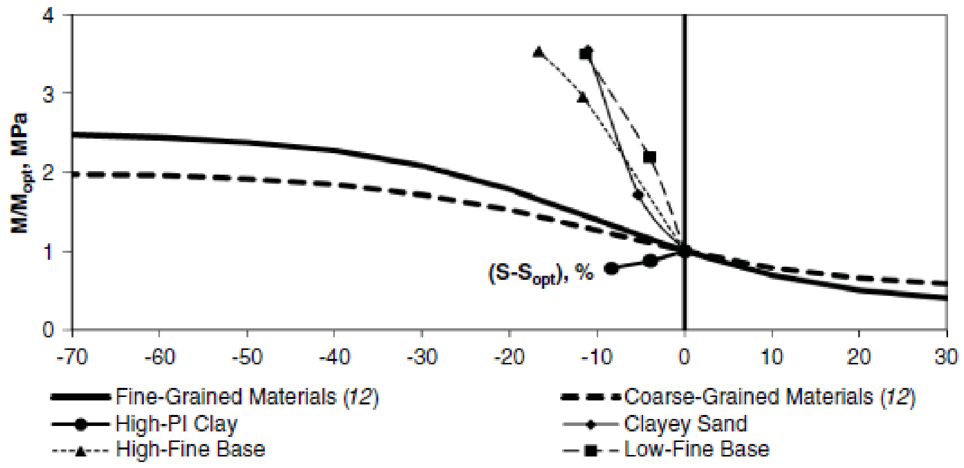
EFFECT OF DENSITY (Pacheco and Nazarian, 2011)

- Nominal relative densities of 96%, 98%, and 100%.
- Compacted at OMC by changing the compaction energy



✓ Lower density does not automatically correspond to a lower modulus!

✓ Lack of success in correlating density to modulus



Task 1: Literature Review

EFFECT OF COMPACTION ENERGY

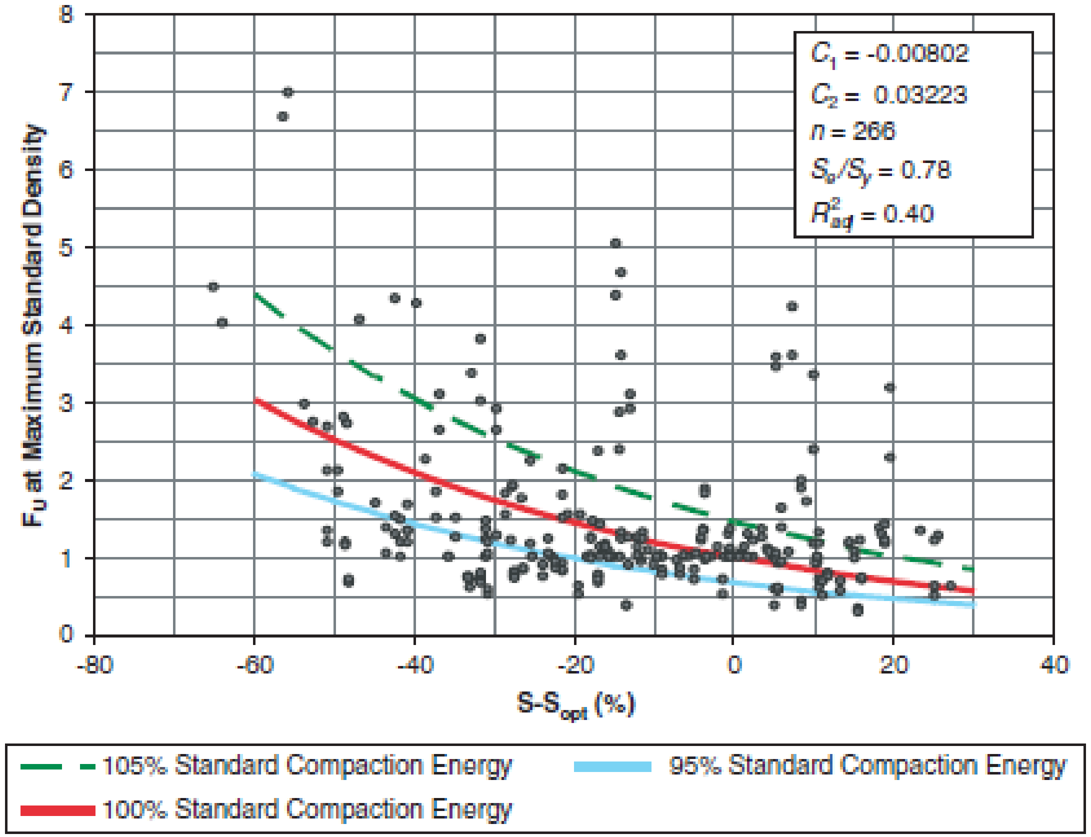
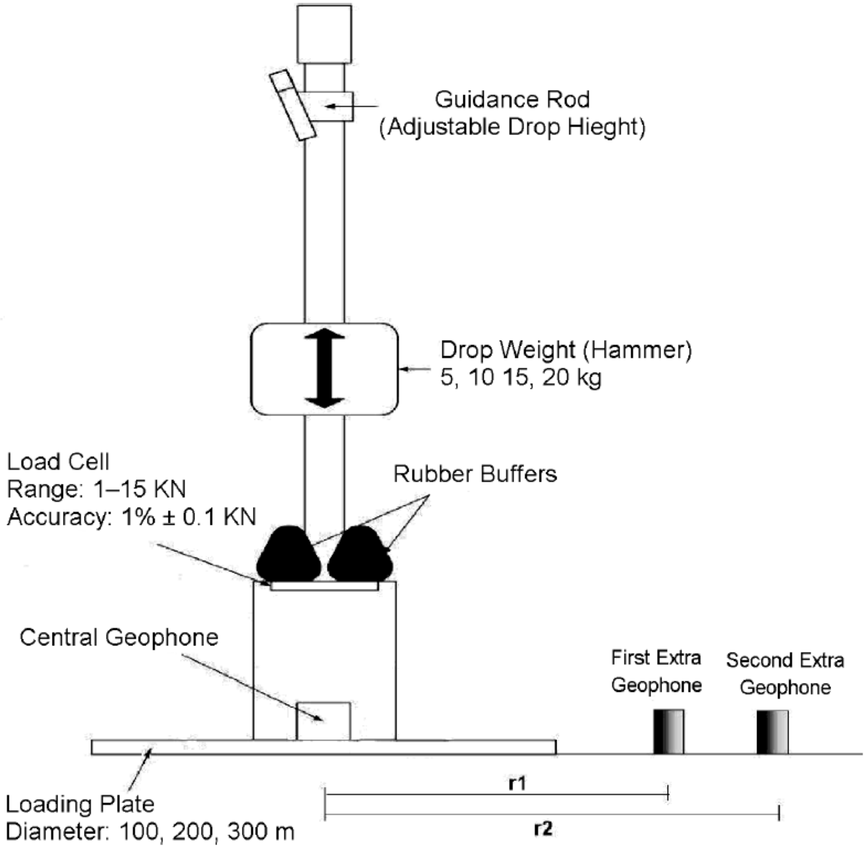


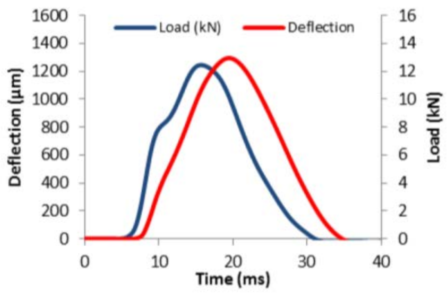
FIGURE 4 Influence of soil compaction energy on prediction of F_U.

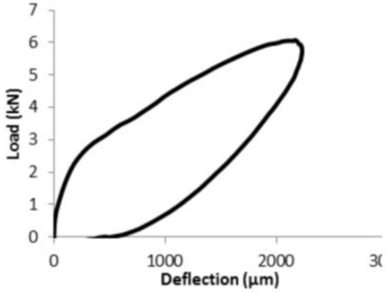
Zapata, 2011

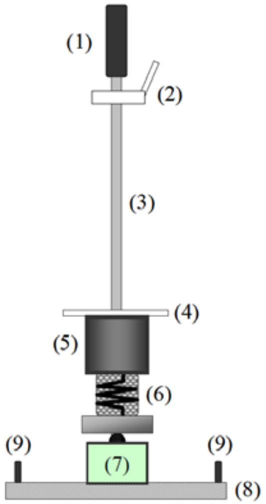
Task 2: Equipment Evaluation : LWD

What is LWD? And what does it measure?









(1) Grip
(2) Top fix and release mechanism
(3) Guide rod
(4) Round grip
(5) Falling weight (10kg)
(6) Set of steel springs (buffer)
(7) Measuring element that contains the sensor
(8) Loading plate (diameter=30cm)
(9) Carry grip

Task 2: Equipment Evaluation : LWD

Device	Plate Style	Plate Diamet er (mm)	Plate Thickness (mm)	Falling Height (cm)	Falling Weight (kg)	Plate Mass (kg)	Maximum Applied Force (kN)	Load Cell	Total Load Pulse (ms)	Type of Buffers	Deflection Transducer	
											Type	Location
Zorn ZFG2000, Germany	Solid	100, 150, 200, 300	124, 45, 28, 20	72	10, 15	15	7	No	18±2	Steel Spring	Acceler-ometer	Plate
Dynatest 3031	Annulus	100, 150, 200, 300	20		10, 15, 20		15	Yes	15-30	Rubber (Flat)	Velocity	Ground
Prima 100, Carl Bro Pavement Consultants, Denmark	Annulus	100, 200, 300	20	Max 85 Variable	10, 20	12	15	Yes	15-30	Rubber (Conical shape)	Velocity	Ground
Loadman, AL-Engineering Oy, Finland	Solid	110, 132, 200, 300	-	80	10	6	18	Yes	25-30	Rubber	Acceler-ometer	Plate
Olson	Solid	100, 150, 200, 300	-	60 v	9		9	Yes	20	Spring	Velocity	Plate
Humboldt	Solid	300			10, 15						Acceler-ometer	Plate

Task 2: Equipment Evaluation : LWD

A. What is the LWD induced contact stress shape?

B. What is the LWD induced peak force magnitude?

C. What affects the measured deflection?

D. What affects the induced response (deformation and/or load time history?

E. How can we calculate the composite stiffness (k) of the soil from LWD?

F. How can we calculate the Young’s modulus (E) of the soil from LWD?

G. How can we calculate degree of compaction? Using the energy loss of the soil?

Task 2: Equipment Evaluation : LWD

A. What is the LWD induced contact stress shape? *For Zorn LWD with solid plate*

Contact between a rigid cylinder and an elastic half-space

If a rigid cylinder is pressed into an elastic half-space, it creates a pressure distribution described by

$$p(r) = p_0 \left(1 - \frac{r^2}{a^2}\right)^{-1/2}$$

where a is the radius of the cylinder and

$$p_0 = \frac{1}{\pi} E^* \frac{d}{a}$$

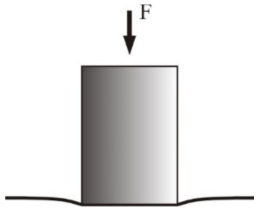
The relationship between the indentation depth and the normal force is given by

$$F = 2aE^*d$$

where

$$\frac{1}{E^*} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}$$

and E_1, E_2 are the elastic moduli and $\nu_1 \nu_2$ the Poisson's ratios associated with each body.



= Boussinesq Equation with *A (Shape factor) equal to* *4*

$$E = \frac{2\,k_s\left(1-\nu^2\right)}{A r_0}$$

$$k_s = \left|\frac{F_{peak}}{w_{peak}}\right|$$

Analytical Solution
For contact stress of
Rigid Cylinder on elastic half space
≈
Cohesive soil (Clay) contact pressure
(Boussinesq Equation)

Are the Boussinesq shape factors correct?

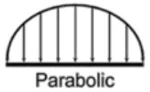
Task 2: Equipment Evaluation : LWD

A. What is the LWD induced contact stress shape? *For Zorn LWD with solid plate*

- Boussinesq theorized that a rigid circular plate produces
  - Inverse Parabolic Distribution on cohesive soils

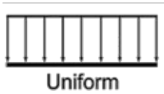
$A = 4$

  - Parabolic Distribution on non-cohesive soils



$A = 3\pi / 4$

  - Uniform Distribution on soils having mixed characteristics



$A = \pi$

Boussinesq Equation with *A (Shape factor) equal to* 4

$$E = \frac{2 k_s (1 - \nu^2)}{A r_0}$$

$$k_s = \left| \frac{F_{peak}}{w_{peak}} \right|$$

Analytical Solution
For contact stress of
Rigid Cylinder on elastic half space
≈
Cohesive soil (Clay) contact pressure
(Boussinesq Equation)

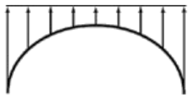
Are the Boussinesq shape factors correct?

Task 2: Equipment Evaluation : LWD

A. What is the LWD induced contact stress shape? *For Zorn LWD with solid plate*

Are the assumed shape factors correct?

Inverse Parabolic



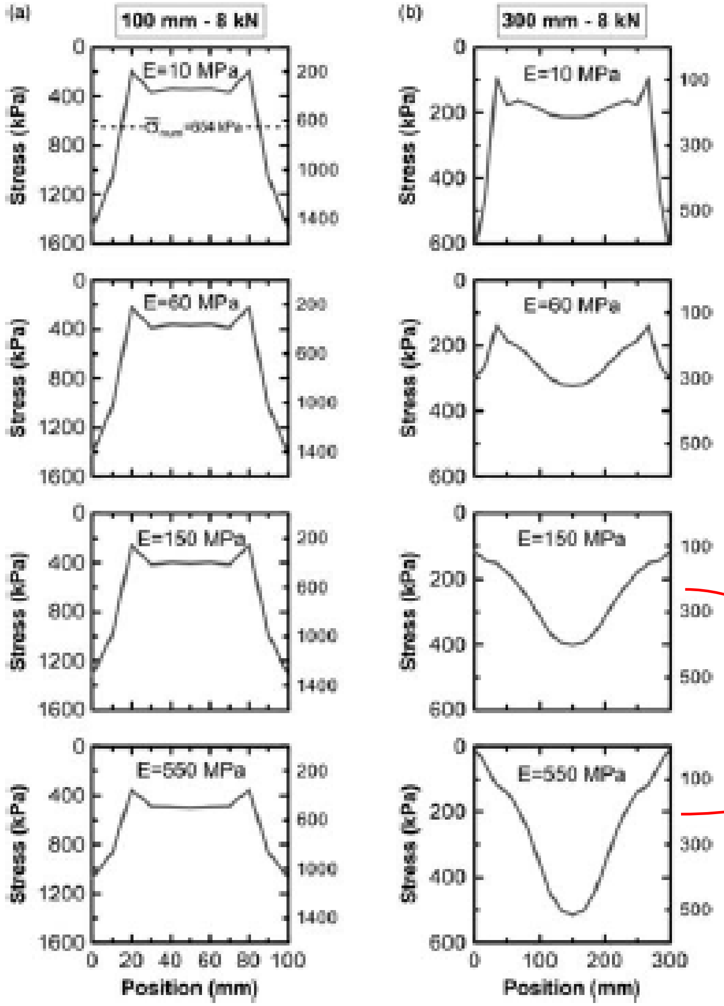


Figure 4. Results of the finite element theoretical analysis of the stress distribution under the PLWD loading plate for (a) 100-mm and (b) 300-mm plates.

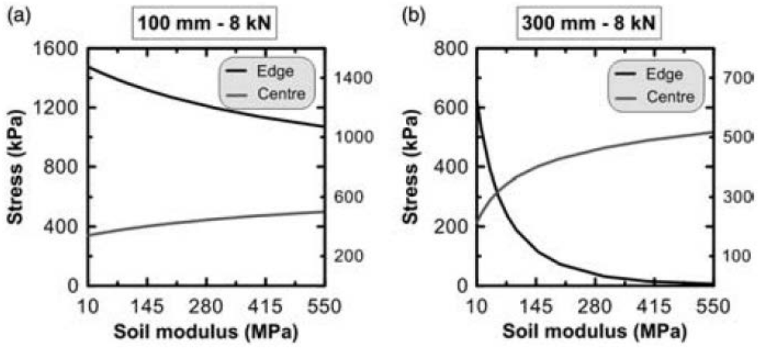


Figure 5. Evolution of stresses under the centre and the edges of the 100-mm and 300-mm plates as a function of soil elastic modulus based on numerical simulations.

Not Inverse Parabolic anymore!

Shows that the 300 mm plate might not be really rigid! Especially if the modulus of the soil is high. Even when the soil is considered linear elastic.

Bilodeau and Dore' (2013)

Task 2: Equipment Evaluation : LWD

A. What is the LWD induced contact stress shape? *For Prima/Dynatest LWD with annulus plate*

Contact between a rigid circular ring and an elastic half-space

The contact pressure distribution is expressed as follows:

$$p = \frac{p_{av}(1-n^2)\sqrt{(\frac{r}{R_2})^2 - m^2}}{2\sqrt{1-m^2}\,E_o(k)\sqrt{\{(\frac{r}{R_2})^2 - n^2\}\{1-(\frac{r}{R_2})^2\}}} \quad \ldots (7.15)$$

where $n = \frac{R_1}{R_2}$

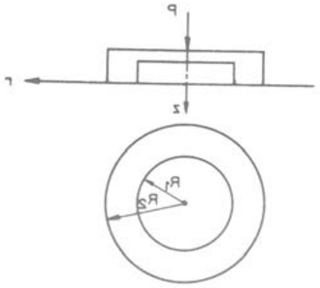
$$p_{av} = \frac{P}{\pi R_2^2(1-n^2)}$$

$$E_o(k) = \int_0^{\pi/2} \sqrt{(1-k^2 \sin^2\theta)}\,d\theta$$

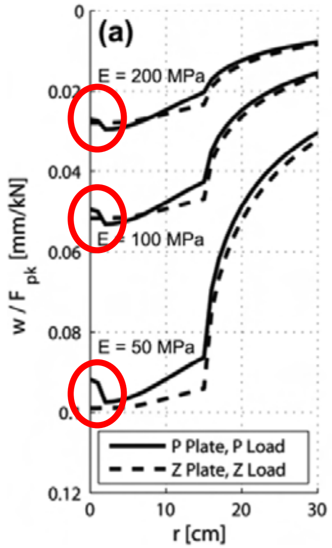
= complete elliptic integral of second kind

$$k = \left(\frac{1-n^2}{1-m^2}\right)^{\frac{1}{2}}$$

$m = 0.8n$ for $0 \le n \le 0.9$, increasing to 1 for $n=1$ (note that $n=0$ is the case of a circle).



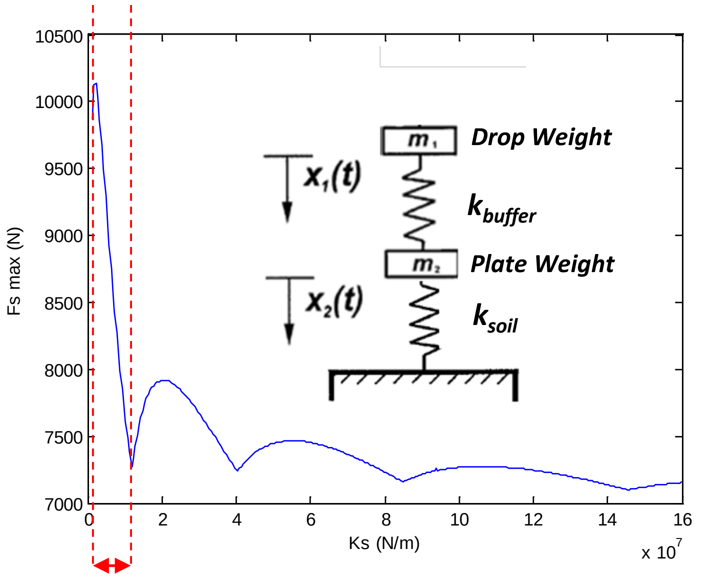
Poulos and Davis (1974) after Egorov (1965)



Stamp and Mooney (2013)

Task 2: Equipment Evaluation : LWD

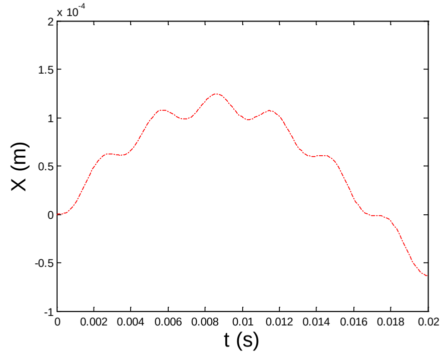
B. What is the LWD induced peak force magnitude? *Is the assumed 7070 N load by Zorn reasonable?*

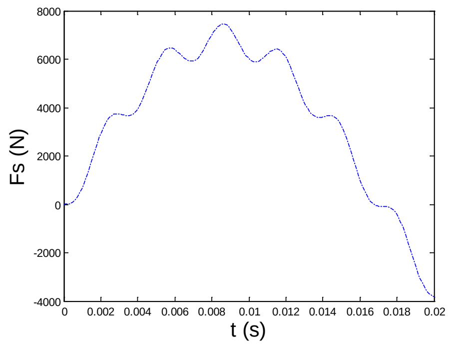


K_{soil}= 1.3e6 – 1.3e7

K_{soil}= 1.3e6 – 1.3e7

Inverse Parabolic	E_{Clay}:	572-5719 (psi)	$A = 4$
Parabolic	E_{Sand}:	971-9709 (psi)	$A = 3\pi/4$
Uniform	$E_{Mixed\ soil}$:	728-7282 (psi)	$A = \pi$





Zorn assumed 7070 N force can induce systematic error in calculation of E especially in soft soils

Task 2: Equipment Evaluation : LWD

B. What is the LWD induced peak force magnitude? *Is the assumed 7070 N load by Zorn reasonable?*

(Stamp and Mooney, 2013) → FE analysis incidentally demonstrated 7.07 kN peak load→ But in their analysis, they assumed E of soil ranging from 7.2 to 87 ksi

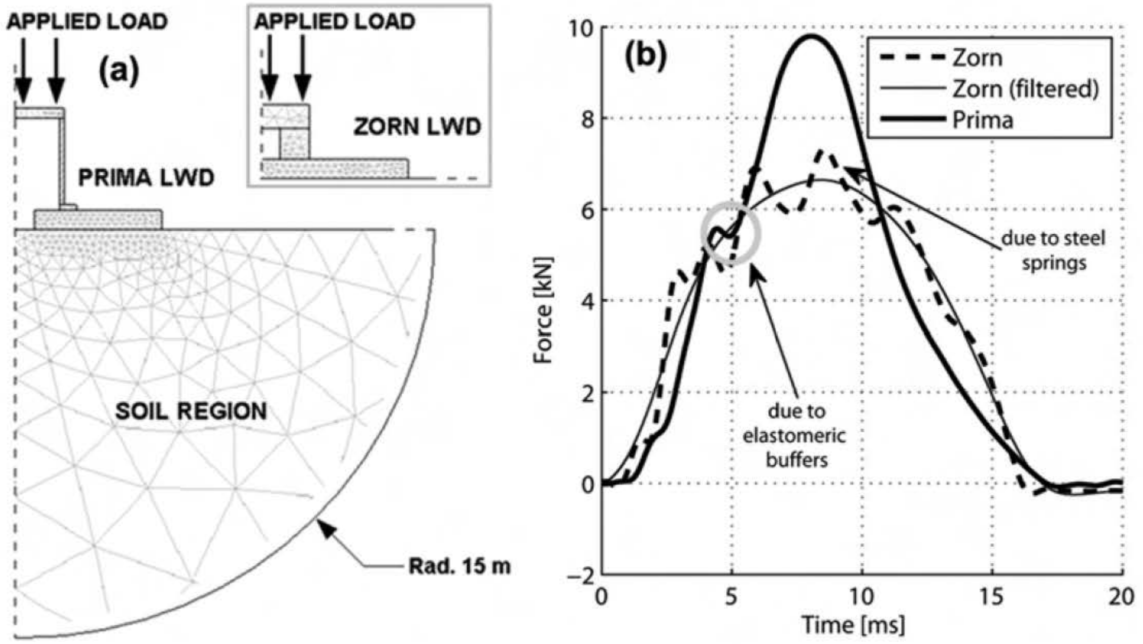


FIG. 7—(a) Schematic of finite element model used for LWD analysis on homogeneous soil regions in COMSOL Multiphysics. (b) Applied load pulses from Zorn and Prima LWDs. Raw Zorn load data have been low pass filtered at 200 Hz to provide an accurate "max" force for standard LWD calculations per manufacturer practice.

Task 2: Equipment Evaluation : LWD

C. What affects the measured deflection?

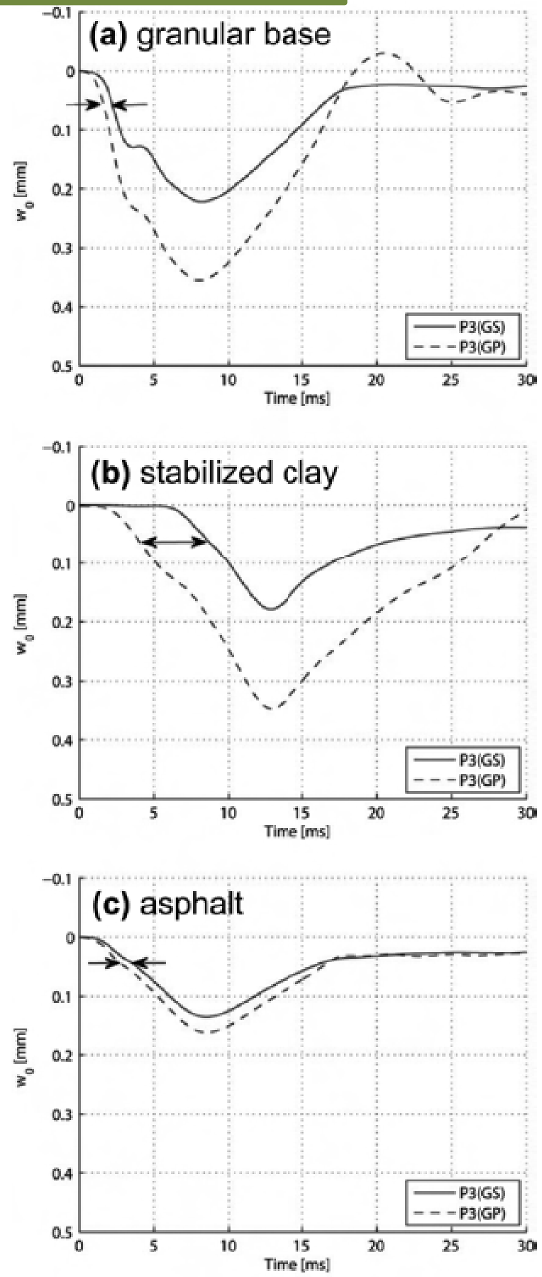
1. Type of deflection transducer (Stamp and Mooney, 2013)

Type of deflection transducer (geophone vs accelerometer)

- Negligible when looking at the peak deflection
- Grows more significant when looking at the entire time history
- Error from accelerometer is higher because of double integration process

2. Location of deflection transducer (Stamp and Mooney, 2013)

Measurements made on top of plate are always higher than measurements made on top of soil!



On soil

On plate

Task 2: Equipment Evaluation : LWD

D. What affects the induced response (deflection and/or load time history?

1. Type of buffers

-Stiffness (k_{buffer}) of the 2DOF system=>Changes the pulse duration (slightly)

2. Drop height

-Changes the potential energy (mgh) =>changes the force and deflection (slightly) Lin et al. (2006)

3. Drop Weight

- Will change the potential energy of the system,
- Mass of the 2DOF system (significant)

4. Plate Diameter

- Rigidity of the plate, contact pressure

5. Plate thickness

-Rigidity of the plate, contact pressure

6. Plate weight

-Mass of the 2DOF system (significant)

7. Modulus of the composite soil system

-k_{soil} of the 2DOF system=>changes the force and deflection
-Relative modulus of plate and soil=>Contact pressure

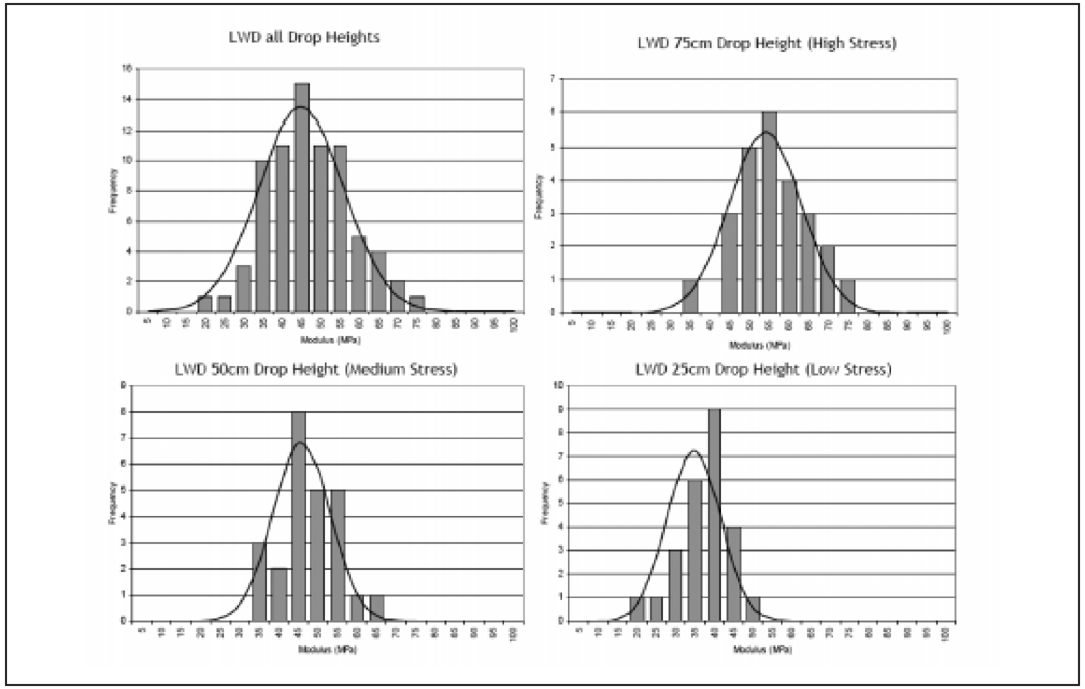


FIGURE 53 LWD moduli predictions and their distribution (Petersen and Peterson 2006).

Effect of Drop height- Prima-100, After NCHRP Synth 382

Task 2: Equipment Evaluation : LWD

E. How can we calculate the composite stiffness (k) of the soil from LWD?

K_{soil} = Fmax/δmax?

Above definition provides dynamic k→ To get the k_{static} , frequency domain analysis is required

This can be a good method to
compare the k from the LWD device to k_{static} of a known material e.g. steel beam

Stiffness Estimates Using Portable Deflectometers

Olivier J.-M. Hoffmann, Bojan B. Guzina, and Andrew Drescher

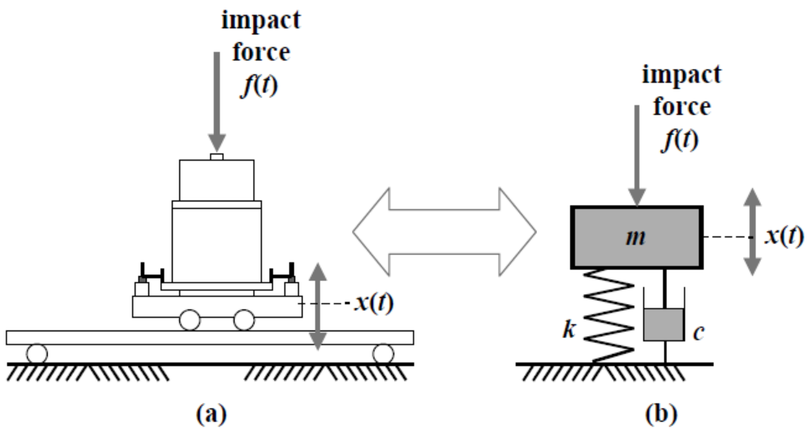


FIGURE 4 SDOF analog for the BVT: (a) four-point beam testing configuration; (b) corresponding SDOF analog.

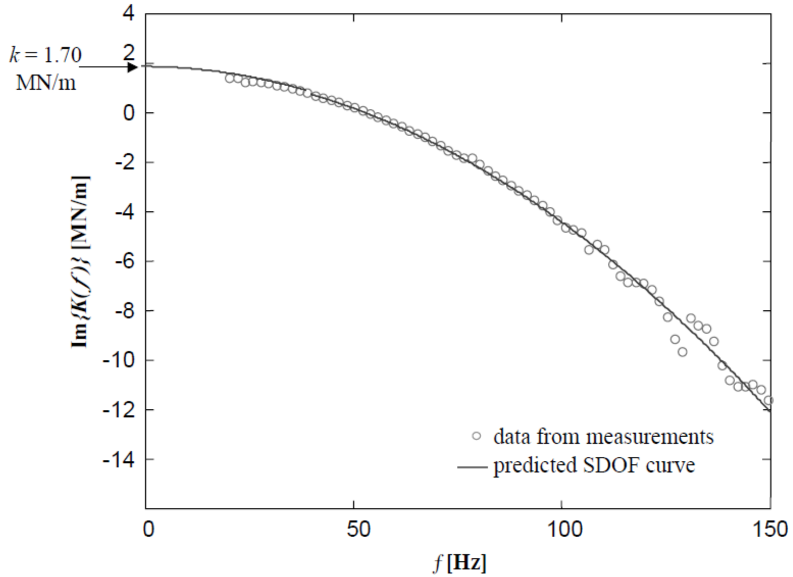


FIGURE 6 Real part of the dynamic stiffness function for the BVT with 60-cm span.

Task 2: Equipment Evaluation : LWD

F. How can we calculate the Young's modulus (E) of the soil from LWD?

Modulus of one-layer system:

Boussinesq Equation for solid plate or Egorov Equation for annulus plate

Modulus of multi-layer system:

-Two layer solution (Burmister)

-One layer equivalent approximation (Odemark)

-Numerical backcalculation using radial sensors

Zone of influence of LWD~0.9 to 1.1 of the loading plate diameter depending on soil type.

$$w_{0,0} = w_{0,h_e} + \left(w_{0,0} - w_{0,h}\right) = \frac{A\left(1-\nu^2\right)F_{max}}{\pi a}\left\{\frac{1}{E_2\sqrt{1+\left(\frac{h}{a}\sqrt[3]{\frac{E_1}{E_2}}\right)^2}} + \frac{\left[1-\frac{1}{\sqrt{1+\left(\frac{h}{a}\right)^2}}\right]}{E_1}\right\}$$

Assuming uniform load distribution

We should be advised that Boussinesq, Egorov, and Brumister are for static condition and should be used with caution since LWD induces a dynamic impact load

We may need to adjust $k_{(from\ LWD)}$ to get the k_{static} (Hoffmann, 2004; Asli et al, 2012)→ Beneficial for checking the calibration and device comparison or directly relate it to Mr in the lab at similar stress states in the process of finding the target modulus (George 2007, Mohammad et al 2009, etc)

Task 2: Equipment Evaluation : LWD

G. How can we calculate the energy loss of the soil and use it for compaction control?

Energy Loss allows to enhance LWD based procedure to evaluate the compaction level achieved on site.

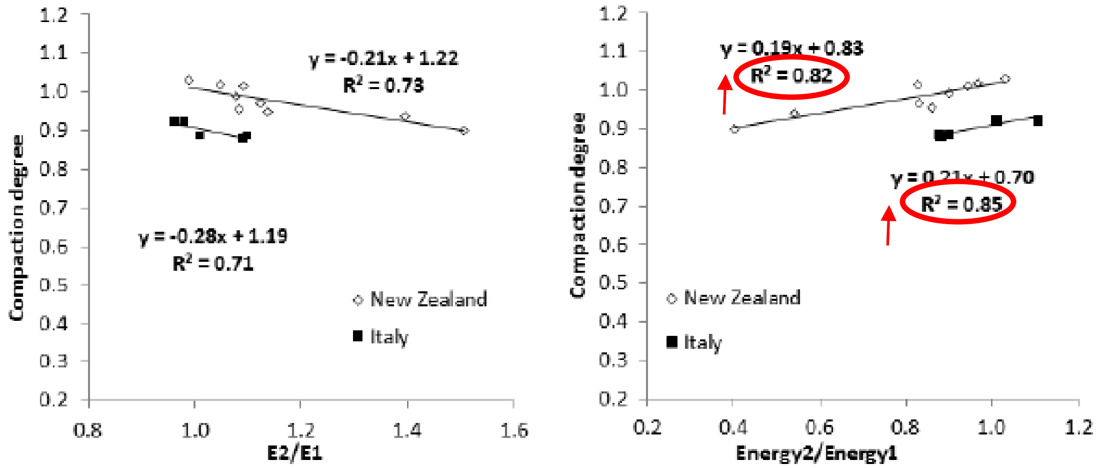
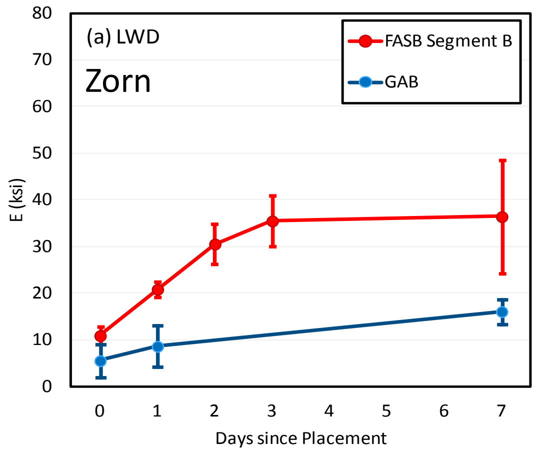


FIGURE 6 Comparison between Compaction Degree and E_2/E_1 and $Energy_2/Energy_1$ values.

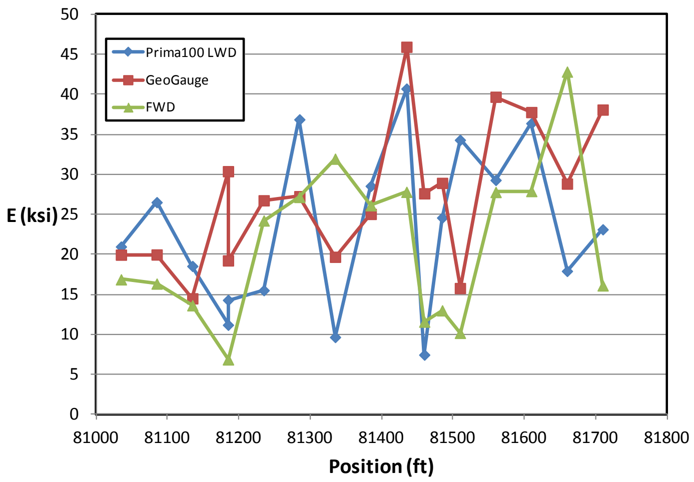
Marradi et al. 2014

Task 2: Equipment Evaluation : LWD

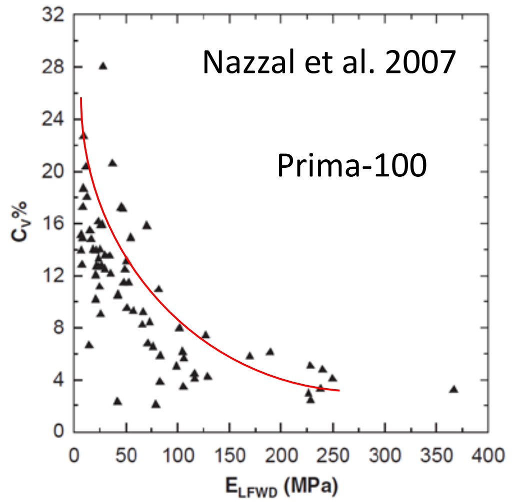
H. How repeatable are the LWDs?



Error bars show one standard deviation.



Spatial Variability



Task 2: Equipment Evaluation : LWD

Selected LWDs for the study

Dynatest 3031
- Load cell available
- Deflection on the ground (geophone)
- Annulus plate
- Extra geophones available
- Drop height can be changed
- Drop weight can be changed
- Plate size can be changed
- Adjustable rubber buffers

Olson LWD-1
- Load cell available
- Deflection on top of plate (geophone)
- Solid plate
- Extra geophones available
- Drop height can be changed
- Drop weight can be changed
- Plate size can be changed
- Spring buffers

Zorn ZFG 3000
- Load cell NOT available
- Deflection on top of plate (accelerometer)
- Solid plate
- Extra geophones NOT available
- Drop height can NOT be changed
- Drop weight can NOT be changed
- Plate size can be changed
- Spring buffers

Task 2: Equipment Evaluation : LWD

Selected LWDs for the study

Zorn ZFG 3000

Dynatest®
A Distinction of Class and Performance

Dynatest 3031 LWD

Back in the early 1970's, as mechanistic (or analytical) approaches to pavement engineering found increased support internationally, Dynatest introduced the world's first portable LWD (Light Weight Deflectometer), as a new method to determine the E-modulus of un-bound materials in pavements.

Over recent years demand for an automated device has arisen and this prompted Dynatest to re-design its 1970 device, enhancing and automating the LWD mechanics by means of the latest technology, adding electronics and analysis software that go far beyond what is currently offered in the market place. The new device has been designed to meet international standards that are under development for this type of equipment.

What's new?

- The release handle and drop weights have been redesigned, improving user friendliness and ease of adding and removing weights
- The buffer system has been developed to optimize the loading impulse while making the change for different weight configurations easier, without the need for tools
- The centre geophone has a unique lever to ensure that the geophone is centred and seated correctly
- A Dual Plate System (DPS) has been developed to allow for the testing at the same position with two different plate sizes. The collected data can be used to back-calculate the layer moduli and estimate the top layer thickness, using the (optional) Dynatest LWDmod
- Dynatest LWDmod – based on the popular and recognized Elmod programme used with FWDs, LWDmod back-calculates layer moduli, confirms the layer thicknesses and calculates overlay thickness to ensure that designs meet specifications

The Dynatest LWD requires no reference measurements and provides a simple, cost effective alternative to time consuming and expensive static plate bearing testing.

The equipment is precision-engineered, using stainless or anodized material for all metal parts. The system is powered by a pack of four AA alkaline or rechargeable batteries, providing approximately 2000 measurements or the equivalent to more than 12 hours of continuous operation.

With the additional (optional) 2 x 5kg (2 x 11 lbs) weights added, the Dynatest LWD can produce up to 15kN (3,300lbf) peak loads. The LWD weighs about 22 kg (48lbs.) (with the standard 10kg (22 lbs.) drop weight), and it is highly portable and easily carried around a construction site. There is an optional, specially designed trolley available.

The Dynatest LWD requires no reference measurements and provides a simple, cost effective alternative to time-consuming and expensive static plate bearing testing.

The LWD is ideal for Quality Assurance / Quality Control on subgrade, subbase and thin flexible pavement constructions to verify that specifications are met. It can also be used to identify weaknesses, leading to further tests using FWDs and other material analysis techniques.

www.dynatest.com EquipmentSales@dynatest.com

Task 2: Equipment Evaluation : LWD

ASTM Standards

REQUIREMENT	E2835-11	E2583-07
Load Pulse	10-30 ms sine/haversine	20-40 ms sine/haversine
Drop Mass	minimal friction, steel springs	minimal friction
Load Plate	rigid	allow deflection measurement through center of plate
Stress Distribution	any	uniform
Deflection Sensor	disp/vel/accel transducer, measure peak deflection of load plate	disp/vel/accel transducer, measure peak deflection of soil
Load Cell	not required	required (load cell type not specified)
Test Drops	6 (3 seating plus 3 testing)	2 testing (1-2 seating optional)
Required Deflection	0.2-3.0 mm	n/a

After Mooney et al. 2013 final draft report (LWD with radial on stabilized soil)

Task 2: Equipment Evaluation : LWD

How to evaluate the LWDs?

- LWD raw measurements: load cell and deflection measurement checks with additional sensors
- Calculation of ks and comparing it with ks of a known material
- Calculation of Young’s modulus and comparing it with reference elastic material
- Relationships between different LWDs and other in-situ devices
- Relationship between LWD modulus and Mr in the lab

Stiffness Estimates Using Portable Deflectometers

Olivier J.-M. Hoffmann, Bojan B. Guzina, and Andrew Drescher

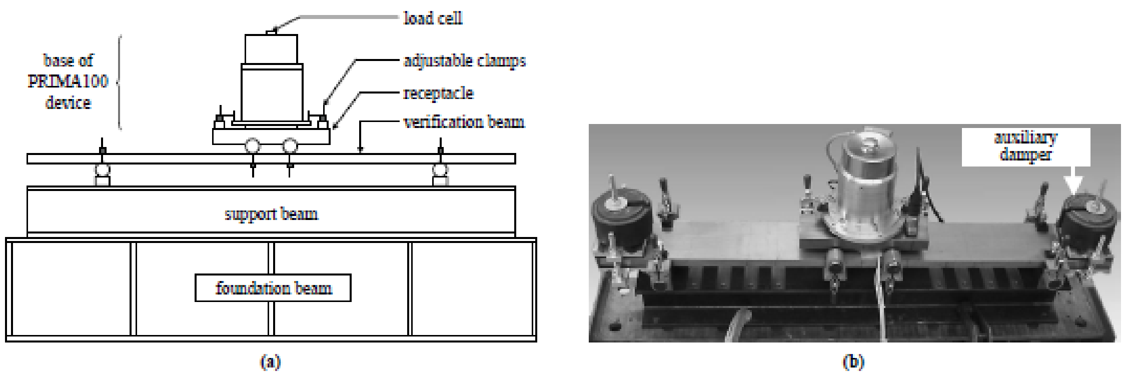
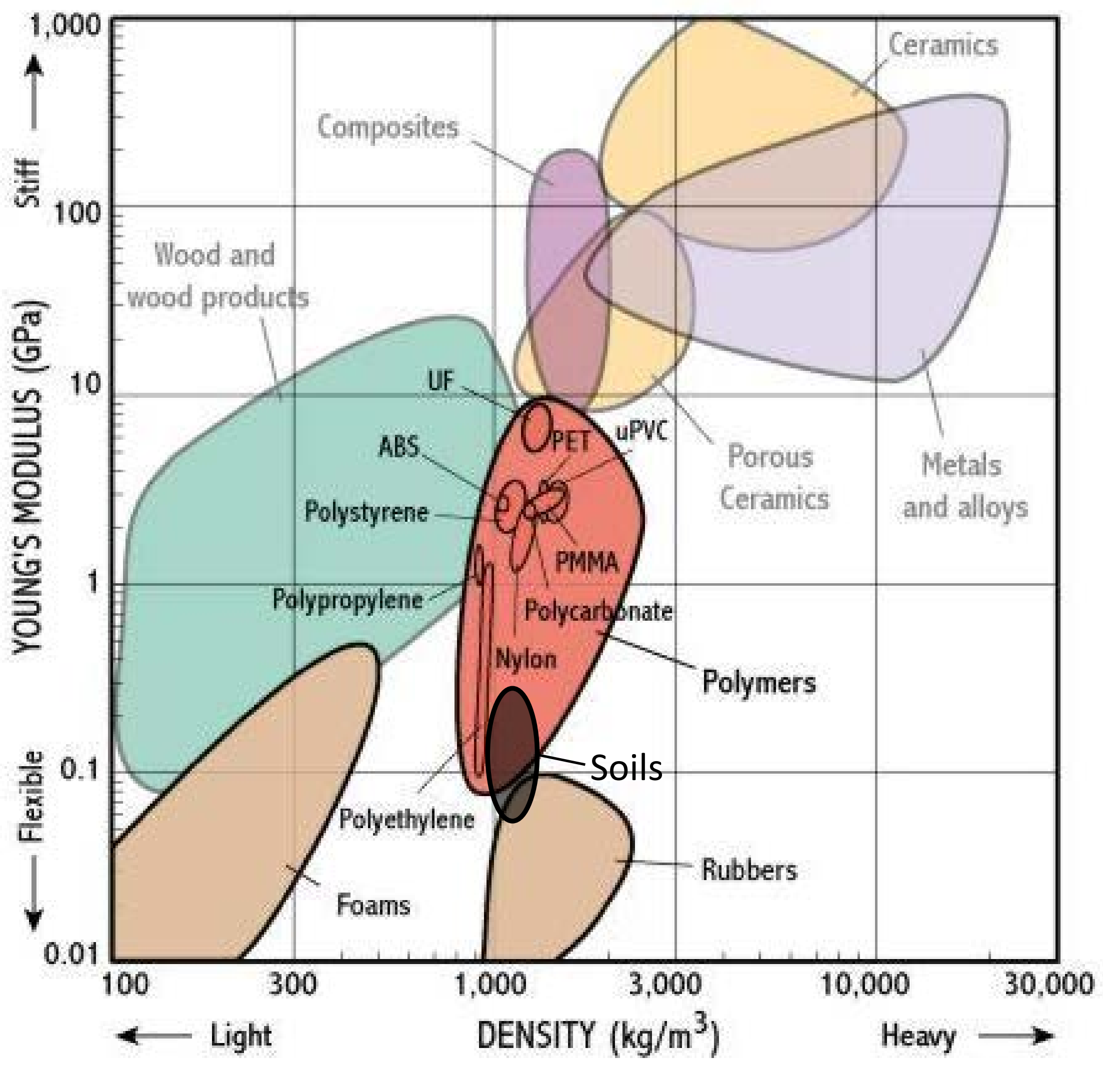


FIGURE 3 Beam verification tester: (*a*) schematics; (*b*) photograph.

Task 2: Equipment Evaluation : LWD

Reference Material for examining the calculated E from LWD devices



http://www-materials.eng.cam.ac.uk/mpsite/interactive_charts/stiffness-density/NS6Chart.html

Task 2: Equipment Evaluation : LWD

Reference Material for examining the calculated E from LWD devices

Approximate Young's modulus for various materials		
Material	GPa	lbf/in² (psi)
Rubber (small strain)	0.01–0.1	1,450–14,503
PTFE (Teflon)	0.5	75,000
Low density polyethylene	0.11–0.45	16,000–65,000
HDPE	0.8	116,000
Polypropylene	1.5–2	218,000–290,000
Bacteriophage capsids	1–3	150,000–435,000
Polyethylene terephthalate (PET)	2–2.7	290,000–390,000
Polystyrene	3–3.5	440,000–510,000
Nylon	2–4	290,000–580,000
Diatom frustules (largely silicic acid)	0.35–2.77	50,000–400,000
Medium-density fiberboard (MDF)	4	580,000

Steel, carbon fiber and glass among others are usually considered linear materials, while other materials such as rubber and soils are non-linear.

Task 2: Equipment Evaluation : LWD

Reference Material for examining the calculated E from LWD devices

Medium-density polyethylene

MDPE	
Density	0.926-0.940 g/cm^3
Young modulus/ E modulus/ Tensile modulus	172–379 MPa
Tensile strength(σ_t)	12.4–19.3 MPa
Elongation @ break	100–150%
Brittleness, low temperature	-118 °C
Vicat	99-124 °C
Specific heat (c)	1.916 kJ/kg.K
Source: J.Brandrup, E. H. Immergut & E.A. Grulke, Polymer Handbook Fourth edition, ISBN 0-471-48171-8	

X Comes in thin sheets

Task 2: Equipment Evaluation : MC devices

MB45 MOISTURE ANALYZER
REDEFINING VALUE IN MOISTURE ANALYSIS

Speedy® 2000 Moisture Device

Sample placed in vessel - measures pressure with calcium carbide

Device	Description	Photo
Oven (2)	Standard (ASTM D2216) forced air laboratory oven with one at 60°C and one at 110°C (tests samples were also sent to outside laboratories for support testing)	
Nuclear Gage	ASTM D6938 - The measurement of moisture Content is based on the thermalization (slowing down) of fast neutron radiation. It is a function of the hydrogen content of the materials and to a lesser degree, by other low atomic number elements e.g., carbon and oxygen.	
Lincoln Soil Moisture Meter	Push probe with measurement based on scale of 1 through 10	
General GLMM200 Moisture Meter	Push probe with measurement based on scale of 1 through 4	
Speedy® 2000 Moisture Device	Sample placed in vessel - measures pressure with calcium carbide	
DMM600 Duff Moisture Meter	Sample placed in vessel - measures pressure with calcium carbide	
Kelway Moisture Meter	Push probe in loosened materials with measurement based on % saturation	
Decagon Devices GS3 Moisture Probe	Push probe with readout box measurement based on conductivity	
Hanna Instruments Soil Moisture Probe	Push probe with readout box measurement based on soil activity	

Task 3: Model Refinement

Predicting of soil suction: Using grain size distribution
Fredlund et al. 2002

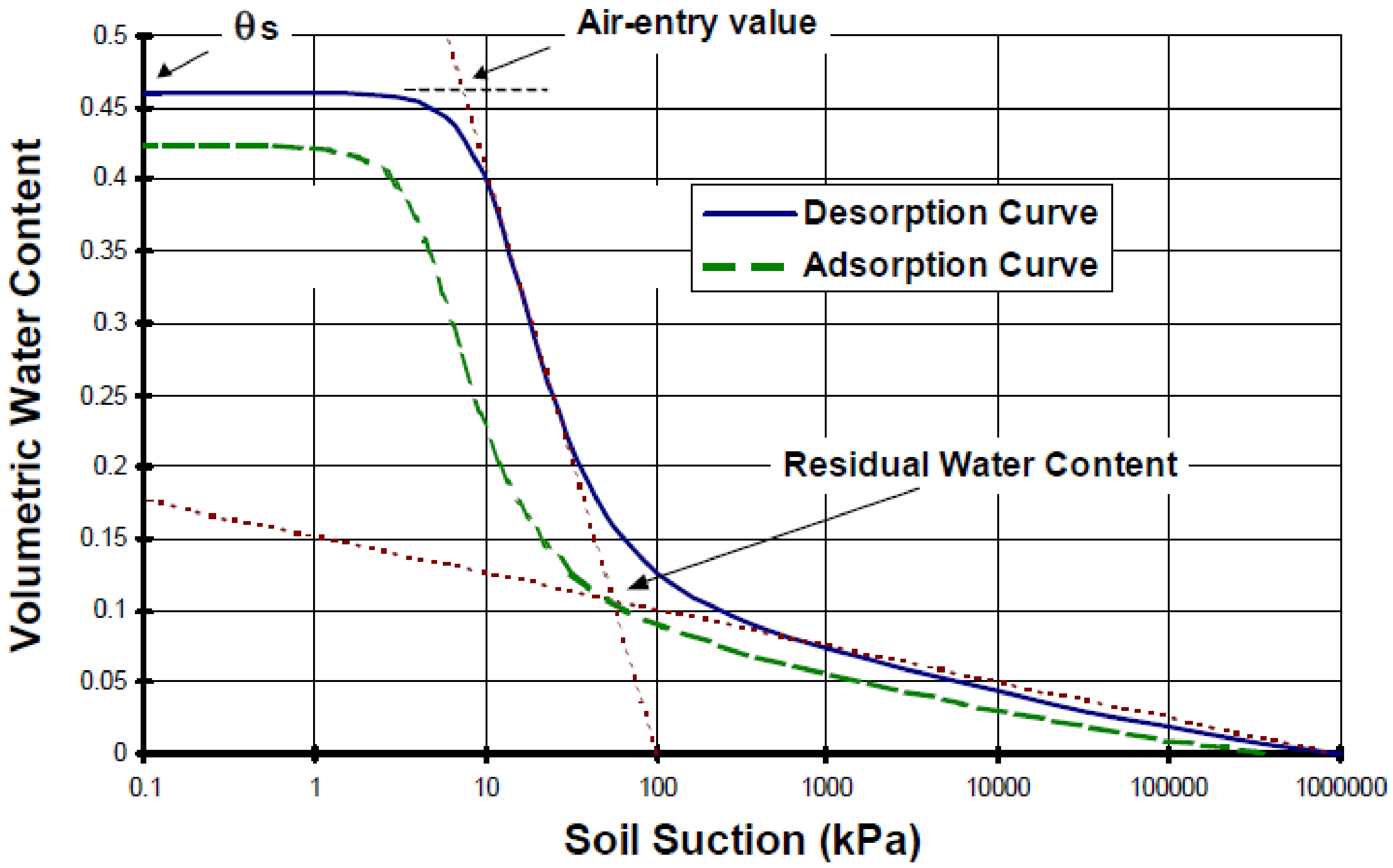


Figure 1 Definition of variables associated with the soil-water characteristic curve.

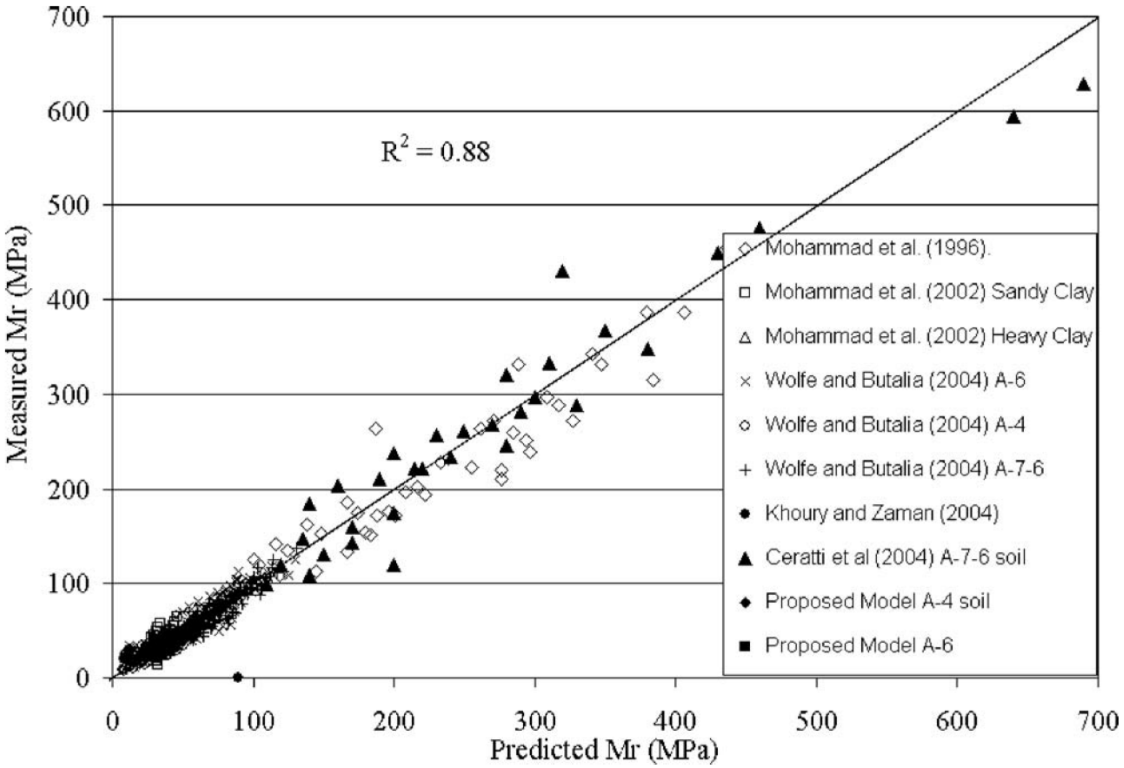
Task 3: Model Refinement

Predicting moisture dependent and stress dependent Mr with suction based on unsaturated soil mechanics (Liang et al 2008)

Table 4. Regression Parameters for Proposed Model for Subgrade Soil

Soil	Moisture content	K_1	K_2	K_3	R^2
A-4	No suction	1.243	0.178	−0.644	0.62
	With suction	0.878	0.404	−0.645	0.94
A-6	No suction	0.625	0.146	−0.458	0.29
	With suction	0.381	0.436	−0.459	0.95

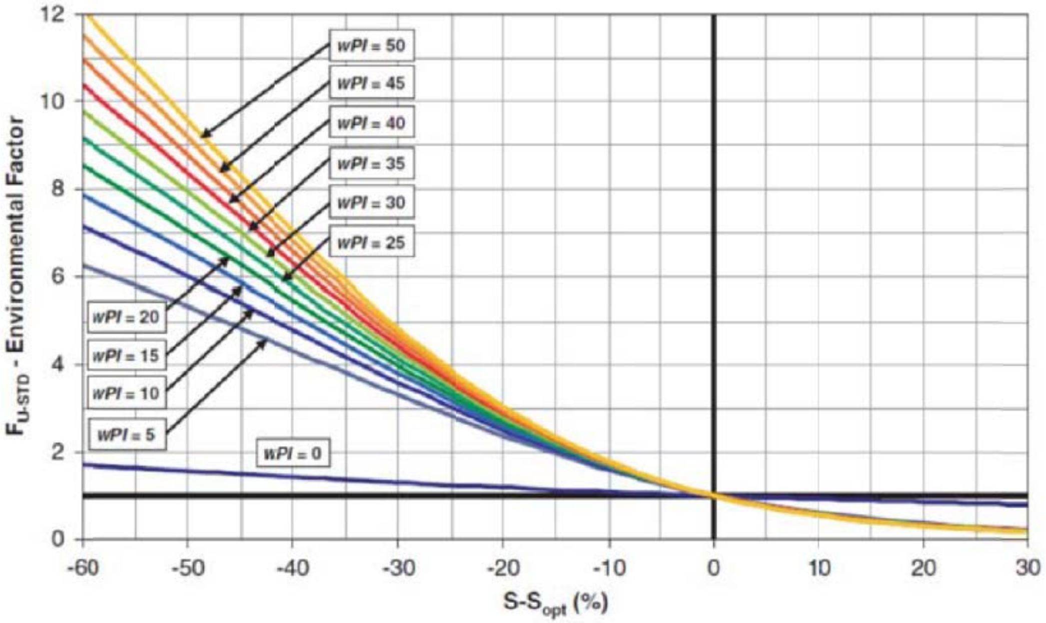
$$M_R = K_1 P_a \left(\frac{\theta + \chi_w \psi_m}{p_a} \right)^{K_2} \left(\frac{\tau_{oct}}{p_a} + 1 \right)^{K_3}$$



Task 3: Model Refinement

Prediction of Mr based on unsaturated soil mechanics

$M_r = f\{S\}$ (Zapata, 2011)



$$LogF_u = a + \frac{b-a}{1+e^{\left(\ln\frac{-b}{a}+k_m\times\left(S-S_{opt}\right)\right)}}$$

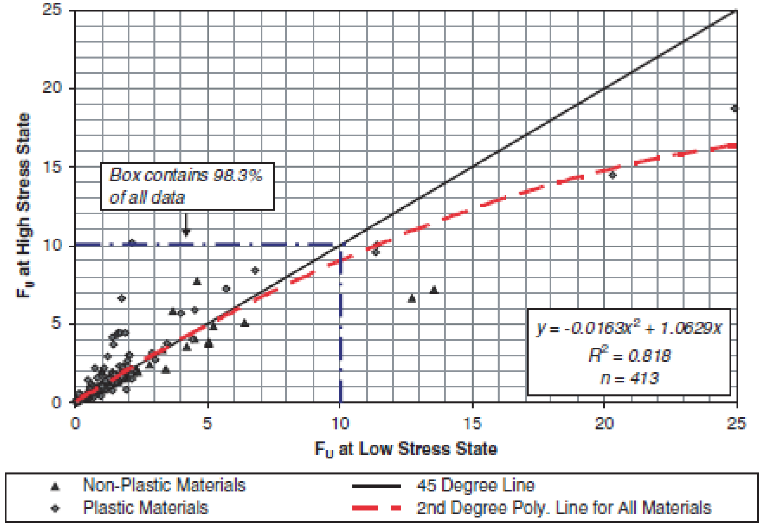


FIGURE 3 Influence of stress state level on prediction of F_U.

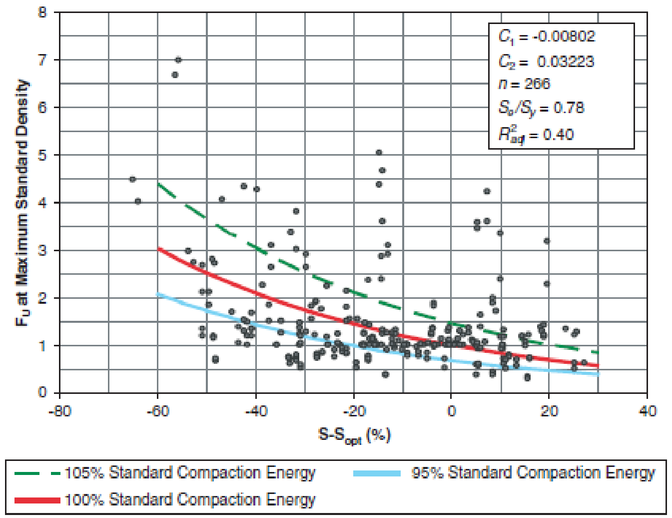
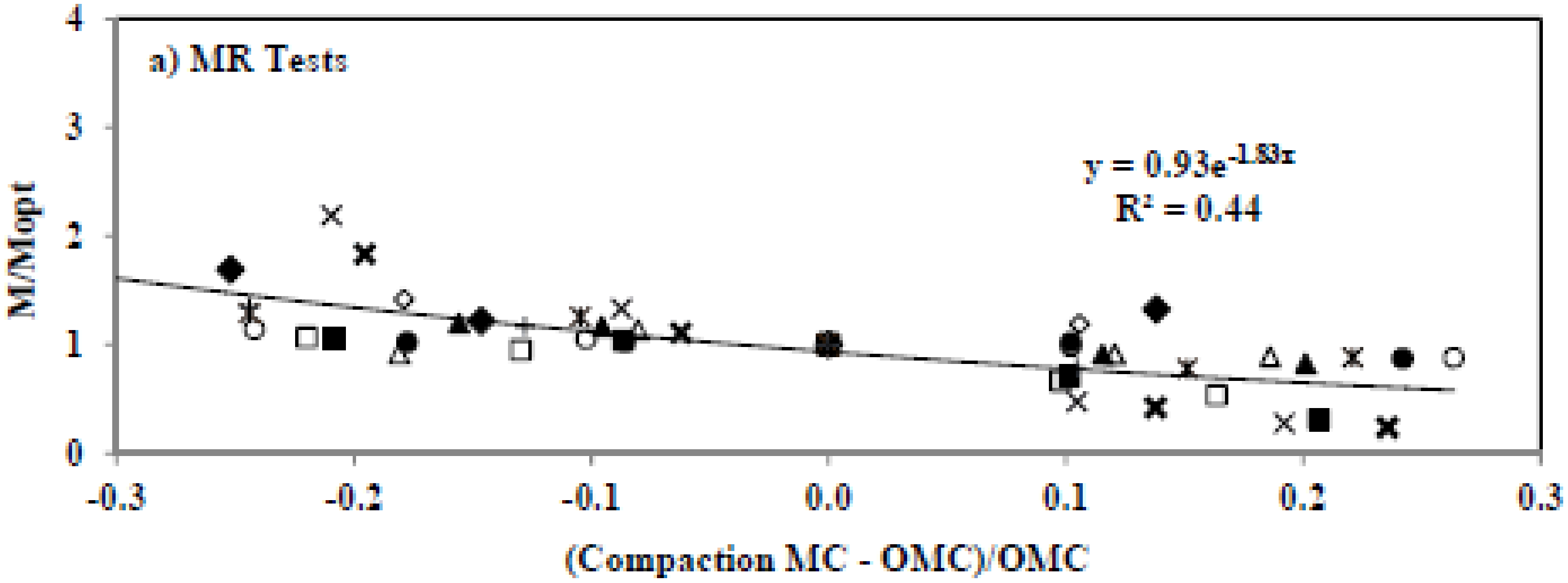


FIGURE 4 Influence of soil compaction energy on prediction of F_U.

Task 3: Model Refinement

Prediction of Mr based on unsaturated soil mechanics

Mr = f{(MC$_{compaction}$-OMC)/OMC} (Nazarian et al. 2013)



Task 3: Model Refinement

Prediction of Mr based on unsaturated soil mechanics

$Mr = f\{(MC_{testing} - MC_{compaction}\}$ (Pacheco and Nazarian, 2011)

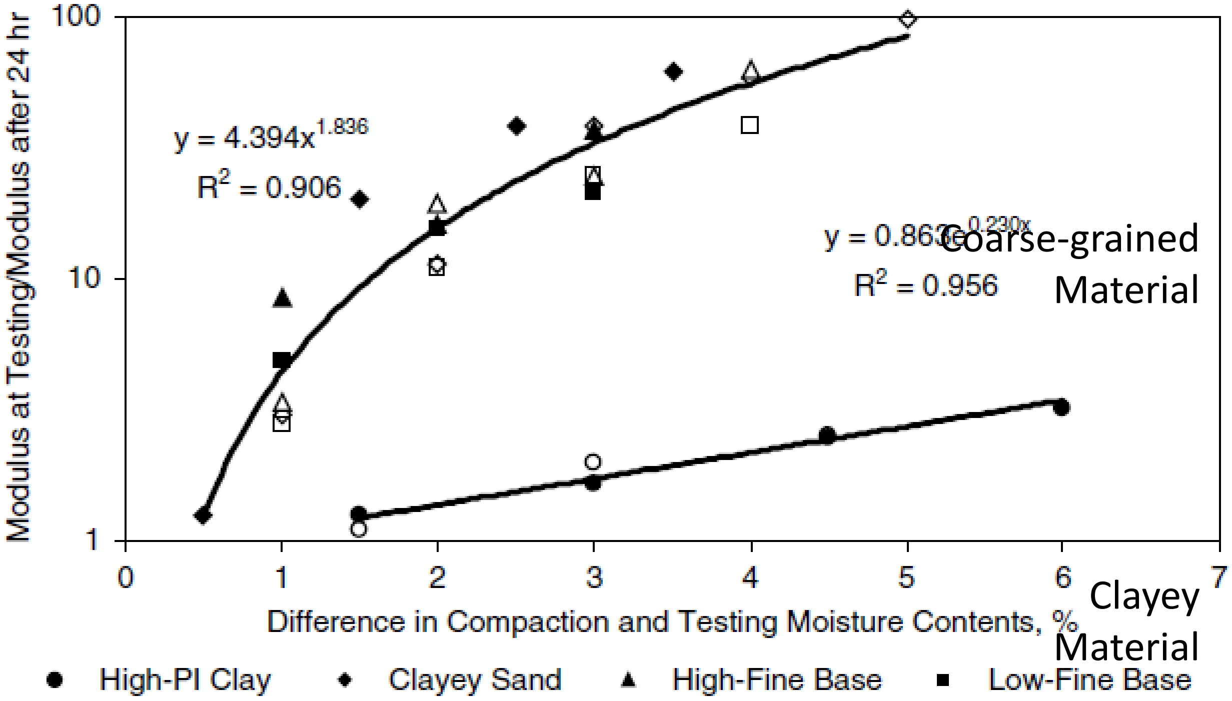


FIGURE 8 Effect of differences between compaction and testing moisture contents on modulus (closed and open markers indicate specimens dried to OMC − 1.5% and OMC − 3%, respectively).

Task 3: Model Refinement

Prediction of MC profile from the time of compaction to time of testing as function of soil properties and environmental condition

PC-PROGRESS
Engineering software developer

Home | News | Programs | Support | Services | Downloads | About us | Contacts

Fulltext search

- Home
- News
- Programs
- Support
- Services
- Downloads
  - HYDRUS 2D/3D
  - Hydrus-1D
  - Hydrus-2D
  - STANMOD
  - RETC
- About us
- Contacts

Home / Downloads / Hydrus-1D

Hydrus-1D Downloads

Here you can download the latest Hydrus-1D installation and several previous versions. Please let us know about any errors and bugs that you may encounter. We greatly appreciate your help. Thank you, Jirka and Mirek.

Installation Programs

Version	Released	Download	Size	Comment
4.16	10.02.2013	Hydrus1D_4.16.0090.exe	28 MB	Patch 27.06.2013 (Fixed error in calculations of the hydraulic conductivity in the Durner's (1994) model)
4.15	04.08.2012	Hydrus1D_4.15.0110.exe	28 MB	
4.14	13.12.2009	H1D_4_14.exe	26 MB	
4.13	31.10.2009	H1D_4_13.exe	26 MB	
4.12	26.04.2009	H1D_4_12.exe	26 MB	
4.11	21.03.2009	H1D_4_11.exe	26 MB	
4.10	15.02.2009	H1D_4_10.exe	26 MB	
4.09	16.01.2009	H1D_4_09.exe	26 MB	
4.08	04.01.2009	H1D_4_08.exe	26 MB	
4.07	06.12.2008	H1D_4_07.exe	25 MB	
4.06	11.09.2008	H1D_4_06.exe	25 MB	

Installation Instructions:
Download the installation package (e.g. Hydrus1D_4.15.0110.exe) and run it.

Installation Instructions for version 4.14 and older:
Download a self-extracting archive (for example H1D_4_08.exe) and run it. Extract setup files to a temporary directory. Go to this directory and run "setup.exe", which will install Hydrus-1D on your computer. Starting with version 4.15, the setup is launched automaticaly after running the installation package Hydrus1D_4.15.0110.exe.

Other Downloads

Task 3: Model Refinement

Lab Mr vs LWD measurements

Lab and Field Comparison for Dynatest (Keros) and Zorn NCHRP Synth 382- White et al. 2007

The KEROS E_{LWD} (modulus) is on average 1.75 to 2.2 times greater than Zorn E_{LWD} (modulus).

The M_R data at high confining and deviatoric stresses (42 kPa and 68.9 kPa, respectively)

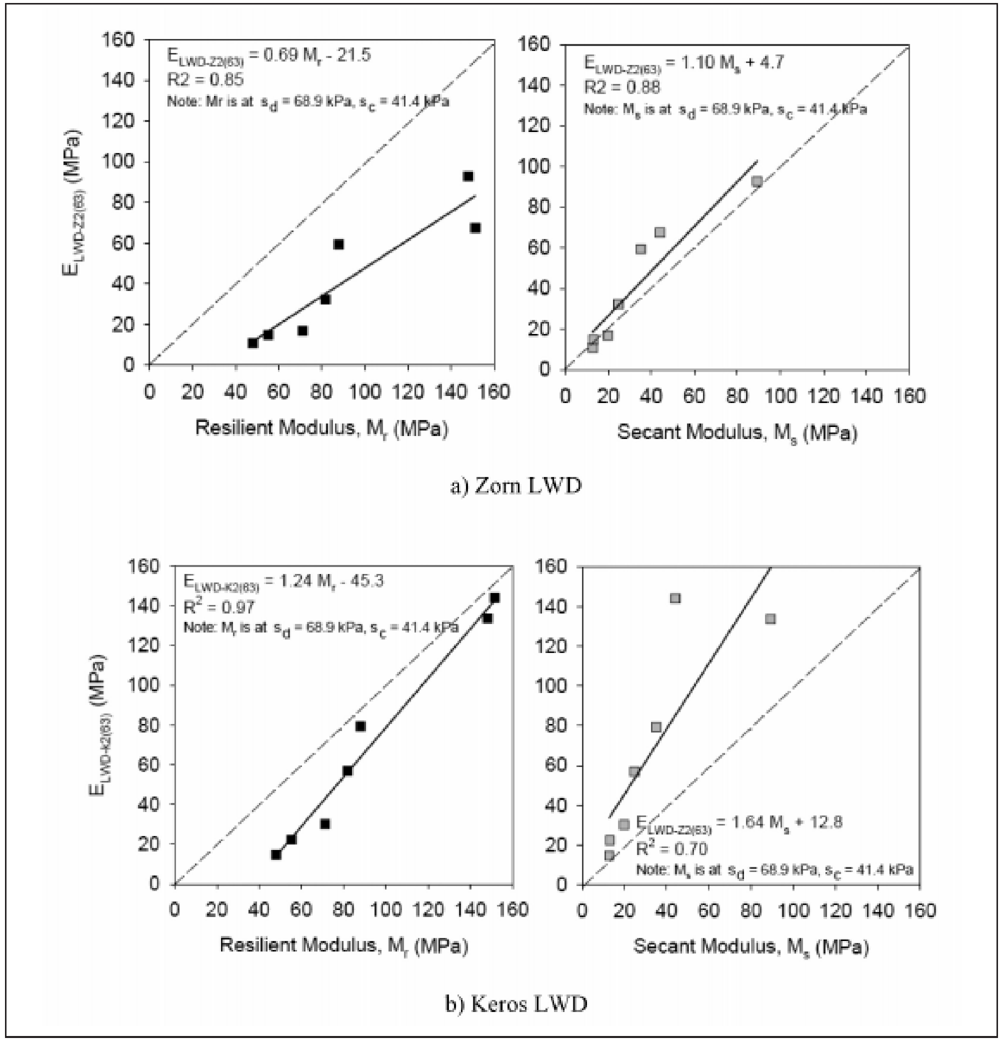


FIGURE 56 Comparisons of moduli determined from LWD and resilient modulus triaxial tests at deviatoric stress of 68.9 kPa (White et al. 2007).

Task 3: Model Refinement

Lab Mr vs LWD measurements
Mohammad et al. (2009)

- Four cohesive subgrade soil types (A-4, A-6, A-7-5, and A-7-6)
- at different moisture-dry unit weight levels
- Prima 100 LWD
- nonlinear regression analysis on the data of each RLT test to determine the resilient modulus parameters of the generalized constitutive model

$$M_r = p_a k_1 \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3}$$

- compute the resilient modulus at an estimate of the state of stress under traffic loading (NCHRP 1-28 A):
  - deviator stress of 41.3 kPa
  - confining pressure of 14 kPa

$$M_r = 27.75 \times E_{LFWD}^{0.18}$$

R^2= 0.54

$$M_r = 11.23 + 12.64\left(E_{LFWD}^{0.2}\right) + 242.32\left(\frac{1}{w}\right)$$

R^2= 0.7

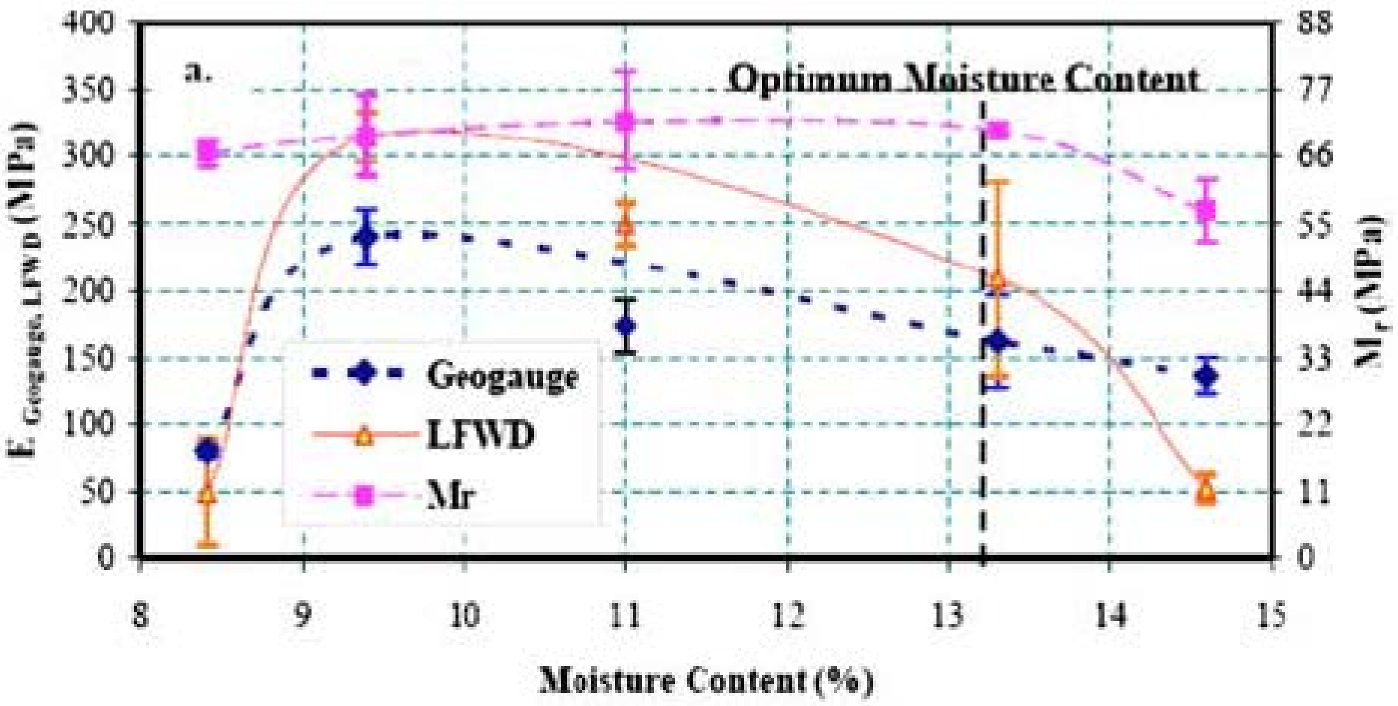
Task 3: Model Refinement

Mohammad et al. (2009)

- Does not peak at OMC
- Peak is on drier side of OMC
- ✓ stiffness behavior of cohesive soils is controlled by the effective stress.

$$\sigma'_v = \sigma_v - u_a + \chi(u_a - u_w)$$

σ_v = total stress,
u_a = pore air pressure,
u_w = pore water pressure,
$(u_a - u_w)$ = matric suction, and
χ = effective stress parameter.



Immediate Next Steps

- LWD Device selection:
  - Olson LWD-1
  - Zorn ZFG 3000
  - Dynatest 3031 LWD
- Moisture measurement devices/techniques:
  - Oven drying
  - Speedy® 2000 Moisture Device
  - MB45 Moisture Analyzer
- Lab Resilient test device → Late July

Immediate Next Steps

- Confirming LWD stiffness measurements

  → Hoffman beam method

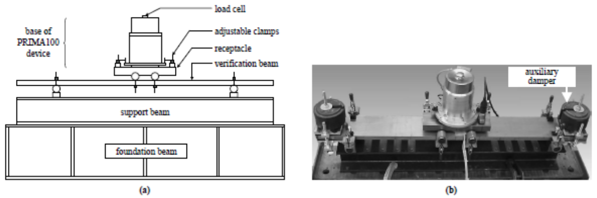


FIGURE 3 Beam verification tester: (*a*) schematics; (*b*) photograph.

- Parametric study using Hydrus program → How much drying within 24 hours after compaction