Appendix A
On-Site TAC Meeting Agenda

TPF-5(285) Standardized Lightweight Deflectometer Measurements
For QA and Modulus Determination in Unbound Bases and Subgrades

Technical Advisory Committee On Site Meeting
University of Maryland – College Park
Marriott Hotel and Conference Center Room 2106
June 2-3, 2015

Agenda

Tuesday, June 2

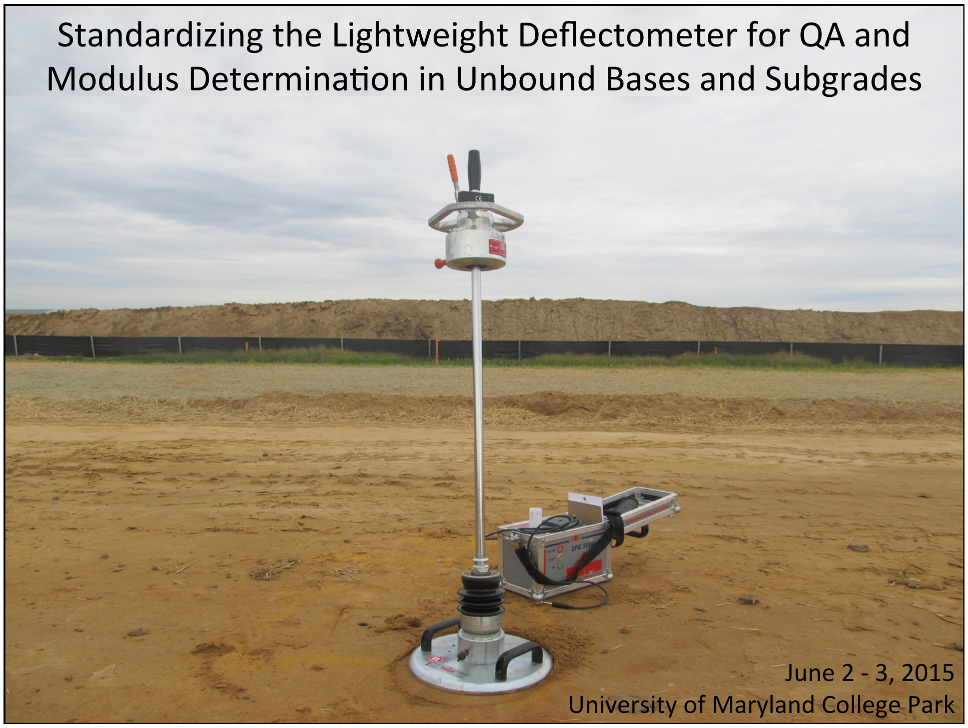
8:00	*Continental Breakfast*	All
8:30	Welcoming Remarks	Sajedi, Wynn, Schwartz
8:40	Introductions	All
8:50	Project Overview	Schwartz
9:30	MN DOT Approach for QA Using LWD	Siekmeier
9:50	IN DOT Approach for QA Using LWD	Siddiki
10:10	*Break*	
10:25	Beam Verification Testing	Khosravifar
10:35	Drying Analyses	Afsharikia
10:55	Laboratory Testing	Khosravifar
11:15	Large Pit Testing	Khosravifar
11:30	Field Testing	Afsharikia
11:45	Discussion	All
12:00	*Lunch at The Commons*	
1:00	*Travel to FHWA Turner-Fairbanks Highway Research Center (TFHRC)*	
1:45	Tour of TFHRC Large Pit, Other Test Facilities	Schwartz, Gibson
3:45	*Return Travel to UMD*	

Wednesday, June 3

8:00	*Continental Breakfast*	All
8:30	Recap of Previous Day/Discussion	Schwartz/All
8:45	Tour of UMD Laboratories, Equipment Demonstrations	All
10:00	*Break*	
10:15	Discussion	All
10:30	Field Test Sites	Schwartz, All
10:50	Final Discussions • Issues/concerns • Panel guidance to research team	All
11:20	Concluding Remarks	Schwartz
11:30	Adjourn	

Appendix B
On-Site TAC Meeting Presentation

"Project Overview" (Schwartz)



Project Objective

The primary objective of this study is to provide state DOT and local government engineers with a practical and theoretically sound methodology for the evaluation of in-place elastic modulus of unbound layers, subgrades, and other earthwork from LWD field test data. This will require the development of techniques to fully account for: (1) the influence of moisture suction pressures on LWD measurements, (2) the differences in the LWD induced stress states/strain levels and the stress states/strain levels induced by construction equipment and long term traffic loads, and (3) the effects of layering on LWD measurements when testing on finite-thickness layers (e.g., base or subbase over subgrade) vs. half-space conditions (e.g., subgrade).

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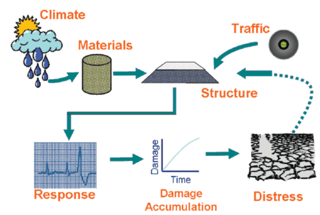
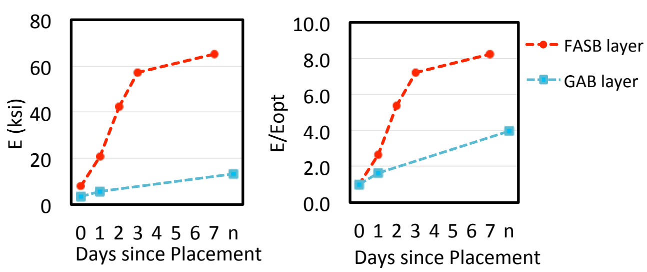
http://www.pooledfund.org/Details/Solicitation/1339

Project Significance

The advantages of using LWD

- Reflects engineering properties of material
- Avoids nuclear QC/QA methods
- Better testing of unconventional materials



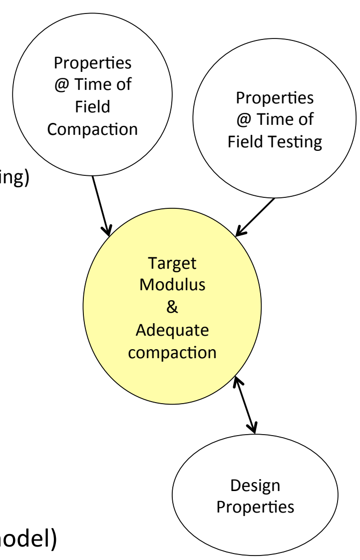


Khosravifar et al. 2013

3

Key Issues

- Stress effects
  - Confining stress stiffening effects on M_R
  - Deviator stress softening effects on M_R
- Moisture effects
  - Compaction moisture effects on M_R
  - Drying profile history (limited time duration)
  - Drying (post-compaction moisture) effects on M_R (stiffening)
- Layered system
  - Subgrade only
  - Stiff base over soft subgrade
  - Stiff base over stiff subgrade
- Individual LWD device details
  - Plate diameter
  - Plate rigidity
  - Contact area stress distribution
  - Loading rate
  - Deflection measurement type and location(s)
- Non nuclear moisture measurement devices (or model)
  - Reliability
  - Speed in giving the results



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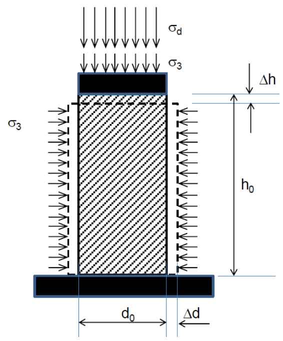
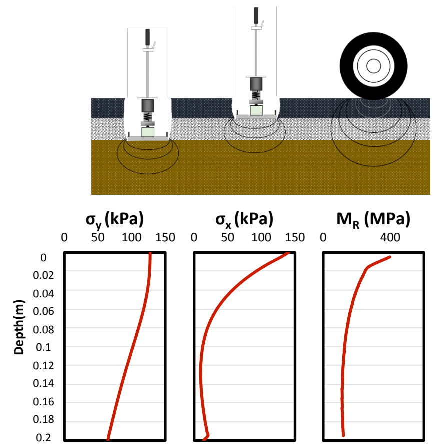
Key Issues

- Stress effects
  - Confining stress stiffening effects on M_R
  - Deviator stress softening effects on M_R





Stress States under LWD versus

1. Design traffic load
2. Laboratory Resilient Modulus (M_R)

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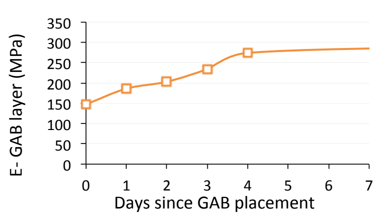
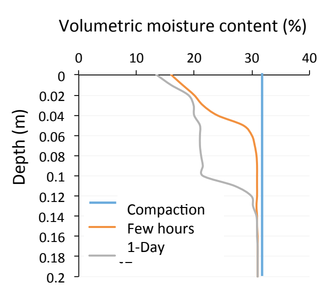
Key Issues

- Moisture effects
  - Compaction moisture effects on M_R
  - Drying profile history (limited time duration)
  - Drying (post-compaction moisture change) effects on M_R (stiffening)



Khosravifar, Asefzadeh, Schwartz (2013)



After Yanful, E. K., and Choo, L. (1997)

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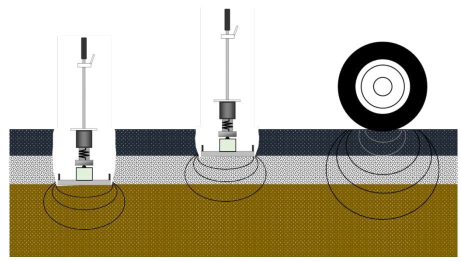
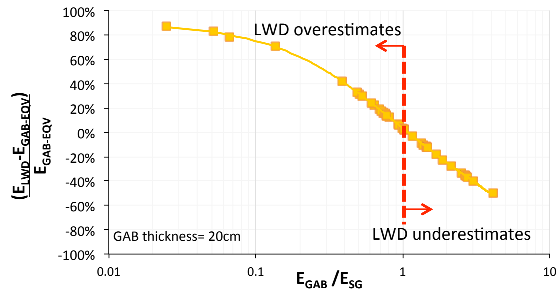
Key Issues



- Layered system
  - Subgrade only
  - Stiff base over soft subgrade
  - Stiff base over stiff subgrade



Khosravifar et al., 2013

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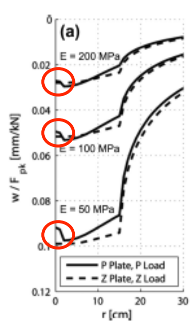
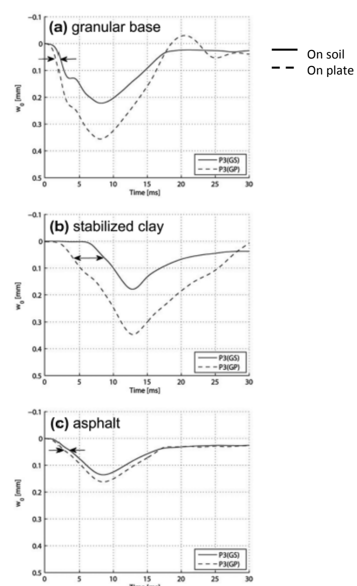
Key Issues





- Individual LWD device details
  - Plate diameter
  - Plate rigidity
  - Contact area stress distribution
  - Loading rate
  - Deflection measurement type and location(s)

Stamp and Mooney (2013)

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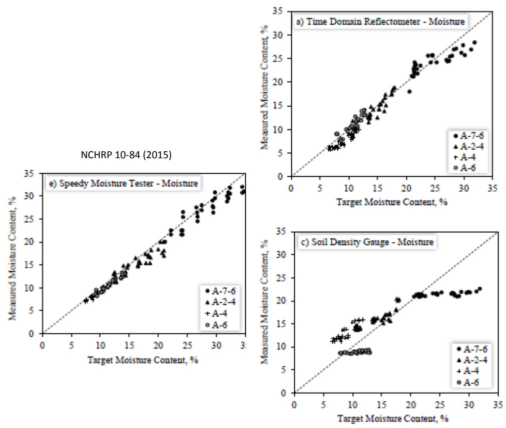
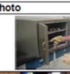
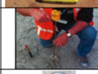
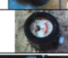
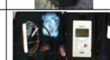
Key Issues



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	

- Non nuclear moisture measurement devices (or model)
  - Reliability
  - Speed in giving the results

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Equipment Evaluation

Selected LWDs for the Study

Dynatest 3031
- Load cell
- Deflection sensor type: geophone
- Annulus plate
- Deflection measured on the ground
- Extra geophones available
- Drop height can be changed
- Drop weight can be changed
- Plate size can be changed
- Adjustable rubber buffers
- Expensive

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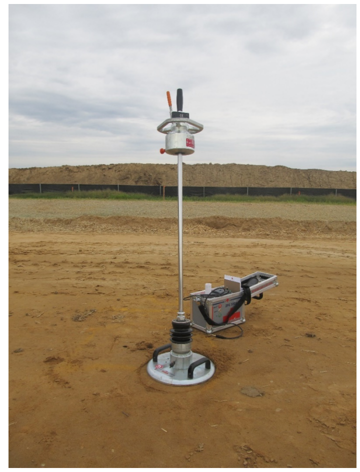
Equipment Evaluation

Selected LWDs for the Study

Zorn ZFG 3000
- Load cell not available
- Deflection sensor type: accelerometer
- Deflection measured on top of plate
- 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- non adjustable
- Inexpensive



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Equipment Evaluation

Selected LWDs for the Study

Olson LWD-1
- Load cell ✓
- Deflection sensor type: geophone
- Deflection measured on top of plate
- Solid plate
- Extra geophones available
- Drop height can be changed
- Drop weight can be changed
- Plate size can be changed
- Spring buffers- non adjustable
- Not yet in production

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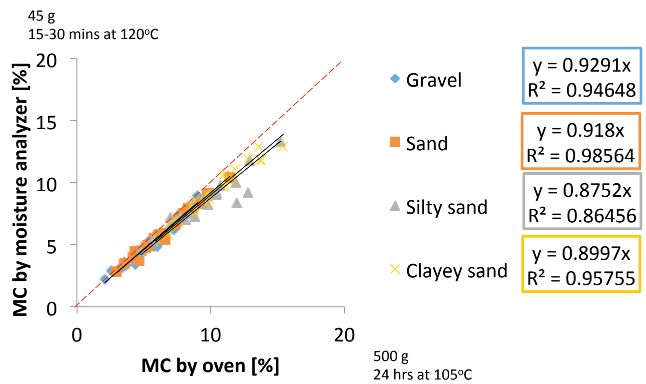
Equipment Evaluation

Selected Moisture Content Devices for the Study



Small but predictable bias;
can be calibrated for site-specific soils if desired

Model Refinement

Three main parts of the model:

- Stress effects
  - Confining stress stiffening effects on resilient modulus (M_R)
  - Deviator stress softening effects on M_R
  - Differences in stress states in field and laboratory

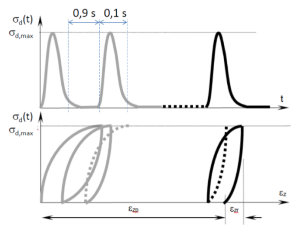
- Moisture and density effects
  - Compaction moisture effects on M_R
  - Compaction density effects on M_R
  - Drying profile history (limited time duration)
  - Drying effects (post compaction moisture changes) on M_R (stiffening)

- Layered system
  - Subgrade only
  - Stiff base over soft subgrade
  - Stiff base over stiff subgrade

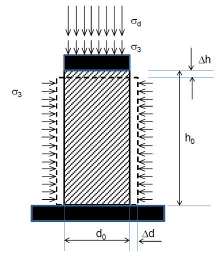
Model Refinement

Three main parts of the model:

- Stress effects -> Resilient Modulus (M_R) – Various Constitutive Model



$M_R = \sigma_d / \varepsilon_r$



$$M_R = (p_a)^\wedge k_1 + (\theta / p_a)^\wedge k_2 + (\sigma_d / p_a + k_5)^\wedge k_3 + (\sigma_3 / p_a)^\wedge k_4 + (p / p_a)^\wedge k_6$$

Reference	Variables	Restrictions on k_i
Hicks and Monismith	q	$k_3 = k_4 = k_5 = k_6 = 0$
Uzan	q, s_d	$k_4 = k_5 = k_6 = 0$
M-EPDG model	q, s_d (or t_{oct})	$k_4 = k_6 = 0$, $k_5 = 1$
Thompson and Robnett	s_d	$k_2 = k_4 = k_5 = k_6 = 0$
Barksdale and Itani	s_d, s_3, p	$k_2 = k_5 = 0$

Model Refinement

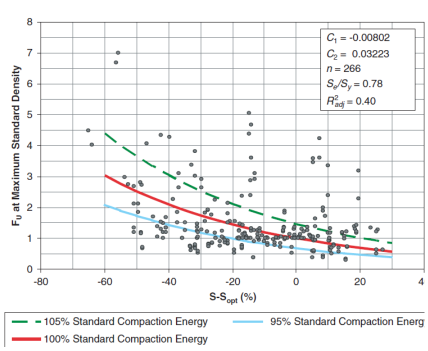
Three main parts of the model:

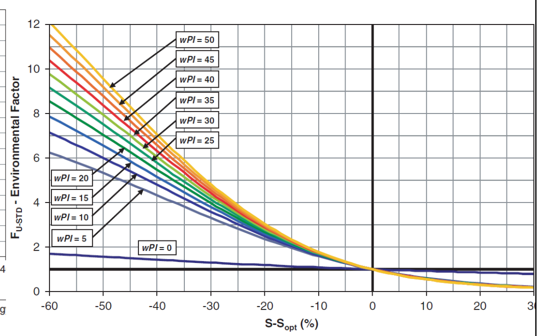
- Moisture and Density effects -> Environmental Factor Scenario

$$F_u = 10^{\left(a + \frac{b-a}{1+e^{\left(\ln\left(-b/a\right) + k_m \times (S - S_{opt})\right)}}\right)} \times 10^{C_2 (PC-100)}$$

$a = -0.40535$
$b = 0.80158$
$k_m = 1.33194$
$C_2 = 0.03223$

Cary and Zapata, 2010: Environmental model for base, subbase, and nonplastic subgrades





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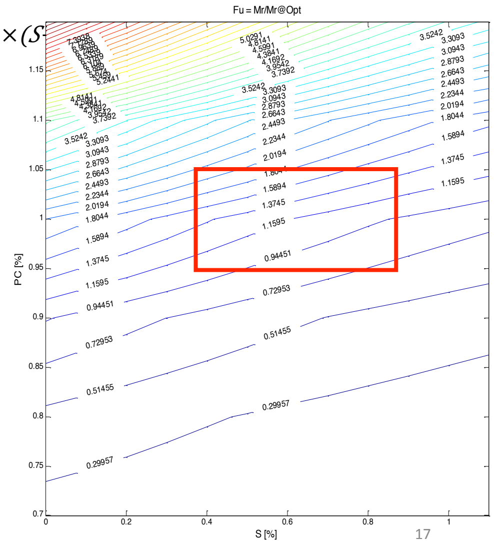


Model Refinement

Three main parts of the model:

- Moisture effects -> Effective Stress Scenario

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w) \approx \sigma + \chi u$$

χ = pore pressure resistance factor
u = matric suction

$$M_R = K_1 P_a \left(\frac{\sigma_{bulk} + 3\chi u}{P_a}\right)^{K_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{K_3}$$

$$M_R = K_1 P_a \left(\frac{\sigma_{bulk} - 3\theta_w f u}{P_a}\right)^{K_2} \left(\frac{\tau_{oct}}{P_a}\right)^{K_3}$$

Gu et al., 2014; Lytton, 1995 ✓

$$\chi = \theta_w f$$

$$f_{upper\ bound} = \left[\left(\frac{\theta_a - \theta_w}{\theta_a - \theta_u}\right) + \frac{1}{\theta_w}\left(\frac{\theta_w - \theta_u}{\theta_a - \theta_u}\right)\right]$$

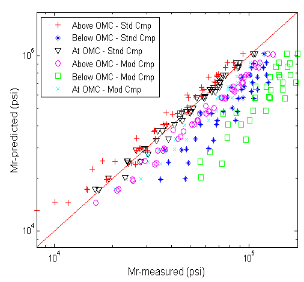
θ_a and θ_u, are volumetric water content of the soil at air entry and unsaturation levels, respectively

Model Refinement

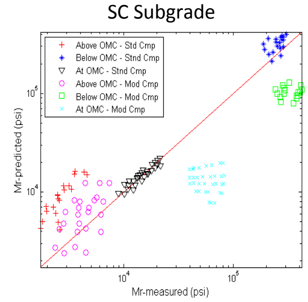
Three main parts of the model:

- Moisture effects -> Effective Stress Scenario

GW Base



SC Subgrade



- Is agreement good enough? Probably not.
- Lubrication effects, and aggregate interlock are important parameters

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Model Refinement

Three main parts of the model:

- Moisture and Density effects →

Environmental models and effective stress models might not be precise enough for the purpose of this work

↓

Experimental model using data from small scale LWD testing on Proctor mold can be an alternative

More info in Small Scale Laboratory Testing

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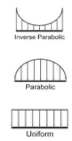
Model Refinement

Three main parts of the model:

- Layered system effects

Modulus of one-layer system: Boussinesq Equation

$$E = \frac{2k_s(1-\nu^2)}{Ar_0} \qquad k_s = \left|\frac{F_{peak}}{w_{peak}}\right|$$



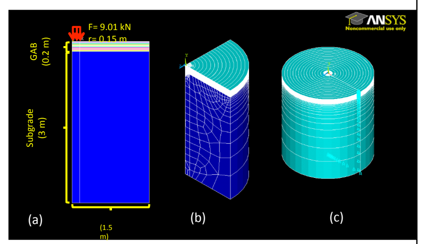
$A = 4$ — • Inverse Parabolic Distribution on cohesive soils

$A = 3\pi/4$ — • Parabolic Distribution on non-cohesive soils

$A = \pi$ — • Uniform Distribution on soils having mixed characteristics

Modulus of multi-layer system:
- Finite element analysis
- Multi layer nonlinear analysis (Kenpave Software)
- Analytical linear elastic Solution: Burmister

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



Small Scale Laboratory Experiments

Objective

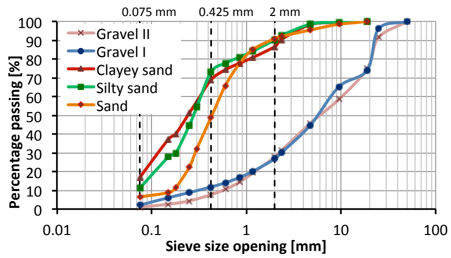
- Characterize the test materials,
- Evaluate the parameters for stress-dependent modulus model,
- Assess the effect of compaction moisture content and density on modulus

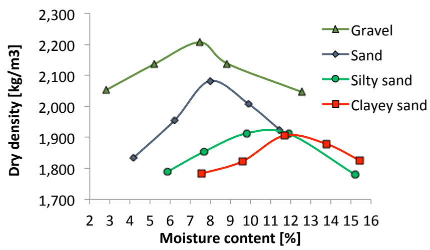
Tests Performed

- Grain size distribution
- Soil classification
- Moisture-density measurements
- Resilient Modulus (M_R)
- LWD testing on Proctor molds → To assess moisture, density, stress dependency

Small Scale Laboratory Experiments

Soil	C_u	C_c	G_s	v
Gravel	26.7	2.3	2.68	0.35
Sand	2.2	1.3	2.63	0.38
Silty-sand	4.4	1.3	2.66	0.42
Clayey-sand	0.6	0.1	2.67	0.42





Soil	OMC [%]	MDD [kg/m³]
Gravel	7.5	2210
Sand	8.2	2082
Silty-sand	11.0	1922
Clayey-sand	12.0	1910

Standard Proctor test- AASHTO T99

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Small Scale Laboratory Experiments

Resilient Modulus Tests

@ 15 sequences according to AASHTO T-307

+

10 high stress levels comparable with those exposed by LWD tests on Mold

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Small Scale Laboratory Experiments

Resilient Modulus Tests

The results will be discussed in more detail:

1. Mr @ low stress levels
2. Mr @ high stress levels
3. Mr @ various MC
4. Mr @ various DD (modified vs. Standard)
5. Mr prediction models:
    - MEPDG (function of bulk stress, deviator stress),
    - Barksdale and Itani (function of confining pressure, deviator stress)

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Small Scale Laboratory Experiments

LWD testing on Proctor molds

Tests performed using all three LWDs.
Tests performed using variable drop heights to assess stress dependency: For the two LWDs with load cells

1. LWD testing concurrentwitho Proctor compaction test at Modified and Standard energy levels
2. LWD testing during drying process
    a. Drying process/ compacted at OMC.
    b. Drying process/ compacted at OMC+2%.
    c. Drying process/ compacted at OMC-2%.

$$E=(1-2\mu^{2}/1-v)4H/\pi D^{2}\ k$$

$$\sigma_r=\sigma_z\times v/1-v$$

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Small Scale Laboratory Experiments

LWD testing on Proctor molds

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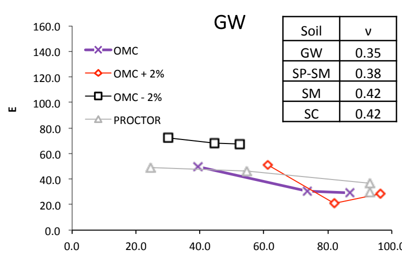
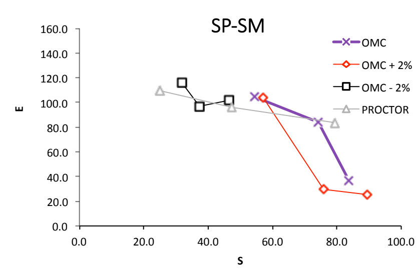
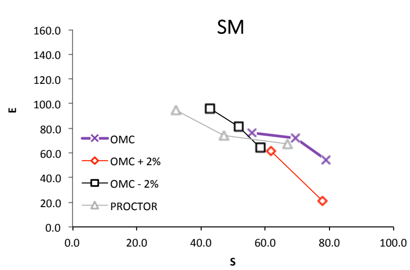
Small Scale Laboratory Experiments

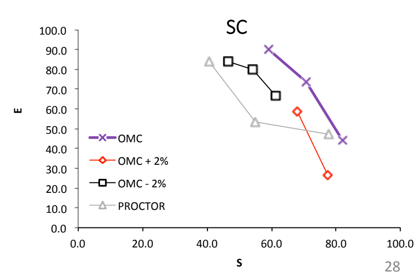
LWD testing on Proctor molds



Soil	v
GW	0.35
SP-SM	0.38
SM	0.42
SC	0.42







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Small Scale Laboratory Experiments

LWD testing on Proctor molds

The results will be discussed in more detail:

1. $E_{LWDonMold}$ @ various stress levels
2. $E_{LWDonMold}$ @ for the three LWDs
3. $E_{LWDonMold}$ @ various moisture levels
4. $E_{LWDonMold}$ @ various DD (Modified vs. Standard)

↓

- Comparisons between Triaxial M_R and $E_{LWDonMold}$
- Use of M_R and $E_{LWDonMold}$ for evaluation of field tests.

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Small Scale Laboratory Experiments

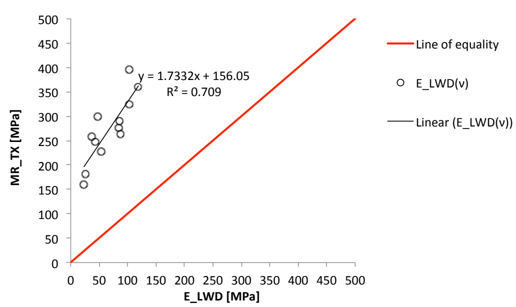
Comparison of moduli from LWD tests on Mold and Triaxial Resilient Modulus tests

There is a strong correlation between the two BUT M_R is about twice the $E_{LWDonMold}$

There are differences in

1. **Induced stress level,**
2. **Error from assuming Poisson's ratio,**
3. **Permanent strains in LWD testing on Mold**

Details on how to correct for these points to follow



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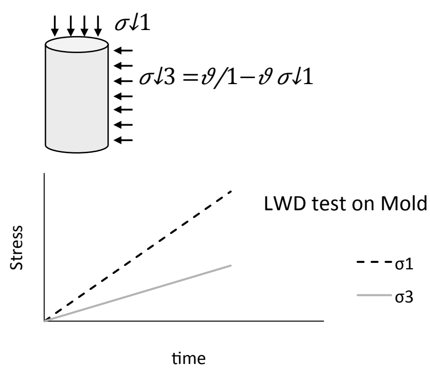
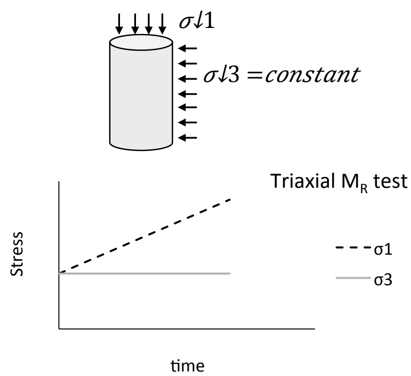
Small Scale Laboratory Experiments





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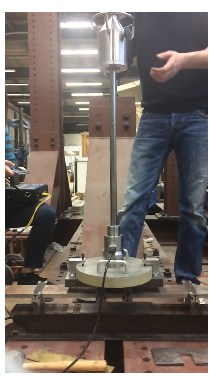
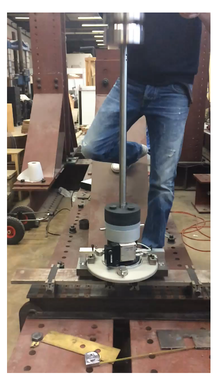
Small Scale Laboratory Experiments

Beam Verification Tester (BVT) by Hoffmann 2004 To assess Individual LWD device details





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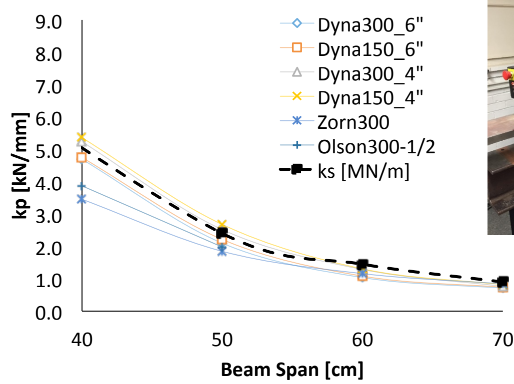
Small Scale Laboratory Experiments



Details to follow

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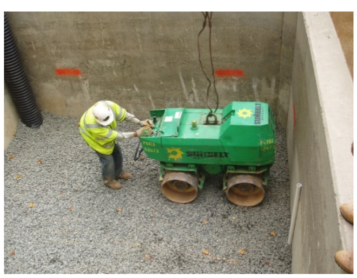
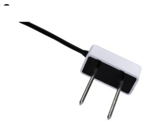
Large Scale Laboratory Experiments



- 15’ x 15’ x 8’
- Equipped with reaction frame with a pneumatic pulsed plate loading capability
- Infrastructure to control and change the water table.
- The test pits will be instrumented with soil moisture sensors and thermocouples. Surface deflection will be measured with Geophone
  - GS1 low cost ruggedized soil moisture sensor by Decagon Devices
  - T-type thermocouples will be fabricated at site



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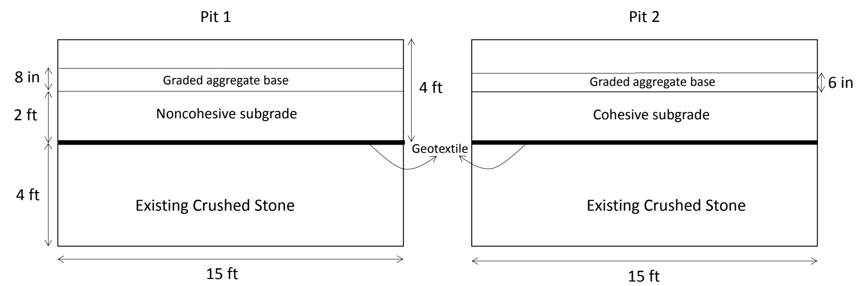
Large Scale Laboratory Experiments

Front view



Material:
- Two kinds of subgrade soils: Virginia Red Clay (cohesive subgrade), ALF subgrade soil
- One kind of graded aggregate base.

Compaction Scenario:
The test sections will be compacted to:
1. Pass the QA target modulus→ Compact at OMC and MDD
2. To fail the QA target modulus→ Compact at OMC-2% and 90%MDD.

Details to follow

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Field Experiments

US 29 NB from MD 32 to MD 175

6 inches of Granular Aggregate Base on top of Subgrade

US 404- Eastern shore Maryland

Sandy subgrade

US 424- Parking lot embankment

Silty clay and Clay silt

Primary purposes: Material for laboratory testing, data for model evaluation

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Field Validation

Project Info	Site ID	
	Address	
	Construction Dates	
	Project Length	
	Agency Contact	
Layer thickness	Base	
	Sub-base	
Soil Classification	Base	
	Sub-base	
	Subgrade	
Local availability of test equipment	LWD-Zorn	
	LWD-Dynatest	
	Nuclear Gauge	
	Other equipment	
Comments		

The objectives of this task include:

1. Validation of the proposed procedure under actual field conditions.
2. Assessment of the repeatability and reproducibility of the test devices in actual construction practice.
3. Estimation of the spatial variability of moisture, density, modulus, and layer thickness in actual construction practices.
4. Final refinement of the practical QC procedure.

Details to follow

Final remarks

- 3 LWDs selected for the study: Dynatest, Olson, Zorn
- Ohaus MB45 selected for moisture measurements
- Several M_R constitutive models and environmental factor models assessed to account for effects of stress and moisture separately and combined
- Application of LWD tests on Proctor mold to characterize the moisture, density, and stress dependency of a particular soil and the link to the field target modulus.
- Application of BVT tests to assess the reliability of the LWD measurements on elastic material with known properties.
- M_R tests based on AASHTO T307+LWD stress states performed on specimens compacted at OMC and MDD.
- Controlled tests to be conducted on instrumented test pits at TFHRC of FHWA.
- Field validations will be performed.