**TRANSPORTATION POOLED FUND PROGRAM**
**QUARTERLY PROGRESS REPORT**

Lead Agency (FHWA or State DOT): ____Maryland Department of Transportation____________

**INSTRUCTIONS:**
*Project Managers and/or research project investigators should complete a quarterly progress report for each calendar quarter during which the projects are active. Please provide a project schedule status of the research activities tied to each task that is defined in the proposal; a percentage completion of each task; a concise discussion (2 or 3 sentences) of the current status, including accomplishments and problems encountered, if any. List all tasks, even if no work was done during this period.*

| **Transportation Pooled Fund Program Project #**<br>*TPF-5(285)* | **Transportation Pooled Fund Program - Report Period:**<br>☐Quarter 1 (January 1 – March 31)<br>☐Quarter 2 (April 1 – June 30)<br>■Quarter 3 (July 1 – September 30)<br>☐Quarter 4 (October 1 – December 31) |
|---|---|

Project Title:
Standardizing Lightweight Deflectometer Measurements for QA and Modulus Determination in Unbound Bases and Subgrades

| **Name of Project Manager(s):**<br>Rodney Wynn | **Phone Number:**<br>443-572-5043 | **E-Mail**<br>RWynn@sha.state.md.us |
|---|---|---|
| **Lead Agency Project ID:**<br>TPF-5(285) | **Other Project ID (i.e., contract #):** | **Project Start Date:**<br>January/15/2014 |
| **Original Project End Date:**<br>December/15/2015 | **Current Project End Date:**<br>December/31/2015 | **Number of Extensions:**<br>0 |

Project schedule status:

☐ On schedule ☐ On revised schedule ☐ Ahead of schedule ■ Behind schedule

Overall Project Statistics:

| Total Project Budget | Total Cost to Date for Project | Percentage of Work Completed to Date |
|---|---|---|
| **$371,984** | **$ 91,340.45** | **22%** |

***Quarterly*** Project Statistics:

| Total Project Expenses and Percentage This Quarter | Total Amount of Funds Expended This Quarter | Total Percentage of Time Used to Date |
|---|---|---|
| **$ 39,888.10**<br>**10.7%** | **$ 39,888.10** | **22%** |
| | | |

**Project Description**:

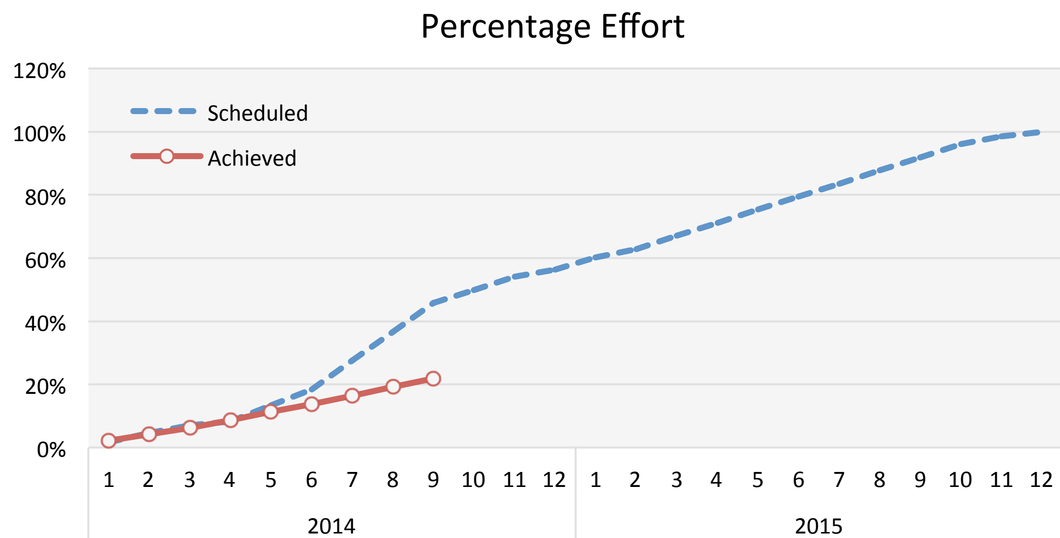
Currently, compaction control using lightweight deflectometers (LWD) is being evaluated in many states and fully implemented for pavement construction quality assurance (QA) in some states and countries. However, there currently is no widely recognized standard for interpreting the load and deflection data obtained during construction QA testing and then relating these measurements to the material properties used during pavement design.

The main goal of this research is to provide a straightforward and practical procedure for using LWD for compaction control that can be implemented by field inspection personnel. This procedure must (1) fully account for the influence of moisture on LWD measurements, (2) include the effects of stress state on measured modulus and the differences between the LWD induced stress state and the stress states induced by design traffic loads, (3) be applicable to LWD testing of half-space conditions (i.e., subgrade) and finite thickness layered conditions (i.e., granular base layers).

**Progress this Quarter (includes meetings, work plan status, contract status, significant progress, etc.):**

Meeting with Dr. Nelson Gibson of Tuner-Fairbank Highway Research Center (TFHRC) of the Federal Highway Administration (FHWA) to discuss the use of test pits at the TFHRC.

The project is behind schedule with respect to the work plan.




The progress with respect to each Task is as followed:

**Task 1. Literature Review (3.3% of the total effort). Percent completion of Task 1: 100%**

The personnel continue the review of the current and upcoming literature when deemed necessary. The most important recent review was the final draft of NCHRP 10-84 project.

Project personnel participating in these activities: Schwartz, Khosravifar, Afsharikia.

**Task 2. Equipment Evaluation (2.4% of the total effort). Percent completion of Task 2: 100%**

The LWD devices selected for further evaluation include: Zorn ZFG 3000, Dynatest 3031 LWD, Olson LWD-1.
The Zorn LWD with 300 mm plate is being provided for evaluation purposes without charge by Kessler Company.

The Olson LWD-1 with 150mm, 200mm, and 300mm plates is being provided for evaluation purposes without charge by the Olson Instruments Company. The Dynatest 3031 LWD will be rented from Dynatest company. We are currently awaiting shipment of the equipment from Dynatest.

The moisture content measurement devices selected for further evaluation included: Oven drying (according to ASTM D2216), Ohaus MB45 moisture analyzer, and Speedy 2000 moisture device. The MB45 moisture analyzer has been purchased from the Ohaus Corporation. A Speedy 2000 moisture device will be purchased if necessary.

Project personnel participating in these activities: Schwartz, Khosravifar, Afsharikia.

**Task 3. Model Refinement/Development (12.6% of the total effort). Percentage completion of Task 3: 75%**

a. Nine existing resilient modulus constitutive and predictive models were assessed using data from the literature (Andrei, 2003). The specific focus of this assessment was the incorporation of partially saturated suction effects on resilient modulus. The most precise model was found to be Lytton et al. (1995) with an upper limit suction control factor. Details of the analysis results are presented in Appendix A. The Lytton et al. (1995) model will be used in this project to predict the resilient modulus at moisture contents of interest.

b. A parametric study of soil drying vs. depth and time was conducted using the HYDRUS 1D program. The objective of this study is to evaluate how much the amount of drying vs. depth and time that can potentially occur within 24 hours after compaction for different soil types and under various climatic conditions. HYDRUS 1D calculates the potential evaporation in partially saturated porous media by simulating the coupled water, vapor and heat transport. To verify the outputs of the HYDRUS 1D software, volumetric water content profiles at different time intervals for two types of soils (clay and top soil) with assumed properties and conditions were simulated and compared to the measured values from laboratory tests performed by Yanful and Choo (1997). The results agreed well qualitatively. Next, two types of homogeneous and layered soil structures with different boundary and weather conditions were simulated. As expected, the coarse grain material exhibited more drying than the fine grain material within the 24 hours of the study span. A one-at-a-time sensitivity analysis of soil and climatic parameters was performed to obtain the sensitivity of moisture content profile to different climatic and soil hydraulic parameters. This study is ongoing. The results will be verified using controlled test pit and field measurements performed in Tasks 4 and 5.

Project personnel participating in these activities: Schwartz, Khosravifar, Afsharikia.

**Task 4. Controlled Trials (18.8% of the total effort). Percentage completion of Task 4: 21%**

**Laboratory resilient modulus tests:** The testing is still on hold until the enhancements to our Universal Test Machine (UTM) are complete. The has been delayed to mid October 2014. A 6 kN load cell and two external LVDTs will be installed to conform to AASHTO T-307 specification.

**Beam verification tester (BVT):** The test device developed by Hoffmann (2004) was selected to compare the static stiffness measured by the 3 different LWDs. The BVT was borrowed from John Siekmeier of the Minnesota DOT. The unit originally designed for testing LWDs with 100 mm plates has been modified to accommodate 200mm and 300mm plate sizes. Preliminary tests have been performed on the beam. A full assessment of all LWDs on the BVT will be performed in the next quarter upon arrival of the Dynatest LWD. The objective of using the BVT is to assess whether there is a systematic error in the static stiffness calculated by each test device when tested on a steel beam with known stiffness properties.

**Controlled soil box tests:** Arrangements have been made to use three large test pits at the FHWA TFHRC for large scale controlled trials. The test pits are 15-foot x 15-foot x 8-foot deep. The test pits are equipped with a reaction frame with a pneumatic pulsed loading capability for plate load tests and infrastructure to control and vary the water table. The test pits will be instrumented with temperature and soil moisture sensors. Pictures are provided in Appendix B.

Project personnel participating in these activities: Schwartz, Khosravifar, Afsharikia.

**Task 5. Field Validation (53.7% of the total effort). Percentage completion of Task 5: 5%**

Two projects in Maryland have been selected for field studies: MD 404 in Denton and US 29 in Columbia.
Testing has been performed at US 29 on a 6 inch granular aggregate base at one day after compaction. The tests included modulus measurements from the Zorn and Olson LWDs and nuclear gauge moisture and density measurements. Preliminary results are shown in Appendix C. There was a strong correlation between the Zorn LWD (300mm) and Olson LWD (200mm). As expected, there was not a strong correlation between measured stiffness and density. The models studied in Task 3 will be used to correct for the moisture influence on resilient modulus. The current available specifications (including the recent NCHRP 10-84 specification) will be evaluated during the next quarter.

**Task 6. Draft Test Specifications (3.3% of the total effort). Percentage completion of Task 6: 0%**

No progress was made on this task during the reporting period.

**Task 7. Workshop and Final Report (5.8% of the total effort). Percentage completion of Task 7: 0%**

No progress was made on this task during the reporting period.

**UMD personnel contact information:**

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**Anticipated work next quarter:**

- Continued monitoring and documentation of the literature.
- Task 3, 4, and 5 will be the main focus of the next quarter. Specific work elements in these tasks to be performed during the next quarter include:
    1. Completion of the parametric study of drying using the HYDRUS 1D program.
    2. Completion of the evaluation of LWD devices using the BVT.
    3. Laboratory resilient modulus testing of soils evaluated in the test pits and field sites.
    4. Design and construction of large scale test pits
    5. Preliminary field evaluations/validations at MD 404, US 29, and perhaps another project in Prince George County.
    6. Model refinement
    7. Arrangements with the Technical Advisory Committee members for potential field projects in each state (Task 5).

**Circumstance affecting project or budget. (Please describe any challenges encountered or anticipated that might affect the completion of the project within the time, scope and fiscal constraints set forth in the agreement, along with recommended solutions to those problems).**

The main circumstance affecting the project has been the installation of the triaxial resilient modulus test unit, which has delayed the laboratory resilient modulus testing progress. The parts shipped by IPC-Global in late August and installed by Instrotek in September were not satisfactory. The current plan is to keep only the new low capacity load cell (6 kN) and the two external LVDTs and use the existing triaxial cell in the UTM unit. This process requires some modifications and machine shop work, which will be handled internally at UMD. The unit is expected to be up and working by end of October.

The arrangements for borrowing/renting the LWDs for evaluation have not been straightforward. We are still waiting for the Dynatest LWD to be shipped.

Field projects have also encountered cancelations due to weather conditions.

**Potential Implementation:**

LWDs should be implemented more widely using standardized testing procedures and data interpretation methods. LWDs are a tool for performance based construction QA testing that should not only result in a better product but also provide quantitative measurement of in place stiffness values. This is critical to better understanding the connection between pavement design and long term pavement performance.  As the benefits of performance based QA testing become increasingly apparent, more public agencies and private consultants are expected to acquire these tools and implement standardized procedures for their use.  The product of this research will enable state DOT modification of their construction specifications to include this new light weight deflectometer (LWD) option for construction QA.

**Appendix A**

# Evaluation of Resilient Modulus Prediction Models for Cohesive and Non-Cohesive Soils

Sadaf Khosravifar[1], Zahra Afsharikia[2], Charles W. Schwartz[3]

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## ABSTRACT

Geomaterials are often in unsaturated condition during their service life and their resilient modulus is influenced by several factors including moisture content, density, void ratio, plasticity, and etc. There are various constitutive models to predict the nonlinear resilient modulus of unbound materials as a function of the aforementioned factors—particularly moisture and stress states based on empirical equations or theoretical unsaturated soil mechanics concepts.

In this study, seven existing constitutive models and two predictive models were evaluated using eight different soil databases with different properties including cohesive and non-cohesive soils. The constitutive models were calibrated based on the data at optimum moisture content and maximum dry density. Consecutively, the calibrated models were used to predict the resilient modulus at other moisture or density conditions. The models were compared in terms of their rationality, accuracy of prediction, and applicability to the widest range of soils.

## INTRODUCTION

Resilient modulus ($M_R$), a measure of stiffness, is a fundamental material property for unbound pavement materials. It is the most important material input for subgrade and base soils required by Mechanistic—Empirical Pavement Design Guide (MEPDG) in design of pavement layers. Soils $M_R$ can significantly vary with changes in density, moisture content, gradation, plasticity index, and the stress levels it perceives (Vanapalli et al., 1999). Uzan (1985) proposed a nonlinear constitutive model based on first stress invariant and octahedral shear stress.

For soils in saturated or unsaturated condition, the mechanical response, is a function of effective stresses rather than total stresses (Bishop, 1960; Terzaghi, 1996). In unsaturated soils, two main factors form the effective stresses; (1) pore air pressure ($u_a$) which is often insignificant, and (2) the difference between $u_a$ and the pore water pressure ($u_w$), designated as matric suction ($u_a - u_w$) or simply $u$ as referred to in this study. Bishop (1960) formulated the effective stress of unsaturated soils as shown in equation 1.

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w) \qquad (1)$$

Matric suction ($u$) is a function of pore size geometry, pore size distribution, and the soil water content and can be predicted from soil-water characteristic curve (SWCC) (Fredlund and Xing, 1994). The effective stress parameter ($\chi$)—also known as pore suction resistance factor—in Equation 1 is a material variable that shows the contribution of the matric suction in the effective stress and is generally considered to vary between zero, and unity, corresponding to a completely dry and fully saturated soil, respectively. At fully saturated condition, the equation reduces to Terzaghi's classic effective stress equation.

While several researchers e.g. Lytton (1995), Khalili and Khabbaz (1998), Roberson and Siekmeier (2002) have proposed different models to quantify pore suction resistance factor, it is not well been accepted in application and $\chi$ equal to 1 is often preferred by researchers (Morgenstern, 1979).

To characterize the nonlinear modulus of soils, tests at various conditions—in particular stress, and moisture—may be required. Yet, routine testing is usually only performed at optimum moisture and density condition. Therefore, implementation of an accurate constitutive model based on mechanics of unsaturated soils capable of predicting the nonlinear $M_R$ at other moisture and density conditions, is a necessity. In this study several resilient modulus constitutive models with slight differences, and two predictive models were evaluated on independent cohesive and noncohesive soils. The models were compared in terms of their rationality, accuracy of prediction, and applicability to the widest range of soils.

## MATERAL PROPERTIES

In this study, 4 types of subgrade and 4 types of base soil data from Andrei (2003) were used to evaluate the models. The soil type and description of each material is presented in **Table 1**. More information about the volumetric and mechanical properties of the soils can be found in Andrei (2003).

**Table 1- Soil Type and Description (From Andrei, 2003)**

| | SOIL TYPES | DESCRIPTION |
|---|---|---|
| SUBGRADE | Phoenix Valley Subgrade (PVSG) | Clayey Sand, SC |
| | Yuma Sand Subgrade (YSSG) | Poorly Graded Gravel with Sand, GP, Non Plastic |
| | Flagstaff Clay Subgrade (FCSG) | Clayey Sand, SC |
| | Sun City Subgrade (SCSG) | Clayey Sand, SC |
| BASE | Grey Mountain Base (GMAB2) | Well Graded Gravel with Sand, GW, Non Plastic |
| | Salt River Base (SRAB2) | Poorly Graded Sand with Gravel, SP, Non Plastic |
| | Globe Base (GLAB2) | Poorly Graded Sand with Silt and Gravel, SP-SM, Non Plastic |
| | Prescott Base (PRAB2) | Poorly Graded Sand with Silt and Gravel, SP-SM, Non Plastic |

All base materials and one of the subgrade soils were non-plastic. The soil water characteristic curve which was a key input to the evaluated models were predicted from the gradation and soil indices using the Fredlund and Xing (1994) procedure. The unconfined compression ($U_C$) which was input to one of the predictive models was also predicted from the soils CBR according to Black (1962).

For all of the soils, the $M_R$ test was performed on specimens compacted with standard and modified proctor, at their corresponding optimum moisture content as well as above and below optimum adding up to a total of 6 scenarios.

## EVALUATED MODELS

Several predictive and constitutive models have been proposed by previous researchers to model the resilient modulus of the soils; 9 of which were selected for evaluation. The parameters of the following models were calibrated—except for M4 and M6 predictive models—based on the measured data at optimum moisture content and maximum dry density of standard compaction test scenario. The models where subsequently used to predict the $M_R$ at the other moisture- density conditions. The evaluated models are explained below:

M1 is the general nonlinear model adopted by MEPDG and is a function of total bulk stresses. This model does not consider the effect of suction *u.*

**M1**: $M_R = K_1 P_a \left(\frac{\sigma_{bulk}}{P_a}\right)^{K_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{K_3}$ (2)

whereby $\sigma_{bulk} = \sigma_1 + \sigma_2 + \sigma_3 = \sigma_d + 3\sigma_c$, $\sigma_1, \sigma_2, \sigma_3 =$ three principal stresses, $\sigma_d$= deviatoric stress, $\sigma_c$= confining stress, $\tau_{oct}$= octahedral shear stress, and the coefficients $K_1$, $K_2$, and $K_3$ are regression coefficients.

M2, the second evaluated model, is similar to M1, with the bulk effective stress $(\sigma_{bulk} + 3u)$ replacing $\sigma_{bulk}$. The reason for the multiplication of suction by 3 is that the term adds up in the three principal effective stresses.

**M2**: $M_R = K_1 P_a \left(\frac{\sigma_{bulk}+3u}{P_a}\right)^{K_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{K_3}$ (3)

M3, proposed by Liang et al (2008) adds a suction dependency term ($\chi$) to the effective stress term. The suction dependency term was proposed by Khalili and Khabbaz (1998). In this model the suction term ($u$) is not multiplied by 3.

**M3**: $M_R = K_1 P_a \left(\frac{\sigma_{bulk}+ \chi\, u}{P_a}\right)^{K_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{K_3}$ (4)

$\chi = \left(\frac{(u_a - u_w)_b}{u_a - u_w}\right)^{0.55} = \frac{u_{air-entry}}{u}$ (5)

$u_{air-entry}$ is the suction at air entry level where air starts to enter the largest pores in the soil. The upper limit of $\chi$ is equal to 1.

M4, proposed by Siekmeier (2011), has been found a suitable predictive model for subgrade and fine soils. The $K_1$-$K_3$ coefficients are also predicted as a function of suction and volumetric moisture content from SWCC of the soils. The equations are shown as followed:

**M4:** $M_R = K_1 P_a \left(\frac{\sigma_{bulk}+ f\, \theta_w\, u}{P_a}\right)^{K_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{K_3}$ (6)

where $K_1 = 800 \times \left(\frac{1}{5\theta_{sat}}\right)^{1.5} \times \left(\frac{1}{log_{10}(u)}\right)$, $K_2 = log_{10}(u) - 1$, $K_3 = -8\theta_{sat}$,

$f = \theta_w^{10\theta_{sat}^3}$, $\theta_w$= Volumetric water content, $\theta_{sat}$= Volumetric water content at Saturation, and $\chi = f\, \theta_w$.

The $\chi$ in M4 model is not bracketed by the upper bound of 1. The M4 predictive model, was re-evaluated (**M5**), in which the K values were calibrated for each soil through nonlinear regression. The formula for *f* was kept the same.

Yan et al. (2013) proposed two predictive models for subgrade soils based on gene expression programming (GEP) to correlate $M_R$ with routine properties of subgrade soils and state of stress. GEP I was computationally unstable for nonplastic soils and was found erroneous for plastic soil, thus excluded from the comparison. The GEP II model, selected for evaluation—labeled as M6—is displayed below:

**M6**:

$$M_R = \text{atan}\left\{\gamma_d * \left[\frac{\gamma_d - U_c}{PI}\right]\right\} + \left\{2 * \left[\frac{sqrt(PI)}{P_{200}}\right]\right\} + \sigma_d + \left\{2 * \sin\left[\frac{\gamma_d * \exp\{\text{atan}[\sin(P_{200})]\}}{P_{200}}\right]\right\} + (\sigma_d * \text{atan}\{sqrt(P_{200}) - [(\sigma_d * P_{200})/\gamma_d]\}) + \{\text{atan}\,[sqrt(U_c) - \gamma_d] + \text{atan}\,(\gamma_d)\} \quad (7)$$

$U_c$ = Unconfined compressive strength, $PI$ = Plasticity Index, $P200$ = Percentage passing sieve #200, $\gamma_d$= Dry density, and $\sigma_d$= deviatoric stress.

Recently, Gu et al. (2014) evaluated a model proposed by Lytton (1995) and reported satisfactory predictions of base course aggregates. The formula is:

$$M_R = K_1 P_a \left(\frac{\sigma_{bulk} - 3\theta_w f u}{P_a}\right)^{K_2} \left(\frac{\tau_{oct}}{P_a}\right)^{K_3} \quad (8)$$

Parameter $f$ in this model is a function of $\theta_a$ and $\theta_u$, which are volumetric water content of the soil at air entry and unsaturation levels, respectively. Parameter $f$ is bracketed by the upper and lower bound, calculated using formulas below:

$$f_{upper\ bound} = \left[\left(\frac{\theta_a - \theta_w}{\theta_a - \theta_u}\right) + \frac{1}{\theta_w}\left(\frac{\theta_w - \theta_u}{\theta_a - \theta_u}\right)\right] \quad (9)$$

$$f_{lower\ bound} = \left[\frac{1}{\left(\frac{\theta_a - \theta_w}{\theta_a - \theta_u}\right) + \theta_w\left(\frac{\theta_w - \theta_u}{\theta_a - \theta_u}\right)}\right] \quad (10)$$

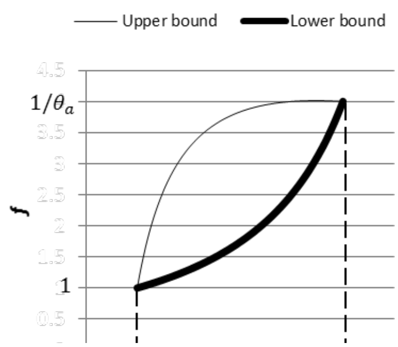



*Figure 1. The bounds of pore suction for Lytton (1995).*

Three $f$ were evaluated in the Lytton model to predict the resilient modulus, resulting in the following models. $\chi = f\theta_w$ ranges from $\theta_u - 1$ and therefore is theoretically sound.

**M7** Equation 8 based on $f = \frac{f_{upper\ bound} + f_{lower\ bound}}{2}$

**M8** Equation 8 based on $f = f_{upper\ bound}$ (Equation 9)

**M9** Equation 8 based on $f = f_{lower\ bound}$ (Equation 10)

## RESULTS

Least square analysis was applied to the measured data at optimum moisture content and maximum standard dry density on all models except for M4 and M6 predictive models to find the best model parameters by minimizing the sum of squared residuals in MATLAB.

To evaluate the performance of the models, root mean square error (RMSE) and average relative error (RE) of model prediction were calculated at each moisture condition (Wet, Dry, Optimum), each compaction energy effort (standard and Modified proctor compaction effort), and overall for each soil and every model. RMSE, a measure of model accuracy, reflects both systematic and nonsystematic error variation and has the same units as the criterion $M_R$ here reported in ksi. RE measures the systematic error or bias of the models. The definitions of these evaluation criteria are given as follows:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left((M_{R-\text{predicted}} - M_{R-\text{measured}})^2\right)} \quad (11)$$

$$\text{RE} = \frac{\frac{1}{n}\sum_{i=1}^{n}\left(M_{R-\text{predicted}} - M_{R-\text{measured}}\right)}{\frac{1}{n}\sum_{i=1}^{n}\left(M_{R-\text{measured}}\right)} = \bar{e}/\overline{M_R} \quad (12)$$

Figure 2 shows the distribution of RMSE of evaluated models at different moisture and compaction energy condition. As expected, all the models performed well in optimum moisture and density, the condition at which was the model parameters were calibrated. Prediction errors stood the highest at dry of optimum at both compaction efforts.

**Figure 3**, presents the prediction bias of the models on the plastic and nonplastic soils. Overall, all models underpredicted at dry of optimum for nonplastic soils.

The overall RMSE of prediction of the models per soil is shown in Table 2. The shaded cells in the table present the most accurate model. Overall model M8—Lytton (1995) with $f_{upper\ bound}$—outperformed the other models in both plastic and neoplastic soils. M2 model which in fact is the effective stress model with f=1, performed very well for nonplastic soils, but did not provide an acceptable prediction accuracy for plastic soils. An example of the measured vs. predicted $M_R$ by M2 for a plastic soil (PVSG) is shown in **Figure 4**.

**Table 3**, shows the RE for each model and soil type. Again, model M8 was overall the most consistent model concerning both plastic and nonplastic soils. Model M4 and M2, while outperformed in several soil types, were erroneous in several others and did not provide a consistent prediction over the range of the evaluated soils.

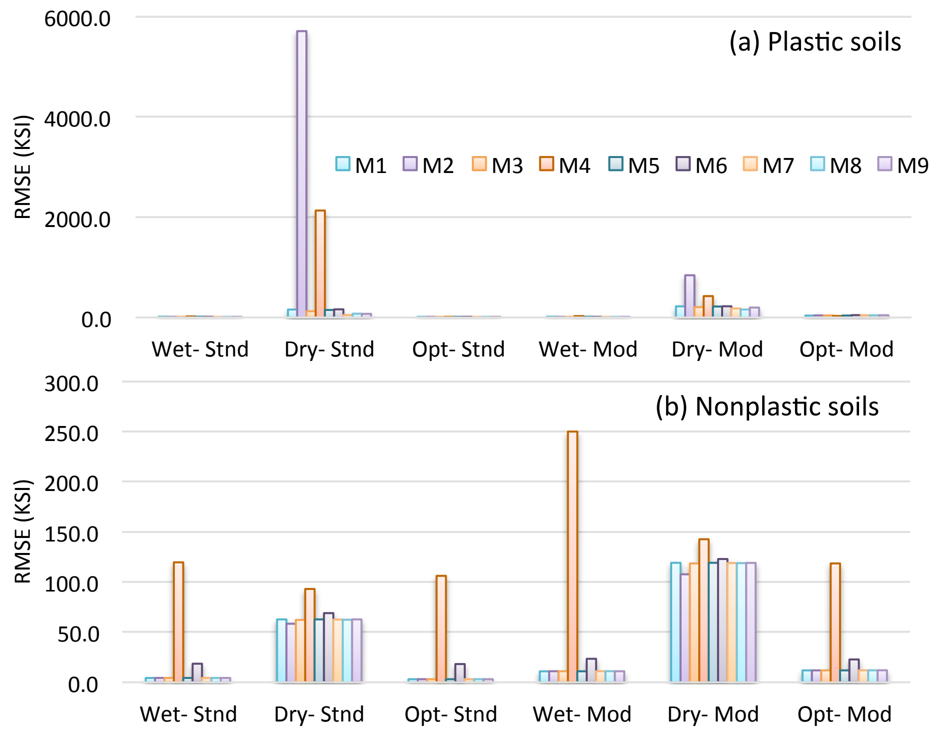



**Figure 2. Distribution of RMSE of evaluated models at different moisture and compaction energy condition for (a) Plastic, and (b) Neoplastic soils.**

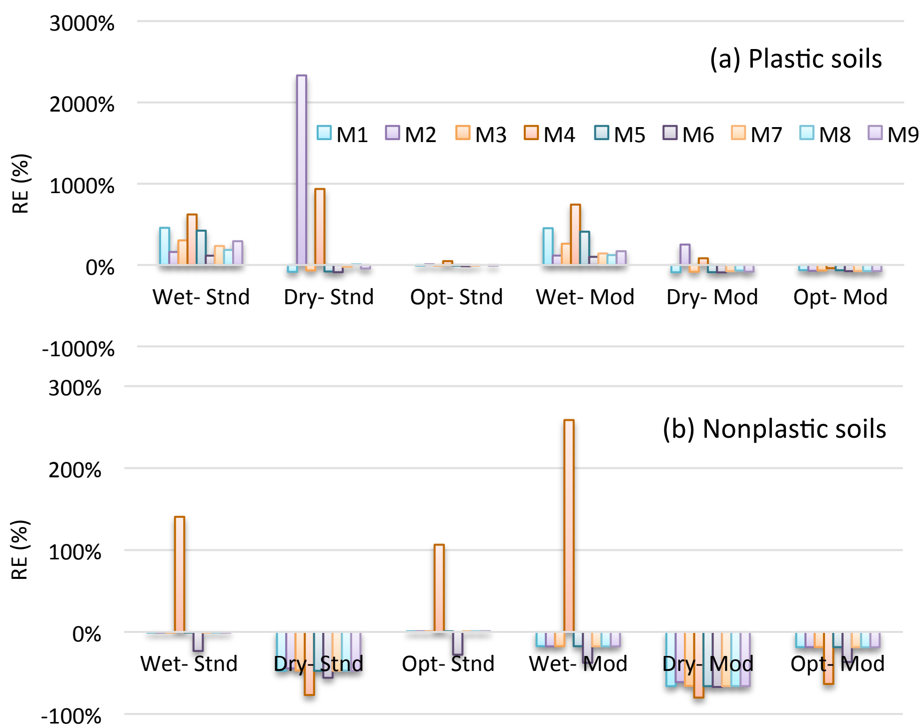



**Figure 3. Distribution of average RE of evaluated models at different moisture and compaction energy condition for (a) Plastic, and (b) Neoplastic soils.**

**Table 2. Overall RMSE of the evaluated models for each soil**

| RMSE (ksi) | M1 | M2 | M3 | M4 | M5 | M6 | M7 | M8 | M9 |
|---|---|---|---|---|---|---|---|---|---|
| 1.PVSG | 143.0 | 3452.0 | 129.8 | 292.4 | 139.8 | 141.9 | 99.9 | 90.3* | 118.0 |
| 2.YSSG | 88.0 | 67.9 | 87.1 | 268.4 | 87.9 | 96.8 | 87.5 | 87.4 | 87.5 |
| 3.FCSG | 49.6 | 49.6 | 49.2 | 46.2 | 49.7 | 55.0 | 51.4 | 50.9 | 52.1 |
| 4.SCSG | 107.7 | 2964.4 | 86.9 | 2138.2 | 102.7 | 110.4 | 57.8 | 60.4 | 64.9 |
| 5.GMAB | 26.9 | 26.8 | 26.9 | 196.0 | 26.9 | 37.5 | 26.9 | 26.9 | 26.9 |
| 6.SRAB | 48.3 | 44.5 | 48.0 | 81.6 | 48.3 | 50.3 | 48.3 | 48.1 | 48.4 |
| 7.GLAB | 41.1 | 39.9 | 40.9 | 67.3 | 41.1 | 43.3 | 41.0 | 40.9 | 41.1 |
| 8.PRAB | 47.0 | 46.0 | 46.9 | 208.7 | 47.0 | 47.7 | 47.0 | 47.0 | 47.1 |
| Plastic | 100.1 | 2155.3 | 88.6 | 825.6 | 97.4 | 102.4 | 69.7 | 67.2 | 78.3 |
| NonPlastic | 50.3 | 45.0 | 49.9 | 164.4 | 50.2 | 55.1 | 50.1 | 50.1 | 50.2 |
| All | 69.0 | 836.4 | 64.5 | 412.3 | 67.9 | 72.9 | 57.5 | 56.5 | 60.8 |

* The shaded cells show the model yielded the lowest RMSE of prediction for each Soil type.

**Table 3. Overall relative bias of the evaluated Models for each soil**

| RE, % | M1 | M2 | M3 | M4 | M5 | M6 | M7 | M8 | M9 |
|---|---|---|---|---|---|---|---|---|---|
| 1.PVSG | -83% | 1310% | -76% | 85% | -81% | -86% | -53% | -30% | -68% |
| 2.YSSG | -55% | -43% | -55% | 127% | -55% | -80% | -55% | -55% | -55% |
| 3.FCSG | -58% | -66% | -65% | -51% | -60% | -75% | -70% | -69% | -71% |
| 4.SCSG | -71% | 1789% | -58% | 1240% | -67% | -83% | -21% | -5% | -35% |
| 5.GMAB | -23% | -23% | -23% | 16% | -23% | -40% | -23% | -23% | -23% |
| 6.SRAB | -36% | -34% | -36% | -28% | -36% | -41% | -36% | -36% | -36% |
| 7.GLAB | -32% | -31% | -32% | -36% | -32% | -38% | -32% | -32% | -32% |
| 8.PRAB | -35% | -34% | -35% | -50% | -35% | -41% | -35% | -35% | -35% |

* The shaded cells show the model yielded the lowest RMSE of prediction for each Soil type.

**Figure 5** presents the RMSE and RE for model M8 at different moisture and compaction effort conditions. M8, albeit better than the other models, underpredicted the moduli at dry of optimum and optimum moisture of modified compaction condition for all soils and overpredicted at wet of optimum of the standard and modified compaction conditions of the plastic soils.

**Figure 6** shows the measured vs. predicted $M_R$ for GMAB and PVSG for which M8 model provided the most and least accurate predictions, respectively.

Overall, M8—the model proposed by Lytton (1995), using the upperbound of the suction resistance factor ($\theta_w f$) based on Equations 8 and 9—was found to be the most accurate model over a wide range of fine and coarse, and plastic and nonplastic soils used in pavements subgrades and bases. However, RMSE for all the models were high, far from acceptance in all the moisture and density conditions. Local biases existed in all the evaluated models. Especially, the models tended to underpredict the moduli at dry of optimum.

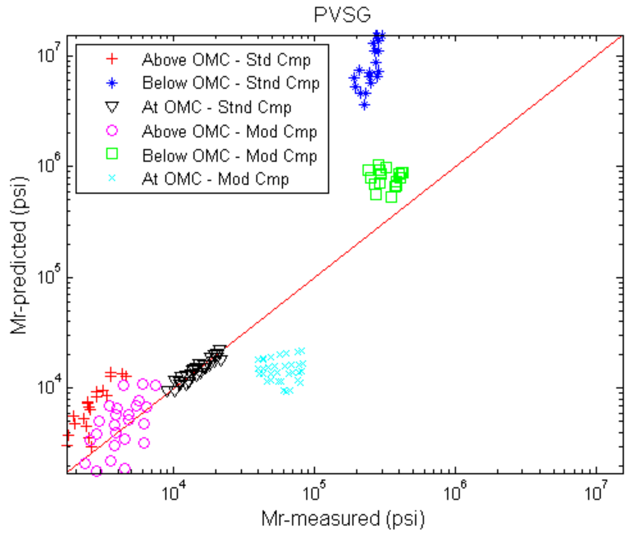



**Figure 4. $M_{R\text{-predicted}}$ VS. $M_{R\text{-measured}}$ - Model M2 for Soil PVSG**

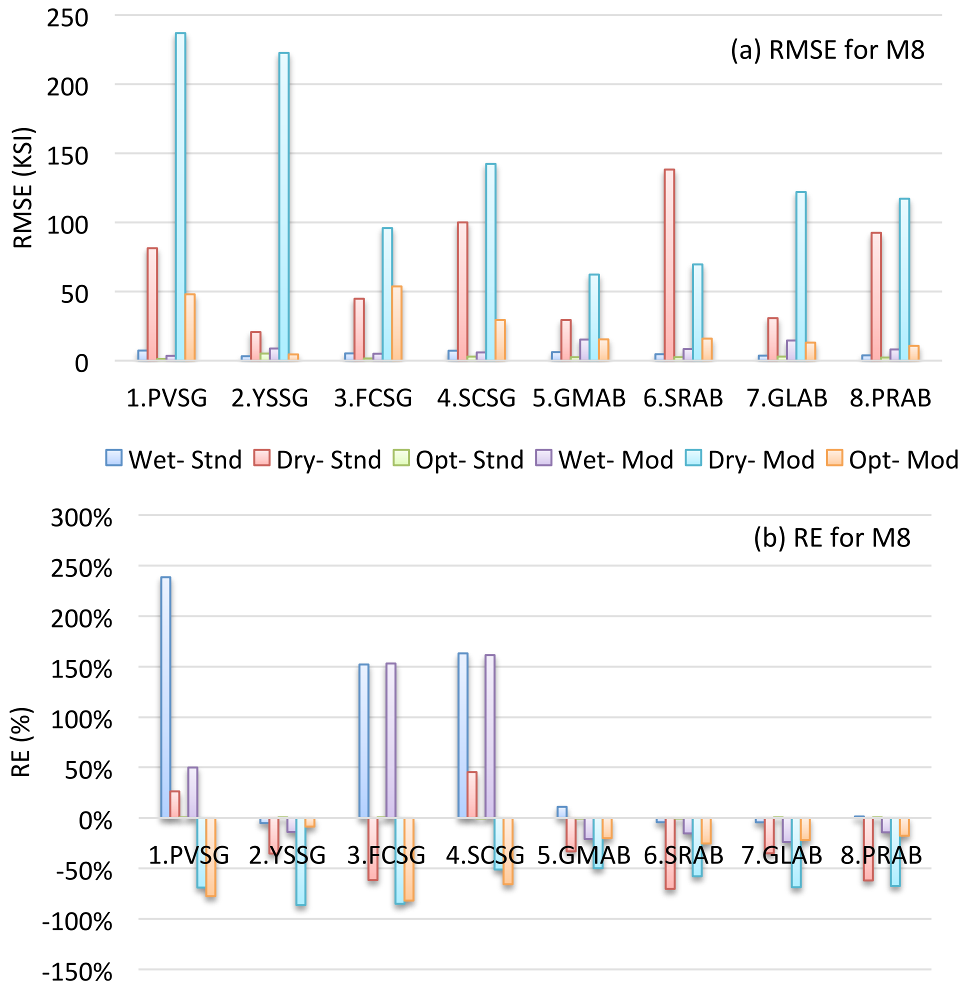
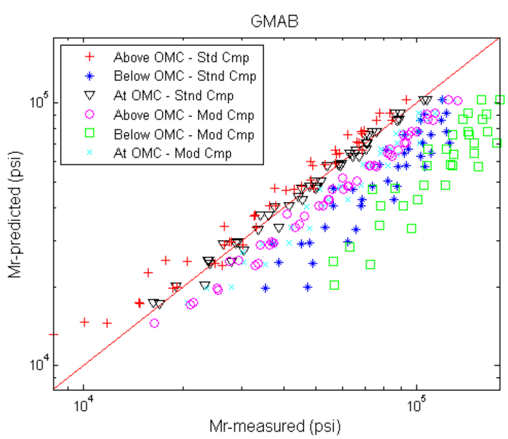



**Figure 5. a. RMSE and b. RE at different moisture and compaction energy conditions for Model 8.**



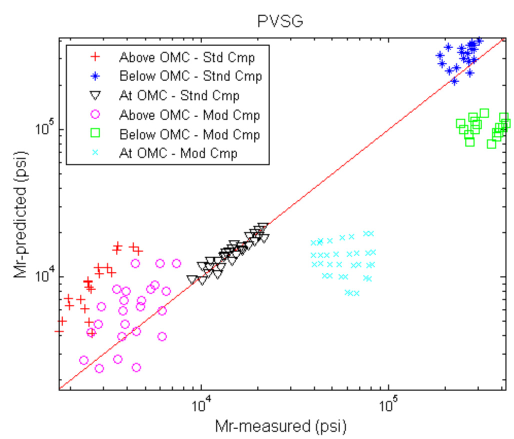




**Figure 6. $M_R$-predicted from model M8 VS. $M_{R\text{-measured}}$ for GMAB and PVSG soils.**

## CONCLUSIONS

Geomaterials are often in unsaturated condition during their service life and their resilient modulus is influenced by several factors including moisture content, density, void ratio, plasticity, and etc. To characterize the nonlinear modulus of soils, tests at various conditions—in particular stress, and moisture—may be required. Yet, routine testing is usually only performed at optimum moisture and density condition. Therefore, an accurate model based on mechanics of unsaturated soils that can predict the nonlinear $M_R$ at other test conditions is a necessity for soils characterization for MEPDG design. In this study several resilient modulus constitutive models with slight differences, and two predictive models were evaluated on independent cohesive and noncohesive soils obtained from Andrei (2003).

The statistical analysis of accuracy and bias on the predicted moduli at various moisture and density conditions showed that the model proposed by Lytton (1995) designated in this paper as model M8, provided the most accurate model of the nine evaluated models. The model is rationally founded on the principals of unsaturated soils, by incorporating the influence of moisture through its effect on pore suction ($u$), and the degree of the contribution of the suction on effective stresses ($\theta_w f$). Overall, the model performed better than the rest in terms of rationality, accuracy of prediction, and applicability to the widest range of cohesive and noncohesive soils.

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**Appendix B: Preliminary Design for Large Scale Test Pits**

Three test pits at TFHRC will be used for large scale controlled trials. The test pits are 15-foot x 15-foot x 8-foot deep; see below for representative photos. The test pits are equipped with a reaction frame with a pneumatic pulsed loading capability for plate load testing and infrastructure to control and change the water table. The test pits will be instrumented with temperature and soil moisture sensors.

The tentative work plan includes:

Materials:

- Two kinds of subgrade soil: Cohesive and Noncohesive
- One kind of Base soil: typical granular aggregate base used in Maryland

Compaction: At OMC and MDD

Test: Every 1 hour with different LWDs for stiffness measurements. Samples will be measured for moisture content using the MB45 Moisture Analyzer.

*Figure 7. Test pit at TFHRC of FHWA*

**Appendix C**

**US 29**

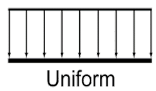
**70 ft test strip.**

**6 inches of Granular Aggregate Base on top of Subgrade**

**9 test locations**

**Tests included: Zorn LWD with 300 mm plate, Olson LWD with 200 mm plate, and Nuclear Gauge**

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




$$A = \pi$$

| | |
|---|---|
| MDD | 143 pcf |
| OMC | 4.5 |
| Olson | 200mm/ 10 kg |
| Zorn | 300mm/10 kg |

| Station # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| MC (%) | 3.8 | 4.1 | 4.3 | 5.4 | 4 | 5.5 | 4.7 | 4.9 | 4.2 |
| DD (PCF) | 133.8 | 137.8 | 139.1 | 137.6 | 144.8 | 130.2 | 138.1 | 133.9 | 135.7 |
| WD (PCF) | 138.9 | 144.4 | 145.1 | 145 | 150.5 | 137.4 | 144.6 | 140.5 | 141.4 |
| PC (%) | 93.6% | 96.4% | 97.3% | 96.2% | 101.3% | 91.0% | 96.6% | 93.6% | 94.9% |
| Olson E (ksi) | 6.8 | 5.3 | 6.6 | 4.8 | 6.3 | 4.3 | 4.1 | 4.0 | 2.4 |
| Zorn E (ksi) | 8.8 | 5.5 | 7.9 | 7.3 | 6.0 | 4.9 | 4.7 | 4.2 | 3.0 |

*Figure 8. Test strip at US 29*

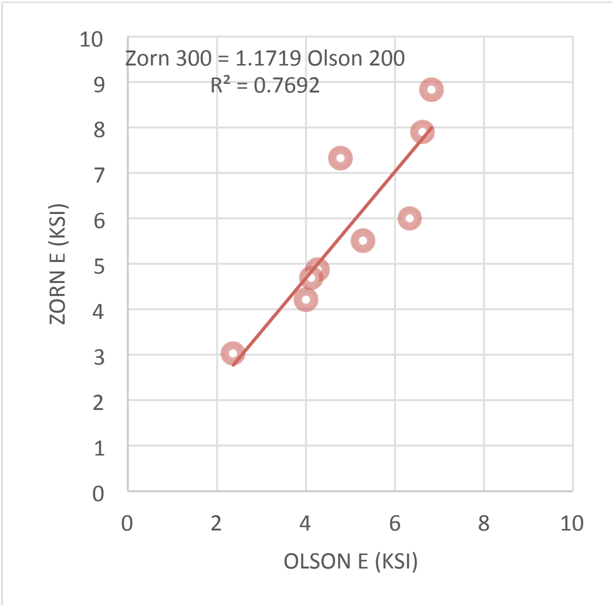



*Figure 9. Modulus (E) from Zorn LWD versus Olson LWD*

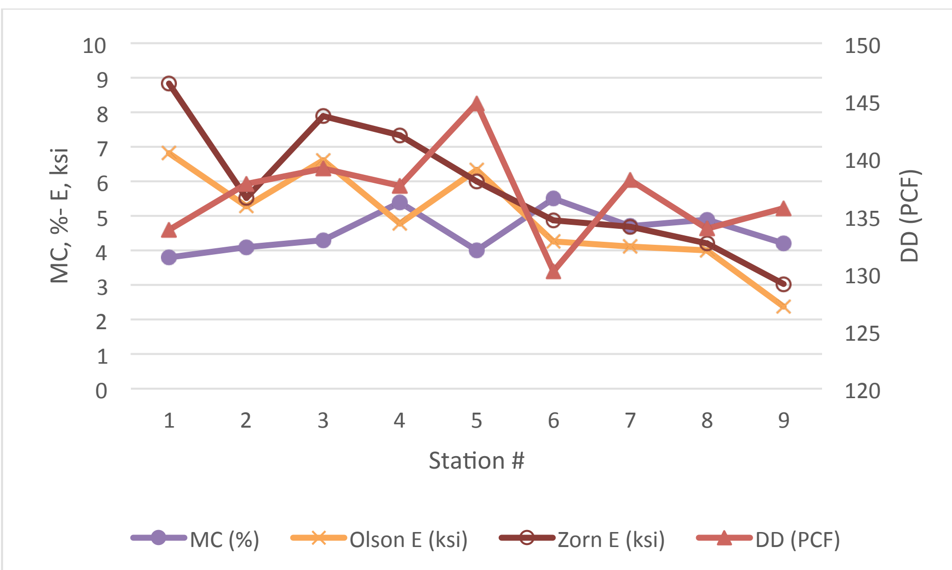



*Figure 10. Spatial variability of moisture content (MC), dry density (DD) and modulus as measured by Olson and Zorn.*