Dynamic Nonlinear Finite Element Simulation of Light Falling Weight Deflectometer (LWD) Tests on Unsaturated Road Foundation Layers

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1 Introduction

As pavement design procedures are gradually making the transition from use of empirical inputs (e.g., CBR, Hveem R-value, etc.) to use of mechanistic structural analysis and design, resilient modulus (M_R) becomes a key mechanistic pavement analysis and design input for measuring the elastic response of pavement geomaterials (i.e., subgrade soil and base/subbase unbound aggregate material) under the repeated application of traffic loads. To this end, light falling weight deflectometer (LWD) has been widely used in modulus-based field compaction quality control/quality assurance (QC/QA) to reliably measure the in-situ stiffness/modulus of pavement foundation layers. Although a variety of models have been introduced and utilized in practice for backcalculating geomaterial moduli from LWD tests, most of them still suffer from some major drawbacks such as relying mainly on the static analysis of linear elastic theory for a multi-layered pavement system, and especially the incapability to consider variations of in-situ moisture levels. In reality, pavement foundation geomaterials are partially-saturated initially during the construction and/or throughout the service life, thus making their strength and stiffness greatly dependent on suction related to in-situ saturation. The primary objective of this study was to address those drawbacks affecting moduli backcalculation of foundation layers from LWD tests.

A two-dimensional (2D) axisymmetric finite element (FE) modeling approach was employed to simulate the dynamic deflection responses of pavement foundation layers subjected to the impulse loading of the LWD test. The dynamic nature of LWD loads, nonlinear material behavior, and in-situ unsaturated moisture condition were properly accounted for by using stress-dependent M_R constitutive models coupled with suction, estimated soil water characteristic curves (SWCC), and transient dynamic analysis. Results from the numerical FE models were then compared with in-situ LWD measurements recorded during field construction projects. The numerical models described could be used for establishing LWD deflection targets for road foundation layers at various moisture levels.

2 Modulus of Unsaturated Granular Materials

To model the nonlinear stress-dependent M_R behavior of unbound granular materials coupled with suction effects, the following Equation 1 was adopted in this study. First introduced for use by Siekmeier et al. (2009), the empirical factors or model coefficients in the equations were implemented subsequently in the FE simulations to produce the design charts of LWD deflection targets at varying in-situ moisture levels. Note that justifying the derivation of the underlying empirical factors is however out of the scope of this study. The origins of the M_R constitutive equation can be found elsewhere (NCHRP 2004), whereas the empirical factors used to estimate the model parameters were derived using the soil suction and index testing completed on Minnesota soils (Siekmeier et al. 2009). As it can be seen, the plastic limit (PL) was used to estimate the volumetric moisture content at saturation, and that the SWCCs were estimated using the plastic limit and a density consistent with a compaction energy delivered during a standard Proctor test (Siekmeier et al. 2009). Both PL and field moisture content were used to estimate LWD target values for compacted fine-grained soils.

$$M_R = k_1 p_a \left(\frac{\sigma_{eb} + f_s \theta_w \psi}{p_a} \right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1 \right)^{k_3} \quad (1)$$

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$$k_1 = 800 \times \left(\frac{1}{5\theta_{sat}}\right)^{1.5}\left(\frac{1}{\log_{10}(\psi)}\right);\ k_2 = \log_{10}(\psi) - 1;\ k_3 = -8\theta_{sat};\ f_s = \theta_w^{10\theta_{sat}^3};\ \theta_w = \left[1 - \frac{\ln\left(1+\frac{\psi}{\psi_r}\right)}{\ln\left(1+\frac{10^6}{\psi_r}\right)}\right] \times \frac{\theta_{sat}}{\left[\ln\left[e+(\alpha\psi)^n\right]\right]^m} \quad (2)$$

$$\psi_r = 500\sqrt{\theta_r};\ \theta_r = 1.6\theta_{sat}^2;\ \alpha = \frac{1}{(100\theta_r)^2};\ \theta_{sat} = -0.000431PL^2 + 0.0336PL - 0.162;\ n = \frac{1}{(1-m)};\ m = 0.8\theta_{sat}$$

3 Finite Element Modeling of LWD Deflection Targets

An axisymmetric dynamic nonlinear FE model was developed using Abaqus® to simulate the LWD testing on top of a geomaterial. The Dynatest LWD was modeled, as shown in Figure 1(a). Both soil and LWD loading plate were modeled by four-node isoparametric elements. The 200-mm diameter LWD loading plate was modeled using a linear elastic material rather than rigid. The simulated LWD impact consisted of a 7.0 kN force with a pulse duration of 20 msec. The example FE model results of vertical stress distribution and LWD deflection targets at varying moisture levels are shown in Figure 2(b) and 2(c), respectively. Such LWD deflection targets can be used in practice for modulus-based assessment of field compaction quality of pavement foundation geomaterials.

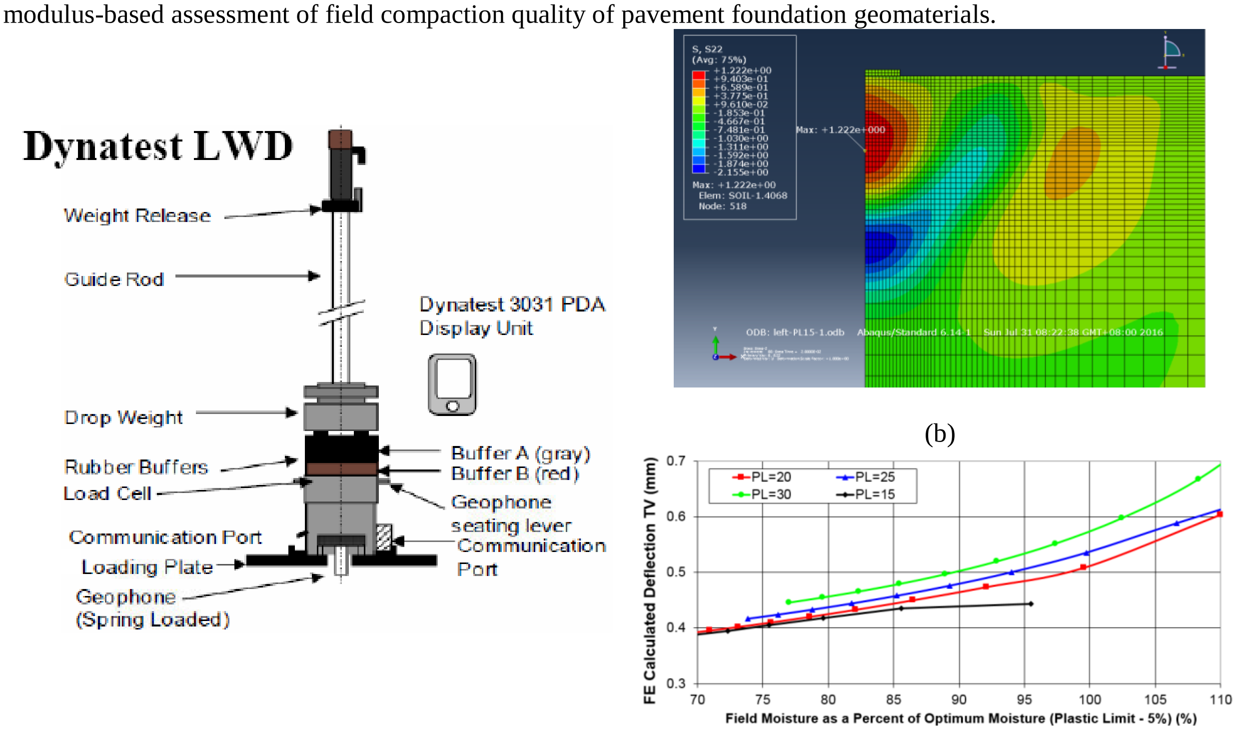

Figure 1: Schematic views of LWD device (a) and example finite element model results of (b) vertical stress distribution and (c) LWD deflection targets at varying moisture levels

References

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