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Resilient modulus prediction of soft low-plasticity Piedmont residual soil using dynamic cone penetrometer

S. Hamed Mousavi*, Mohammed A. Gabr, Roy H. Borden

Department of Civil, Construction, and Environmental Engineering, North Carolina State University, Raleigh, NC 27695-7908, USA

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A B S T R A C T

Dynamic cone penetrometer (DCP) has been used for decades to estimate the shear strength and stiffness properties of the subgrade soils. There are several empirical correlations in the literature to predict the resilient modulus values at only a specific stress state from DCP data, corresponding to the predefined thicknesses of pavement layers (a 50 mm asphalt wearing course, a 100 mm asphalt binder course and a 200 mm aggregate base course). In this study, field-measured DCP data were utilized to estimate the resilient modulus of low-plasticity subgrade Piedmont residual soil. Piedmont residual soils are in-place weathered soils from igneous and metamorphic rocks, as opposed to transported or compacted soils. Hence the existing empirical correlations might not be applicable for these soils. An experimental program was conducted incorporating field DCP and laboratory resilient modulus tests on "undisturbed" soil specimens. The DCP tests were carried out at various locations in four test sections to evaluate subgrade stiffness variation laterally and with depth. Laboratory resilient modulus test results were analyzed in the context of the mechanistic-empirical pavement design guide (MEPDG) recommended universal constitutive model. A new approach for predicting the resilient modulus from DCP by estimating MEPDG constitutive model coefficients (k_1, k_2 and k_3) was developed through statistical analyses. The new model is capable of not only taking into account the in situ soil condition on the basis of field measurements, but also representing the resilient modulus at any stress state which addresses a limitation with existing empirical DCP models and its applicability for a specific case. Validation of the model is demonstrated by using data that were not used for model development, as well as data reported in the literature.

1. Introduction

The resilient modulus of subgrade soils is a fundamental parameter in the design of pavement structures, as recommended in the mechanical-empirical pavement design guide, MEPDG (NCHRP, 2004). The resilient modulus is defined as the ratio of the applied cyclic axial stress to the recoverable axial strain (NCHRP, 2003):

$$M_r = \frac{\sigma_{cyclic}}{\varepsilon_r} \tag{1}$$

where M_r is the resilient modulus, σ_{cyclic} is the cyclic axial stress $0.9\sigma_d$, and ε_r is the resilient axial strain.

While the resilient modulus can be determined from laboratory testing, performing the test requires a well-trained operator and substantial time, as well as advanced apparatus. An alternative to laboratory testing is the use of empirical correlations developed on the basis of statistical analyses and utilizing the physical and engineering properties of soils. Carmichael and Stuart (1985), Elliott et al. (1988), Drumm et al. (1990), Farrar and Turner (1991), and Hudson et al. (1994) all proposed models to estimate the resilient modulus of subgrade soils on the basis of material index properties.

As an alternative, Hasan (1996), Rahim and George (2004), Herath et al. (2005), and Mohammad et al. (2008) have proposed correlations to predict M_r from in situ dynamic cone penetrometer (DCP) data. The advantage of using DCP is that of testing the soil in its natural density and moisture content state. These correlations, however, provide the M_r at only one specific stress state, i.e. at a confining pressure of 13.8 kPa (2 psi) and a deviatoric stress of

* Corresponding author.
E-mail address: smousav3@ncsu.edu (S. Hamed Mousavi).
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41.7 kPa (6 psi). These values represent the stress level at the top of the subgrade layer under standard single axle loading of 80 kN (18 kips) and tire pressure of 689 kPa (100 psi) with a 50 mm asphalt wearing course, a 100 mm asphalt binder course and a 200 mm aggregate base course (Asphalt Institute, 1989; Rahim and George, 2004; Mohammad et al., 2008). Since the resilient modulus depends on the confining pressure and applied deviatoric stress, any change in the pavement structure, axle load and tire pressure will lead to a change in the stress state at the surface of the subgrade. Accordingly, the predicted M_r by existing correlations may not be representative of the field stress conditions.

On the other hand, many studies have been performed over the past two decades to model the stress dependency of the resilient modulus by predicting the coefficients of a general constitutive model (e.g. Dunlap, 1963; Seed et al., 1967; Witczak and Uzan, 1988; Pezo, 1993; NCHRP, 2003) on the basis of soil index properties. These properties included water content, w, plastic limit, PL, liquid limit, LL, percentage passing the No. 4 sieve, P_4, and percentage passing the No. 200 sieve, P_{200}, etc. Yau and Von Quintus (2002), Elias and Titi (2006), Nazzal and Mohammad (2010), and Titi and English (2011) have each proposed different models to estimate the NCHRP (2004) constitutive model coefficients (k_1, k_2 and k_3), expressed in Eq. (2); however, these models have been developed based on the compacted specimens and do not consider the properties of the undisturbed soil in its natural state.

$$M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau}{P_a} + 1\right)^{k_3} \tag{2}$$

where P_a is the atmospheric pressure; σ_1, σ_2 and σ_3 are the principal stresses, $\theta = \sigma_1 + 2\sigma_3$ is the bulk stress; $\tau = (\sqrt{2}/3)(\sigma_1 - \sigma_3)$ is the octahedral shear stress; k_1, k_2 and k_3 are the regression constants.

In the MEPDG recommended model, M_r is linearly influenced by k_1, while the exponents k_2 and k_3 respectively define the rate of increase and decrease of stiffness hardening and soil softening (Yau and Von Quintus, 2002) with respect to the confining and deviatoric stresses. However, as currently formulated, all three coefficients are independent of the stress state.

This paper includes a review of models that are based on correlating k_1, k_2 and k_3 to basic soil properties. This is the context of the proposed approach, albeit using dynamic cone penetration index (DCPI) instead of basic soil properties. A model is proposed in this paper to calculate the resilient modulus of the low-plasticity Piedmont residual subgrade soils from the DCP data. Piedmont residual soils are in-place weathered soils from igneous and metamorphic rock, as opposed to transported or compacted soils. Hence the existing empirical correlation might not be applicable for these soils (Borden et al., 1996). The model is developed based on the in situ DCP measurements and laboratory resilient modulus on the undisturbed specimens retrieved from Shelby tubes. The model is based on calculating M_r to predict the constitutive model coefficients (k_1, k_2 and k_3) from the in situ DCP data. By utilizing in situ measured DCP data in predicting the constitutive model coefficients, the proposed approach allows for taking into account the stress dependency of the resilient modulus, as well as properties of the soil in its natural state. The validity of the proposed model is examined with the portion of data set not used in the model development, as well as reported data in the literature.

2. Background

DCP is a portable instrument widely used in geotechnical and pavement design for estimating the shear strength and stiffness properties of soils (Gabr et al., 2000, 2001; Chen et al., 2005). As shown in Fig. 1, and presented in ASTM D6951-09 (2009), DCP consists of an 8 kg sliding hammer, with a 57.5 cm (22.6 in) drop height, a 111 cm (44 in) driving shaft and a 60° angle cone tip. During the DCP test, the sliding hammer falls 57.5 cm vertically and drives the cone tip attached to the bottom of the DCP rod into the ground. The penetration depth is recorded after each drop (blow) on a vertical stake positioned next to the DCP rod. DCPI is expressed in inch or mm per blow.

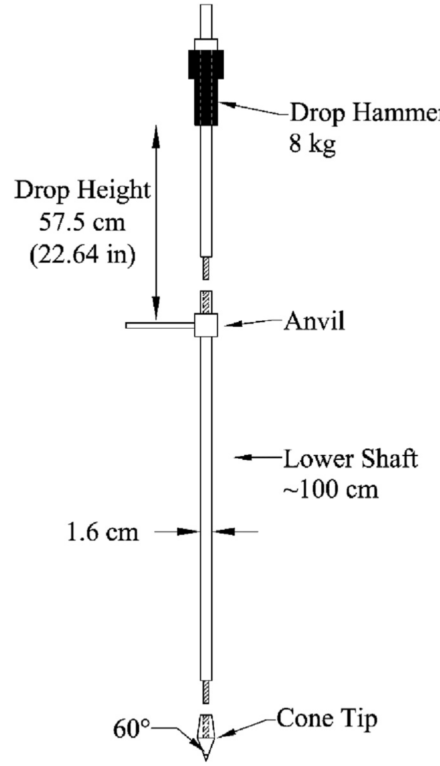

Fig. 1. DCP sketch (after ASTM D6951-09, 2009).

Several correlations have been proposed in the literature between DCPI, soil shear strength and stiffness properties, such as those for the California bearing ratio (CBR) (NCDOT, 1998; Gabr et al., 2000), the undrained shear strength (S_u) (Ayres, 1997), the elastic modulus (E) (Chai and Roslie, 1998; Abu-Farsakh et al., 2004; Chen et al., 2005), and the resilient modulus (M_r) (Hasan, 1996; Herath et al., 2005).

Existing empirical correlations, which correlate DCPI to M_r, are summarized in Table 1. These models are capable of providing an estimate of stiffness properties of soils; however, they are restricted to a confining pressure of 13.79 kPa (2 psi) and a deviatoric stress of 41.37 kPa (6 psi).

3. Experimental program

The experimental program included a series of laboratory resilient modulus and in situ DCP tests. The sampling and field testing programs were performed at four 4.88-m (16-ft) wide by 15.24-m (50-ft) long test sections located in the Piedmont area, North of Greensboro, North Carolina. The DCP tests were performed at four locations in each test section, as shown in Fig. 2. The laboratory testing, including the resilient modulus and index properties, was performed on undisturbed soil specimens retrieved from Shelby tubes. These tubes were taken from boreholes located between each pair of DCP tests, as indicated in Fig. 2. More details on

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