Soils and Foundations 2014;54(1):36–44

The Japanese Geotechnical Society

Soils and Foundations

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journal homepage: www.elsevier.com/locate/sandf

Comparison of numerical and experimental responses of pavement systems using various resilient modulus models

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Received 1 September 2012; received in revised form 23 May 2013; accepted 15 June 2013
Available online 18 January 2014

Abstract

The accuracy of the structural design of flexible pavements based on mechanistic approaches is directly related to the appropriateness of the structural response algorithm and the material resilient modulus models selected. Mechanistic response algorithms can be based on layered theory or finite element algorithms. The geomaterials can be modeled as linear or nonlinear. To evaluate the appropriateness of the numerical models and the available resilient modulus models for estimating the response of pavements, several small-scale pavements were constructed and tested under different loads, loading areas and moisture conditions. A nonlinear numerical structural model was then utilized with different resilient modulus models to match the experimental responses. With some modifications, a three-parameter nonlinear model provided the same patterns as the experimentally measured values as long as the weight of the material was considered. In all cases, a transfer function was necessary to accommodate the differences in stiffness properties due to the differences between the field and the laboratory compaction methods.

Keywords: Resilient modulus models; Pavement response; Unbound materials; Light weight deflectometer; Plate load test; IGC: D00; D09; E02

1. Introduction

The development and implementation of mechanistic pavement design approaches, such as the Mechanistic-Empirical Pavement Design Guide (MEPDG) in the United States, have been vigorously pursued over the last 20 years. In a mechanistic approach, the relationship between the structural response (stress, strain or deflection) and the physical parameters is described through a numerical model. Brown (1996) discussed a spectrum of analytical and numerical models that can be used for this purpose. The models are incorporated in several well-known computer programs with different levels of sophistication.

Multi-layer linear systems are the most common algorithms used. In these models, the basic assumptions include that each layer is homogeneous, isotropic and linearly elastic, and that the material is massless. Multi-layer nonlinear systems, which are the most comprehensive approaches for studying pavement responses, can only be implemented through advanced numerical analyses, such as finite element methods. Multi-layer equivalent-linear models are a compromise between the multi-layer and the finite element options. These models utilize the multi-layer linear elastic layered theory combined with an iterative process to consider the nonlinear behavior of the pavement materials in an approximate fashion (Ke et al., 2000). Since the lateral variation in modulus within a layer cannot be considered in a linear-elastic layered solution, a set of stress points at different radial distances are considered to compensate for this disadvantage to some extent.

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Peer review under responsibility of The Japanese Geotechnical Society.

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http://dx.doi.org/10.1016/j.sandf.2013.12.004

The material-related input parameters for the pavement response models are primarily the stiffness parameters and Poisson′s ratio for each pavement layer. The resilient modulus model for a linear elastic material is rather simple, since the stiffness parameter is a modulus that is independent of the state of stress applied to the pavement. Bounded materials (e.g., hot mix asphalt and stabilized layers) generally display a linear or a nearly linear stress–strain relationship. Unbound geomaterials can exhibit nonlinear and anisotropic behaviors. A material is considered nonlinear if its modulus depends on the state of stress. The nonlinear behavior of granular materials may be explained by hyperbolic constitutive relationships (Maheshwari and Khatri, 2012). Granular materials generally exhibit stress-hardening behavior as their stiffness increases with an increase in stress. Fine-grained soils, which generally display a decrease in modulus with an increase in stress, are defined as stress-softening.

Resilient modulus (MR) tests are commonly used to measure the stiffness parameters of materials. In general, these tests measure the stiffness of a cylindrical specimen subjected to numerous repeated axial stresses and confining pressures. Cyclic load triaxial tests have also been employed in geotechnical and railway studies by many researchers, such as Fortunato et al. (2010), Trinh et al. (2012), Inam et al. (2012), Dash et al. (2010) and Youngji et al. (2010). The most commonly applied resilient modulus models are the so-called universal models that relate the modulus to the deviatoric stress, confining pressure or a combination of them (Puppala, 2007). Andrei et al. (2004) recommended the following equation to determine the resilient modulus:

$$MR = k_1 P_a \left[\frac{\theta - 3k_6}{P_a}\right]^{k_2} \left[\frac{\tau_{oct}}{P_a} + k_7\right]^{k_3} \tag{1}$$

where MR = resilient modulus, P_a = atmospheric pressure, θ = bulk stress, τ_{oct} = octahedral shear stress and k_1 through k_7 are regression constants. Parameter k_6 is intended to account for pore pressure or cohesion; it is a measure of the material′s ability to resist tension. Even though Eq. (1) is fundamentally appealing, Eq. (2) (a.k.a., the $k_1 - k_3$ model) is more widely used.

$$MR = k_1 P_a \left[\frac{\theta}{P_a}\right]^{k_2} \left[\frac{\tau_{oct}}{P_a} + 1\right]^{k_3} \tag{2}$$

The procedure for conducting MR tests has been under continuous modification. The American Association of State Highways and Transportation Officials (AASHTO) alone have adopted several test protocols over the last 20 years (e.g., T292-91, T294-92, TP46-94 and T307-03). The so-called NCHRP 1-28A (Witczak, 2004) protocol is also gaining popularity. These approaches differ in specimen size, the compaction method, loading time, stress sequence, and type and location of the displacement transducers (i.e., inside or outside the confining chamber and mounted on the specimen or platen-to-platen measurements). As such, they may yield different $k_1 - k_3$ values. For example, Gupta et al. (2007) indicated that the resilient moduli from internal displacement measurements are up to three times greater than those made outside the confining cell.

The main objective of this paper is to demonstrate the implication of various MR test methods and resilient modulus models on the accuracy and the reliability of the prediction of the response parameters (e.g., displacements) of pavement layers. The secondary objective is to discuss the need for transfer functions between the measured and the estimated responses of geomaterials prepared to the same densities and moisture contents as the MR laboratory specimens. To that end, several model pavements were constructed and tested under different loads, loading areas and moisture conditions with different sources of geomaterials. Nonlinear numerical structural models were then utilized with different resilient modulus models to match the experimental responses. The results of that investigation are presented in this paper.

2. Laboratory testing

Laboratory resilient modulus tests are used to determine the impact of load-related parameters that affect the behavior of pavement layers. Such tests consist of applying cyclic axial loads at different confining pressures to a cylindrical specimen. The resilient modulus is then defined as the ratio of the applied deviatoric stress and the resulting axial resilient (recoverable) strain (Andrei et al., 2004). The focus of this study is a granular base and four fine-grained soils with the index parameters shown in Table 1. Table 1 also contains information related to an SM soil that was used as common subgrade in all the small-scale specimens prepared in this study. MR tests for all geomaterials were carried out as per AASHTO T307 (but with internal load and displacement sensors) and additionally as per NCHRP 1-28A (for granular base materials only).

Two compaction methods were used to prepare the specimens: constant energy and constant density. The constant energy method (a.k.a., the Proctor method) has been the traditional means of estimating the moisture–density curve for at least the

Table 1
Index properties and classification of geomaterials.

Material	USCS classification	Gradation %			Atterberg limits		Moisture density[a]	
		Gravel	Sand	Fines	LL	PI	OMC[b], %	MDD[c], kg/m^3
Granular base	GW	60	30	4	13	9	5.7	2356
Fine-grained soils	CL	8	28	64	27	14	10.0	1996
	CH	0	3	97	86	53	25.9	1533
	ML	0	42	59	NP[c]	NP	9.4	1995
	SC	0	55	45	23	12	11.4	1945
Common subgrade	**SM**	**0**	**73**	**27**	**NP[d]**	**NP**	**15.2**	**1794**

[a]From modified Proctor test (AASHTO T180) for granular base and standard Proctor test (AASHTO T99) for fine-grained soils.
[b]OMC = Optimum Moisture Content.
[c]MDD = Maximum Dry Density.
[d]NP = Non-Plastic.