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International Journal of Pavement Research and Technology xxx (2017) xxx–xxx

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Quasi-static analysis of flexible pavements based on predicted frequencies using Fast Fourier Transform and Artificial Neural Network

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Received 13 July 2016; received in revised form 6 September 2017; accepted 11 September 2017

Abstract

New trend in design of flexible pavements is mechanistic-empirical approach. The first step for applying this method is analyzing the pavement structure for several times and computation of critical stresses and strains, which needs a fast analysis method with good accuracy. This paper aims to introduce a new rapid pavement analysis approach, which can consider the history of loading and rate effect. To this end, 1200 flexible pavement sections were analyzed, and equivalent frequencies (EF) were calculated using Fast Fourier Transform (FFT) method at various depths of asphalt layer. A nonlinear regression equation has been presented for determining EF at different depths of asphalt layer. For more accurate predicting of EF at low frequencies, a feed-forward Artificial Neural Network (ANN) was employed, which allows accurate prediction of EF. The frequencies obtained by the proposed regression equation and ANN were compared with frequencies observed in Virginia Smart Road project, and it was found that there is a good agreement between observed and predicted frequencies. Comparison of quasi-static analysis of flexible pavements by frequencies obtained using FFT method and full dynamic analysis by 3D-Move program approves that the critical responses of pavement computed by proposed quasi-static analysis approach are comparable to critical responses computed using full dynamic analysis.

Keywords: Equivalent frequency; Fast Fourier Transform (FFT); Pavement quasi-static analysis; Dynamic modulus; Artificial Neural Network (ANN)

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1. Introduction

Accurate prediction of pavement responses and performance is critical to improve the design of new and existing pavements. Poor performance contributes to reduced pavement life and costly maintenance due to frequent repairs. Several developments over recent years have offered a potential for more rational and rigorous pavement design procedures. Improved material characterization and constitutive models make it possible to incorporate some material characteristics such as non-linearity and rate effects [1]. These achievements provided the technical foundation that made possible for the development of the mechanistic-empirical pavement design approach which is used by several countries for design of pavements [2–5]. This approach provides a more realistic characterization of both flexible and rigid pavements and provides uniform guidelines for designing of different types of pavements.

In order to consider the effect of loading time on dynamic properties of asphalt mixtures, in mechanistic-empirical pavement design methods such as MEPDG program, usually a quasi-static analysis instead of dynamic

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Peer review under responsibility of Chinese Society of Pavement Engineering.

https://doi.org/10.1016/j.ijprt.2017.09.002
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Please cite this article in press as: A.R. Ghanizadeh, M. Fakhri, Quasi-static analysis of flexible pavements based on predicted frequencies using Fast Fourier Transform and Artificial Neural Network, Int. J. Pavement Res. Technol. (2017), https://doi.org/10.1016/j.ijprt.2017.09.002

analysis is employed [2]. In quasi-static approach, asphalt materials were considered as linear elastic material. To this aim, it is required to determine the loading frequency and temperature at different depths of asphalt layer. Knowing loading frequency and temperature of asphalt mixture at a specific depth, dynamic modulus of asphalt mixture at that depth can be determined using dynamic modulus master curve of asphalt concrete. This dynamic modulus is then employed in pavement analysis using layered elastic theory. In the field of pavement engineering, commonly the loading time is calculated and then converted to frequency. Since the NCHRP Project 1–37A released the MEPDG in 2004, several concerns about the HMA dynamic modulus have been raised. For example, Brown et al. [6] noted in the NCHRP Research Results Digest 307 that "in its present form, the guide procedure for estimating complex modulus in the HMA layers results in unrealistic values, particularly for thick layers, showing a decrease in predicted modulus with depth in hot weather that is counterintuitive. This quandary results from the loading time/frequency effect overriding the temperature effect." In the MEPDG, the pavement temperature is well modeled by the enhanced integrated climatic model (EICM). Thus, all the issues on HMA modulus are related to the loading time, which has been a topic discussed in recent years [7–10].

In 1971, Barksdale [11] used finite element modeling and elastic theory to calculate the vertical compressive stress pulse width as a function of speed and depth. He found that the pulse shape varies from approximately a sinusoidal one at the surface to more nearly a triangular one at depths below approximately the middle of the base. The pavement geometry was found not to affect the pulse shape and duration. Change of the resilient modulus values of the pavement materials due to change in environment was found also not to affect the pulse shape and duration. With these findings, Barksdale developed a chart of the vertical sinusoidal and vertical triangular pulses time as a function of vehicle speed and depth beneath the pavement surface. Brown [12] derived an equation to calculate the loading time as a function of both vehicle speed and depth beneath the pavement surface. The loading time was considered as the average of the pulse times of the stresses in the three directions as obtained from the elastic layered theory. The relationship between the loading time t (s), depth d (m), and vehicle speed V (km/h) is as follows:

$$\log(t) = 0.5\mathrm{d} - 0.2 - 0.94\log(V) \tag{1}$$

The loading time as defined in Eq. (1) is equal to the inverse of the angular frequency of the applied sinusoidal wave. Brown [13] showed that his loading time is equal to 0.48 times the loading time as defined by Barksdale. In 1974, McLean [14] developed a chart to determine the pulse width of an applied square wave as a function of vehicle speed and depth underneath the pavement surface. The pulse time of the square wave is shorter than that of the triangular or sinusoidal pulse [15]. In MEPDG, loading frequency is determined based on the length of vertical stress pulse produced at desired depth and calculated using equivalent thickness method [2]. Regarding that all layers have the same modulus under this condition, the stress distribution angle is constant throughout pavement depth and is considered equal to 45 degrees (Fig. 1). Effective depth is calculated using Eq. (2).

$$Z_{\mathrm{eff}} = \sum_{i=1}^{n}\left(h_i\sqrt[3]{\frac{E_{\mathrm{i}}}{E_{\mathrm{SG}}}}\right) + h_n\sqrt[3]{\frac{E_n}{E_{\mathrm{SG}}}} \tag{2}$$

where, Z_{eff} denotes effective depth, E_{i} is modulus of ith layer, h_{i} is thickness of ith layer and E_{SG} and h_n represent stiffness modulus of subgrade and thickness of the layer at which desired point is located, respectively. For example, if the effective depth is considered for the middle point of third layer, the value of n will be 3 and $h_n = h_3/2$.

After calculation of effective depth, loading pulse time (t_{p}) is measured using Eq. (3):

$$t_{\mathrm{p}} = \frac{2(a + Z_{\mathrm{eff}})}{V} \tag{3}$$

where a and V denote contact radius and speed of moving wheel, respectively.

The Caltrans Mechanistic-Empirical Flexible Pavement Design program (CalME), makes use of the Ullidtz [16] relation for calculating the loading pulse time, which is a different approach compared that utilized by the NCHRP 1–37A.

$$t_{\mathrm{p}} = \frac{2(a + Z)}{V} \tag{4}$$

In this equation, Z represents the actual depth in the pavement structure. Hu et al. [17], found that the loading time is not only a function of the vehicle speed and the depth beneath the pavement surface but is also a function of the moduli ratio between the layer of interest and the immediate succeeding layer below. Furthermore, they found that the loading waveform changes with depth beneath the pavement surface and the moduli ratio. They proposed some equations for determining the loading time and loading waveform, which is a function of HMA thickness, the depth beneath the pavement surface and the moduli ratio. Al-Qadi et al. [8] used viscoelastic 3D finite

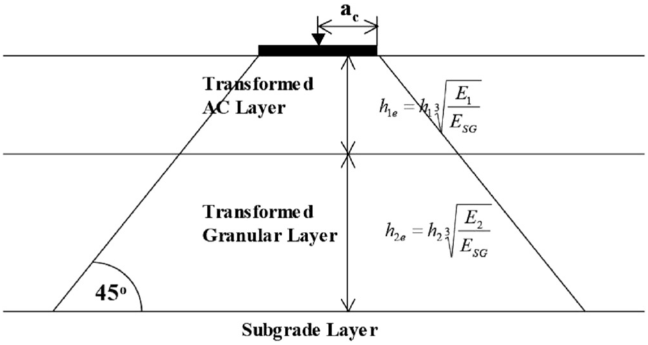

Fig. 1. Calculation of effective depth by equivalent thickness of layers [2].

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