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Viscoelastic response modelling of a pavement under moving load

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Abstract

This paper demonstrates the application of a generalized layered linear viscoelastic (LVE) analysis for estimating flexible pavements' structural response. The procedure is based on the Multi-Layered Elastic Theory (MLET) and the elastic-viscoelastic correspondence principle using a numerical inverse Laplace transform. A comparison of the direct layered viscoelastic responses with approximate solutions based on the elastic collocation method was also carried out. Furthermore, it is proposed to use the collocation method using LVE solutions at selected time durations in order to improve the accuracy of the elastic collocation method. The LVE collocation method was further extended for analysis of moving loads. The method was illustrated by analysing a pavement structure subjected to moving wheel loads of 30, 50, 60 and 80 kN using a Heavy Vehicle Simulator (HVS). The various responses (stresses and strains) in the pavement, at different pavement temperatures, were measured using various types of sensors installed in the structure. The LVE calculations agreed very well with the measurements.

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Keywords: Viscoelasticity; elastic-viscoelastic principle; layered elastic theory; accelerated pavement testing

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1. Introduction

In Mechanistic-Empirical (M-E) pavement design and performance prediction procedures a mathematical model is used to calculate the pavement responses under traffic loading and prevailing environmental conditions. The responses are then related to the performance of the pavement through transfer functions. Frequently the Multi-Layered Elastic Theory (MLET) (Burmister 1943, 1945) is employed to calculate the responses of layered systems under concentrated or distributed loading (Huang 1968, Bufler 1971, Maina and Matsui 2005, Khazanovich and Wang 2007, Erlingsson and Ahmed 2013).

It is well known that asphalt mixtures exhibit unique characteristics of both viscous and elastic properties, and hence are categorized as viscoelastic materials. Moreover, understanding the viscoelastic properties of asphalt mixtures are important to achieve performance-based structural design of bituminous layers (NCHRP 2004). Therefore it is important to extend the theory of MLET to account for the effect of viscoelasticity. This can be accomplished through the elastic-viscoelastic correspondence principle in which the elastic solution is used to derive solutions of linear viscoelastic (LVE) problems.

Erlingsson and Ahmed (2013) introduced a method to improve the computational performance of MLET. The MLET was developed for use in the M-E performance prediction program for flexible pavement structures. The main objective of the study presented here is to extend this work for problems involving LVE materials such as asphalt mixtures. Finally, as viscoelastic materials such as asphalt mixes possess time-dependent or rate sensitive stress-strain relations, their stress-strain relationship will change as the loading speed (or strain rate) changes. The viscoelastic solution is therefore extended to simulate the response of layered systems subjected to a moving wheel load.

2. Linear viscoelastic analyses

Flexible pavement structures consist of layers of finite thickness resting on half space. The top layers are bitumen bounded aggregate layers that are highly viscoelastic in nature when subjected to heavy traffic loading. Below are aggregate and soil layers that can be treated as elastic or elastic-plastic material layers. The mechanical response of such systems can be analysed with the aid of the MLET.

The axisymmetric layered elastic responses (stresses and displacements) under concentrated load can be obtained from a stress function ϕ that satisfies boundary and continuity conditions (Timoshenko and Goodier 1951, Huang 2004):

$$\begin{bmatrix} \sigma_z^c \\ \sigma_r^c \\ \sigma_t^c \\ \tau_{rz}^c \\ w^c \\ u^c \end{bmatrix} = \begin{bmatrix} (2-\nu)\frac{\partial}{\partial z} & -\frac{\partial^3}{\partial z^3} \\ \nu\frac{\partial}{\partial z} & -\frac{\partial}{\partial z}\frac{\partial^2}{\partial r^2} \\ \nu\frac{\partial}{\partial z} & -\frac{\partial}{\partial z}\frac{1}{r}\frac{\partial}{\partial r} \\ (1-\nu)\frac{\partial}{\partial r} & -\frac{\partial}{\partial r}\frac{\partial^2}{\partial z^2} \\ \frac{1+\nu}{E}(1-2\nu) & \frac{1+\nu}{E}\left(\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}\right) \\ 0 & -\frac{1+\nu}{E}\left(\frac{\partial^2}{\partial r \partial z}\right) \end{bmatrix} \begin{bmatrix} \nabla^2\phi \\ \phi \end{bmatrix} \tag{1}$$

where σ_z^c, σ_r^c and σ_t^c are normal stresses in vertical, radial and tangential directions, respectively; τ_{rz}^c is the shear stress; and w^c and u^c denote the vertical and radial deflections, respectively. The superscript c indicates responses for concentrated load; ν and E are Poisson's ratio and elastic modulus, respectively.

The responses under uniform contact pressure q distributed over a circular area of radius a are then derived from the integral: