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Dynamic inelastic analysis of 3-D flexible pavements under moving vehicles: A unified FEM treatment

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ABSTRACT

The dynamic response of flexible road pavements to moving vehicles is numerically obtained by the time domain finite element method under three-dimensional conditions with the aid of the commercial program ANSYS. The pavement structure is modeled as a system of three layers with the top one (asphalt concrete) exhibiting viscoelastic or viscoplastic and the other two elastic or elastoplastic Drucker-Prager material behavior. The dimensions of the pavement domain, its degree of discretization, its kind of boundaries (rollers everywhere) and the appropriate time step are selected to provide solutions of acceptable accuracy in an efficient manner. Symmetry considerations are also taken into account. The moving with constant speed distributed loads (wheels) of the vehicle are simulated by assigning time dependent load values at all the pavement surface nodes along the vehicle path, which are activated at the time it takes for every load to travel the distance from the origin to every node's location. Comparisons of the dynamic response results in terms of deflections, stresses and strains of the above inelastic models against those corresponding to elastic material behavior under moving or static loads as well as those coming from two field experiments are made and useful practical conclusions are drawn.

1. Introduction

Since the early 1980's analytical and experimental research on the analysis and design of flexible pavements has been intensified, as it is evident in the books of Huang [1] and Cebon [2] dealing with both rigid and flexible pavements as well as the book of Ulidtz [3] and the recent review article of Monismith [4] dealing with flexible pavements. The importance of considering the dynamic character of the problem in order to have more realistic results has also been stressed during the last 35 years or so, as described in the recent review paper of Beskou and Theodorakopoulos [5] on both rigid and flexible pavements.

Originally, the layered system for modeling the flexible pavement was assumed to exhibit linear elastic material behavior and be subjected to static, stationary, distributed load. Then, the load was assumed to be stationary but dynamic (impact load) to simulate the experimental process of deflectometry. Finally, the load was considered to be constant or time dependent and moving. A good review on the above subject concerning linear elastic material behavior can be found in the very recent work of Beskou et al. [6].

Elastic material behavior simplifies the problem of determining the pavement response, provides a good insight into the phenomenon and even allows for hand computations if the load is static and stationary [1,3,6]. Of course, for problems with realistic boundary conditions and dynamic and/or moving load, even for elastic material behavior in all the layers, use of numerical methods of solution, such as the finite element method (FEM) is necessary [6]. However, elastic solutions represent an approximation and are not close to experimental results. It is obvious that inelastic material behavior is required in order to achieve more realistic simulations and obtain response results closer to the experimental ones.

Use of linear viscoelastic material behavior for the top asphalt concrete layer, while retaining all the other layers linear elastic, certainly improved the results [7–13] but there was still a difference between analytical and experimental results of about 15% [8,11,12]. In the above works, use was made of either the three-dimensional (3-D) method of a system of horizontal layers in the frequency domain [7,11], or the 3-D time domain FEM under moving (dynamic) or quasi-static loads. Quasi-static loads are time- dependent but applied statically, resulting in more efficient procedures than in cases with moving loads at the expense of neglecting the pavement structure inertia and damping. However, this negligence may reduce the response by 10–39% [10]. Further improvements were achieved by using viscoelastic material

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behavior for the top layer and non-linear elastic one for the other layers. More specifically, this nonlinear behavior was simulated by using stress-dependent moduli and employment of iterations to obtain convergent response results. One can mention here the works of Huang [1], Duncan et al. [14], Taylor [15], Elliott and Thompson [16], Harichandran et al. [17], Balay and Kabre [18], Guezouli et al. [19], Van Schelt et al. [20], Gomes Correia and de Almeida [21], Helwany et al. [22], Hadi and Bodhinayake [23], Kim [24], Kim et al. [25], Steven et al. [26] and Al-Qadi et al. [27]. In almost all the above cases use was made of the FEM under two-dimensional (2-D) or three-dimensional (3-D) conditions and the load was assumed to be a stationary and static one with the exception of references [22], where the load is moving and [26,27], where it is dynamic, but stationary (impact load). A comparison between linear elastic and non-linear pavement models has been reported by Chen et al. [28].

A more rational way to describe non-linear material properties is by using theories of plasticity and viscoplasticity. Thus, Zaghloul and White [29], Zaghloul et al. [30] and White et al. [31] assumed linear viscoelastic material behavior for the top layer and elastoplastic one of Drucker-Prager and Cam-Clay types for the base and subgrade layers, while Sukumaran et al. [32] elastic material behavior for the top layer and elastoplastic one of the Mohr-Coulomb type for the other layers. In [29–32] use was made of the 3-D FEM and the loads were assumed to be moving ones with constant speed, except in [30] where the load was dynamic but stationary. Weissman and Sousa [33], Fang et al. [34,35], Shen and Kirkner [36], Saad et al. [37], Johnson et al. [38], Ali et al. [39] and Huang et al. [40] also considered non-linear behavior of the layers: viscoplastic in all layers in [33–35], viscoplastic in the top layer and linear elastic [40] or Drucker-Prager elastoplastic [38,39] in the other layers and elastic in the top layer and Drucker-Prager [36] or Drucker-Prager and Cam-Clay elastoplastic [37] in the other layers. In [32–40] use was made of 2-D and 3-D FEM and the loads were assumed to be quasi-static ones.

In this work a 3-D finite element methodology is developed with the aid of the commercial software ANSYS [41] for the determination of the time domain response of inelastic layered flexible pavements to moving loads on their surface. The asphalt concrete top layer is modeled as a viscoelastic or viscoplastic material, while the other two layers (base and subgrade) are modeled as elastic or elastoplastic Drucker-Prager materials. It should be noted that the term 'inelastic' is used here in a broader sense (non-elastic) and includes linear viscoelastic material behavior. The dimensions of the pavement domain, its degree of discretization, its kind of boundaries (rollers everywhere) and the appropriate time step are selected to provide solutions of acceptable accuracy in an efficient manner. This is done on the basis of work reported in [6] for the case of linear elastic material behavior. However, in the present work, the time step values finally selected are smaller than the ones in [6] because of the nonlinearities of the problem.

The wheel loads of the vehicle are assumed in this work to be distributed constant in magnitude loads moving with constant speed. They are simulated by assigning time dependent load values at all the domain surface nodes along the vehicle path, which are activated at the time it takes for every load to travel the distance from the origin to every node's location. This is a more natural and realistic way to model vehicular load than by assuming the loads to be stationary or move quasi-statically without taking inertia and damping effects into account.

The above methodology is validated with the aid of two field experiments and compared against methods assuming linear elastic material behavior and static or moving loads. On the basis of these studies, useful practical conclusions are drawn.

2. Fem modeling in space and time

This section deals with the finite element modeling of the pavement structure, the modeling of the moving vehicle loads and the finite element solution in the time domain. The first two subsections actually represent a summary of two full sections in [6] and are described here for reasons of completeness. The third subsection is an extension of the time domain solution from the elastic [6] to the present inelastic case.

2.1. Finite element modeling of pavement structure

The typical three-dimensional (3-D), three layer flexible road pavement structure model used in [6] for dynamic linear elastic analyses, is adopted here for the present dynamic inelastic analyses in a slightly modified form. The modification consists of reducing the travel distance AB (Fig. 1) from 12.00 m in [6] to just 3.60 m here in order to reduce the simulation time, which is much higher here due to the nonlinear nature of the problem. The model, as shown in Fig. 1, has dimensions 29.45 m along the vertical z direction, 15.00 m along the lateral (transverse) y direction and 30.00 m along the longitudinal x direction. It consists of three layers fully bonded to each other with the top one being the asphalt concrete layer of thickness 0.15 m, the intermediate one the granular base layer of thickness 0.30 m and the bottom one the subgrade layer of thickness 29.00 m. It should be noticed that the lateral face of the model designated by the zx plane is a plane of symmetry and that the x axis represents the axis of the road pavement (Figs. 1 and 2). The above model is supported at its bottom and its three lateral faces (its fourth face is the plane of symmetry zx) by rollers as described in detail in [6]. Adoption of rollers at the boundaries has been found in [6] to provide almost the same response results with those obtained by using viscous absorbers at the boundaries for the selected domain dimensions and linear elastic material behavior. The above pavement structure is descretized into a finite number of 8-noded 3-D solid elements (bricks) with 24 in total degrees of freedom (SOLID 185 type in ANSYS [41] program). The finite element mesh is shown in Fig. 2 and consists of 82080 elements or 88257 nodes (3*88257 = 264771 degrees of freedom).

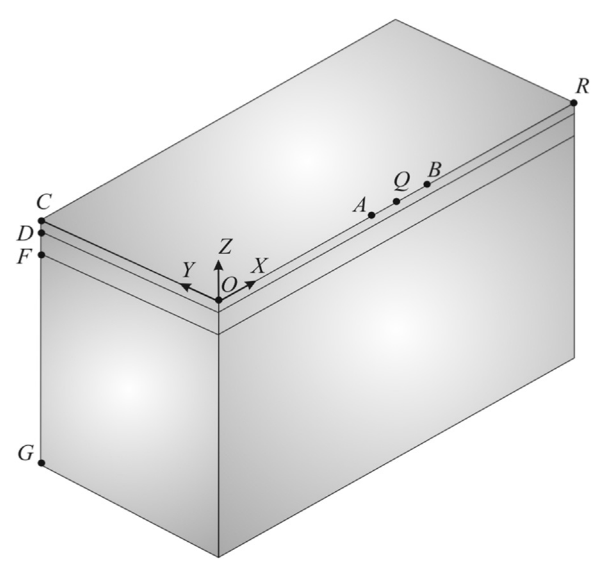

Fig. 1. General geometry of half of pavement structure domain (symmetry with respect to the X–Z plane): (OA = BR = 13.20 m, AQ = QB = 1.80 m, OR = 30.00 m, OC = 15.00 m, CD = 0.15 m, DF = 0.30 m, FG = 29.00 m).