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SYNOPSIS Two important applications of a recently developed moving load model are described. The model uses an efficient semianalytical "finite layer" formulation of the porous medium. One application is a response of a layered sandy nonlinear porous medium, while the other is a viscoelastic pavement layer system. The study reveals that the properties of the layers and porefluid and the moving velocity of the load are important factors that affect the response of the layered system.

INTRODUCTION

The dynamic response of layered media subjected to moving surface loads is of great interest to many engineers and researchers. For example, engineers need to understand the behavior of soil deposits to traveling surface pressure waves created by gas or nuclear explosions occurring at the surface to design underground bunkers and other protective facilities. Knowing the response of pavement structures and rail beds is essential in the design of such systems and also in the study of traffic-induced ground-born vibrations. There are many other applications. For example, biomedical engineers study the response of articulating cartilage and often model its behavior using a dynamic moving load across a porous media.

Recently, a computationally efficient semianalytical "finite layer" model has been developed by the first author and his coworkers (Siddharthan et al., 1993a,b). The model uses Biot's formulations for porous medium where the layered system can be saturated, unsaturated, or a combination of both. The approach can handle complex surface loading such as multiple loads and nonuniform loaded areas. Though the layered system can be elastic or viscoelastic, nonlinear hysteretic behavior can also be accommodated using an equivalent (iterative) elastic procedure. The original plane strain model has also been extended to include moving recangular loads (Zafir et al., 1994). The predictive capability of this model and the associated computer code have been verified using laboratory model tests and available classical solutions (Siddharthan et al., 1993b).

This paper describes two very important applications of the model described above: (1) the response of a layered nonlinear porous medium subjected to a moving strip load and (2) the response of pavement structures to moving semitrailer loads.

BRIEF DESCRIPTION OF THE MOVING LOAD MODEL

Siddharthan et al. (1993a,b) and Zafir et al. (1994) reported on the formulation of a continuum-based "finite layer" model to evaluate the response of a layered system subject to moving surface loads. Complex surface loadings, such as multiple loads and nonuniform surface pressures, can be handled relatively easily since the method uses the Fourier transform technique. The layered system may be characterized as consisting of a number of elastic or viscoelastic horizontal layers (as many as necessary) with each layer characterized using a set of uniform properties. Such a representation is needed to model cohesionless soil behavior since it exhibits strong stress and, thus, depth-dependent material behavior. Each layer's properties are defined in terms of Young's modulus (or shear modulus), Poisson's ratio, and material damping. In the case of viscoelastic layers, the above properties will be a function of frequency. The approach accounts for important factors such as the two-dimensional nature of wave propagation, the effects of inertia and damping, and the compressibility of porefluid. Further, the nonlinear hysteretic behavior of the layers can also be considered using an iterative elastic approach. For more details on the formulation of and a description of the model, see Siddharthan et al. (1993a,b) and Zafir et al. (1994).

Since the surface load moves at a constant speed, c, and the layer properties do not vary in the horizontal direction, any response, for example, the displacement (u) using Fourier transform, can be written as

$$u = u(x - ct) = Re \sum_{n=0}^{N} U_n e^{i\lambda_n (x-ct)} \qquad (1)$$

in which U_n is the variation in u with only z for the n^{th} harmonic, λ_n is the wave number, N is the number of harmonics considered, and $i = \sqrt{-1}$. When responses are written in the form shown in Eq. 1, the derivatives with respect to x and t are simply

$$\frac{\partial u}{\partial x} = i\lambda_n u \qquad and \qquad \frac{\partial u}{\partial t} = -i\lambda_n c u \qquad (2)$$

GOVERNING EQUATIONS AND SOLUTION SCHEME

A Darcian flow of compressible porefluid in a compressible porous medium under dynamic loading leads to the following form of the consolidation equation for plane strain conditions (Biot, 1941; Zienkiewicz and Shiomi, 1984).

$$K_x \frac{\partial^2 p}{\partial x^2} + K_z \frac{\partial^2 p}{\partial z^2} - \gamma_w n_o \beta \frac{\partial p}{\partial t} = \gamma_w \frac{\partial \epsilon_v}{\partial t}$$

$$- \frac{\gamma_w}{g} K_x \frac{\partial^3 u}{\partial x \partial t^2} - \frac{\gamma_w}{g} K_z \frac{\partial^3 w}{\partial z \partial t^2} \qquad (3)$$

Here, K_x and K_z are the principal permeabilities in the x and z directions, respectively; p is the excess porewater pressure (above the static value); ϵ_v is the volumetric strain defined as positive in expansion; β is the compressibility of the porefluid; g is the gravitational constant; u and w are displacements in the x and z directions, respectively; and t is time.

Dynamic equations of motion under plane strain conditions based on effective stress principle can be written as

$$G\nabla^2 u + \frac{G}{1 - 2\nu} \frac{\partial \epsilon_v}{\partial x} = \frac{\partial p}{\partial x} + \rho \frac{\partial^2 u}{\partial t^2} \qquad (4)$$

and

$$G\nabla^2 w + \frac{G}{1 - 2\nu} \frac{\partial \epsilon_v}{\partial z} = \frac{\partial p}{\partial z} + \rho \frac{\partial^2 w}{\partial t^2} \qquad (5)$$

in which G is the shear modulus. ν is Poisson's ratio, and ρ is the mass bulk density of the soil.

Using the simplification shown in Eq. 2, it is possible to rewrite Eqs. 3-5, resulting in three equations in terms of the unknowns U_n, W_n, and P_n in which W_n and P_n are the variations of w and p, respectively, with z only for the n^{th} harmonic. After a number of algebraic manipulations, a sixth order ordinary differential equation in terms of U_n only can be obtained; and its solution can be obtained using the method of characteristics. Finally, the response of all of the harmonics can be algebraically added to acquire the complete response (Siddharthan et al., 1993a; Zafir et al., 1994).

A computer code, MOVLOAD, has been developed incorporating the solution procedure above. This program can handle any number of layers with any type of load distribution at the surface. The higher the number of layers, the larger the computational effort. Since the solutions for the layered media response are obtained from an analytical expression, the response variation within a layer is exact. Therefore, it is possible to consider a layer of any thickness so long as the layer has uniform material properties. It has been found that it is not necessary to consider all of the harmonics since the contribution of the harmonics with large wave numbers (λ_n) is quite small. The computational effort associated with the proposed model can be reduced substantially by specifying a cut-off wave number above which the computation of the response is avoided.

The formulation presented above is for a plane strain case. By incorporating two special viscous boundaries (front and back) connected to the loaded area, the plane strain formulation can be extended to represent rectangular loaded areas (Zafir et al., 1994). It may be noted that, when the first equation and the porewater pressure term in the equations of motion are neglected, the above formulation reduces to an unsaturated layer case. If necessary, a combination of unsaturated and saturated layers can also be represented by this model.

MATERIAL CHARACTERIZATION

Soil Layers

One needs to use two elastic constants (G and ν) to solve the problem above. In the case of soil deposits, it is customary to assume a constant value for ν. Therefore, only the Variation of G needs to be specifically addressed. The shear stress-strain relationship of soil is, in general, nonlinear, hysteretic, and effective stress dependent. Research over the past two decades or so has led to a number of constitutive models based on plasticity and endochronic formulation. Some of these models can simulate both drained and undrained behavior under static and cyclic loads while retaining some of the convenient features of classical plasticity theory.

In the proposed study, it was decided to keep the shear stress-strain relationship as simple as possible. The nonlinearity of the soil is modeled through the use of an equivalent elastic (secant) approach (Schnabel et al., 1973; Seed and Idriss, 1970). In Seed's approach, strain compatible shear modulus and damping are obtained by an iterative process. Based on a collection of laboratory test results on sands, Seed and Idriss (1970) assessed the likely range in variation of the normalized modulus, G/G_{max}, with shear strain, as presented in Fig. 1. G_{max} is the shear modulus at a low strain level (10^{-4} percent) which may be evaluated in psf units using the equation

$$G_{max} = 1000(K_2)_{max}(\sigma_m')^{\frac{1}{2}} \qquad (6)$$

in which $(K_2)_{max}$ is a constant that depends on the relative density of the sand and σ_m' is the effective mean normal stress which is computed as the sum of two components, i.e., the geostatic stress and the load induced stress.

The material damping can be accounted for using the correspondence principle of viscoelasticity, which requires that the shear moduli be replaced by its complex form G* as

$$G* = G(1 + 2i\zeta) \quad (7)$$

in which ζ is the damping ratio. In all locations, G* is substituted for G in the governing equations (Rosset, 1980). Similar to the shear modulus, the strain compatible damping ratio can also be incorporated into the analysis by an iterative process. It should be noted that the radiation damping is implicitly incorporated into the proposed analysis.

Pavement Layers

Since pavement layers are subjected to a large number of repetitions of load, the resilient behavior is the one that should be modeled. The surface asphalt concrete (AC) layer exhibits strong frequency-dependent resilient behavior, while the base and subgrade layers essentially show elastic behavior. The resilient modulus of the AC layer as a function of frequency can be obtained from laboratory tests on a triaxial device or from the recently developed SUPERPAVE shear test device (Harrigan et al., 1994). Field falling weight deflectometer (FWD) testing may also be used to acquire the material resilient properties of the pavement layers.

APPLICATION TO FIELD PROBLEMS

Strip Load Over a Saturated Medium

To illustrate the application of the proposed approach, the response of a uniform medium dense sand of relative density D_r = 55% was evaluated (Fig. 2). This deposit was subjected to a strip load 4m wide with a pressure of 400 kN/m^2 moving at two speeds: 20 and 100 m/s. The saturated soil deposit is 18m thick and was divided into 21 layers in the analysis. The thickness of the layers near the surface is finer, and it increases as the depth of the layer increases. Table 1 shows the material properties used in the analysis.

Figure 3 presents the effect of the speed of the moving load on the vertical displacement. The influence of the speed can be viewed as the contribution from the dynamic effects. This is because low speed represents a case close to a static loading case. When the speed increased from 20 to 100 m/s, the surface displacement increased from 17.5mm to 27.5mm, an increase of as much as 57%. A difference in displacement is present to a depth of as much as 10m below the surface.

The dissipation of the porewater pressure generated by the moving load is a function of the permeability of the soil. Finn et al. (1983) have shown that the porewater pressure induced by ocean waves depends on, among other properties, the permeability of the soil deposit. Figure 4 shows the influence of the permeability on the porewater pressure generated by the moving load. The porewater pressures were computed at a location 2m from the surface. The permeability values selected are 10^{-3} and 10^{-5} m/s.

The figure shows that, in the case of higher permeability, the porewater pressure increased as load moved closer to the plane of observation and then indicated negative porewater pressure as the load moved away. On the other hand, the soil with lower permeability showed only positive porewater pressure. Higher maximum porewater pressure was generated in the case of $K_x = K_z = 10^{-5}$ m/s, and it is within 10% of the value computed with $K_x = K_z = 10^{-3}$ m/s.

To investigate the origin of negative porewater pressure, the moving load induced octahedral normal stress, $\Delta\sigma_{oct}$, and octahedral shear stress, $\Delta\tau_{oct}$, were computed. It was found that the load induced octahedral stresses are not sensitive to permeability. Since the proposed model does not incorporate dilation, the induced porewater pressure under undrained conditions is given by $\Delta\sigma_{oct}$ (Lamb and Whitman, 1979). However, in the case of the more permeable soil, porewater pressure dissipation is possible during the time the load is present near the plane of observation. Burke and Kingsbury (1984) who computed the response of a single poroelastic layer under pseudo static loading conditions also reported negative porewater pressure as the load moves away from the plane of observation.

Tandem Axle Loading on Pavement

The medium thick AC pavement structure shown in Fig. 5 was subjected to a tandem axle dual tire load of 20 kN/tire along with a tire pressure of 862 kPa moving at 30 and 80 km/hr. The field investigations showed that the bottom stiff layer is at 24.43m from the surface. Figures 6 and 7 show the viscoelastic material properties (frequency dependent), such as the resilient modulus, Poisson's ratio, and internal damping. Figure 5 shows the material properties of other pavement layers. The tandem axle load was represented by using two rectangular loaded areas of 0.183m x 0.253m separated by 1.22m. The tire-pavement interface was assumed to be smooth.

Figure 8 depicts the variations of the maximum principle shear strain, γ_{max}, induced within the AC layer for both the levels of speed. The γ_{max} is an important pavement response parameter that governs the rutting of the AC layer. The γ_{max} variation for both speeds clearly shows that the pavement strains are a strong function of the vehicle speed. The highest γ_{max} occurs either near the surface or at the interface between the AC and the base layer. The maximum γ_{max} increases by as much as 32% when the vehicle speed reduces from 80 to 30 km/hr. Sebaaly et al. (1991) made a similar observation with respect to the measured longitudinal strain at the bottom of the AC layer in their field test.

CONCLUSIONS

The paper presents two very important applications of a recently developed moving load model to study the response of layered media.

First, the response of a nonlinear compressible porous medium saturated with compressible fluid is presented. The results of the analysis show that the responses of near surface and soil layers are substantially affected by the properties of the soil and the porefluid. The influence of the speed of the moving load and the permeability of the soil are reported. Secondly, the response of a medium thick asphalt concrete pavement subjected to a moving semitrailer is presented. The study reveals that the speed of the vehicle is a very important factor that affects the strain induced on the pavement. The maximum shear strain induced increases by as much as 32% when the vehicle speed decreases from 80 to 30 km/hr. This is an important observation since higher shear strain leads to much earlier deterioration of pavements.

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Table 1. Material Properties for Sandy Soil

PARAMETER	VALUE
Shear Modulus Constant, $(K_2)_{max}$	52.0
Poisson's Ratio, ν	0.35
Mass Density, ρ (kg/m^3)	1816.0
Angle of Internal Friction, ϕ_f' (°)	33
Coefficient Lateral Earth Pressure, K_o	0.45
Porosity, n_o	0.40
Compressibility of Porefluid, β	0.0
Permeability, $K_x = K_z$ (m/s)	10^{-3} or 10^{-5}

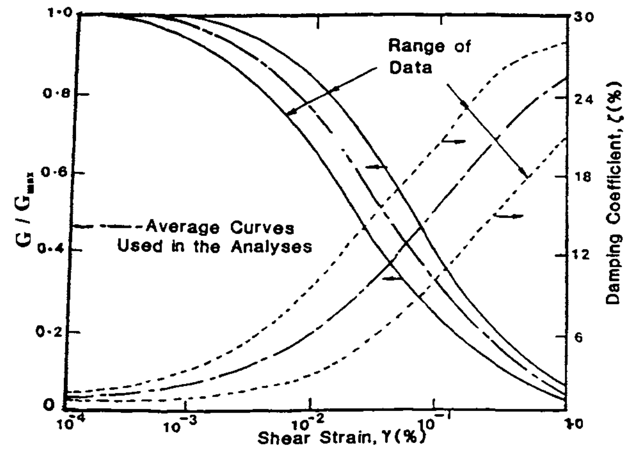

Fig. 1 : Shear Modulus and Damping Values For Sandy Soils (After Seed and Idriss, 1970)

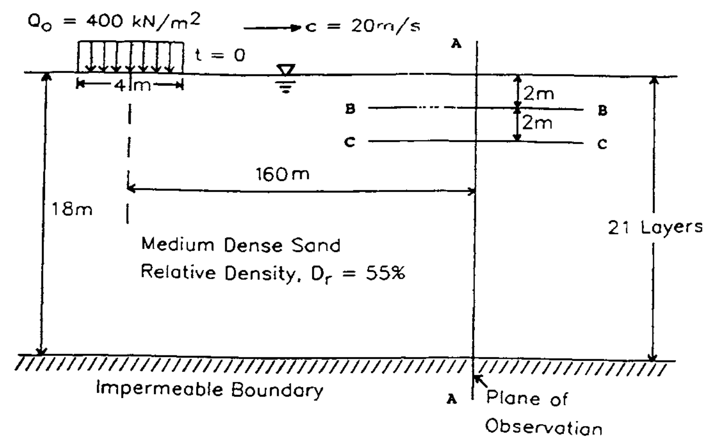

Fig. 2 : Soil Deposit Subjected to Moving Load

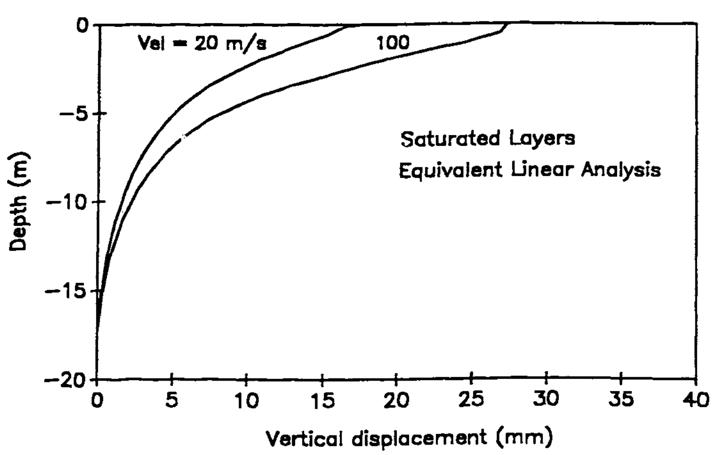

Fig. 3 : Vertical Displacement Induced by the Moving Load

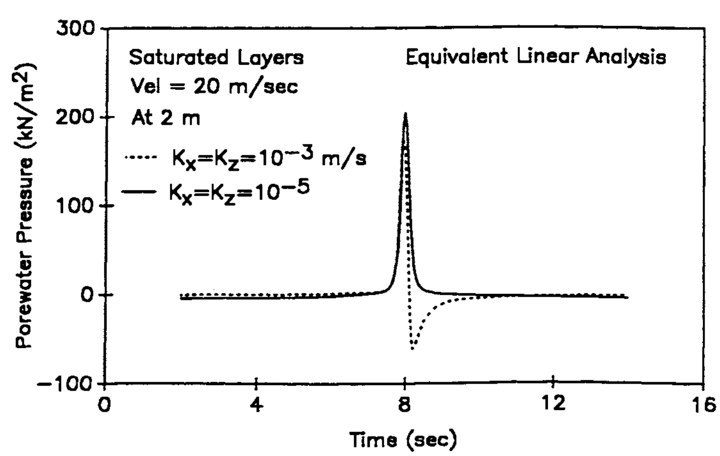

Fig. 4 : Influence of Permeability on the Load Induced Porewater Pressure

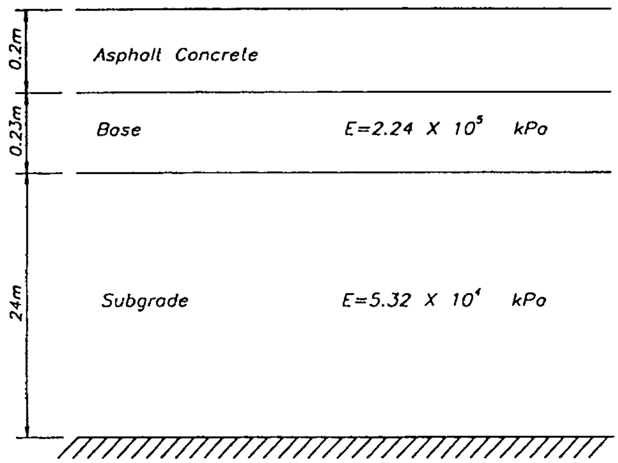

Fig. 5 : Asphalt Concrete Pavement Structure Used in the Study

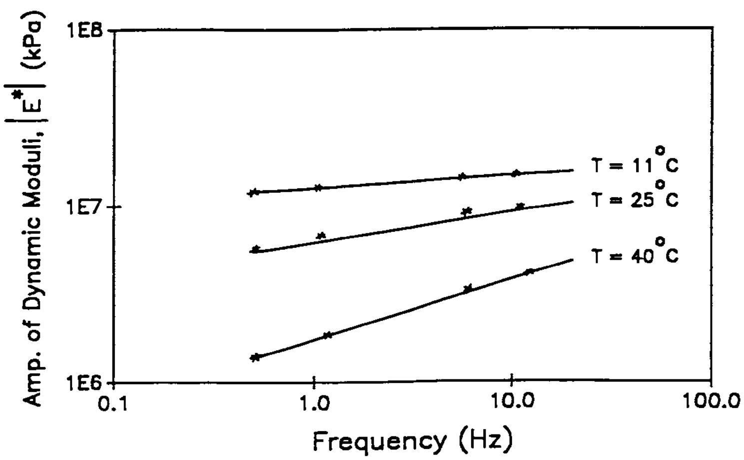

Fig. 6 : Viscoelastic Behavior of Asphalt Concrete : Resilient Modulus

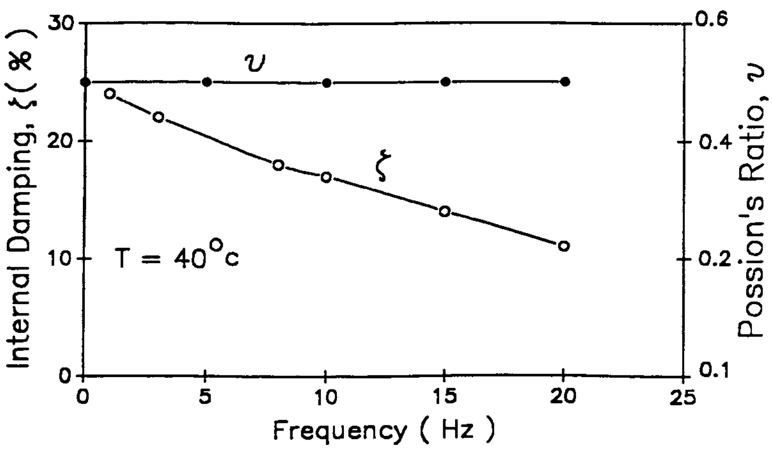

Fig. 7 : Viscoelastic Behavior of Asphalt Concrete: Poisson's Ratio and Damping

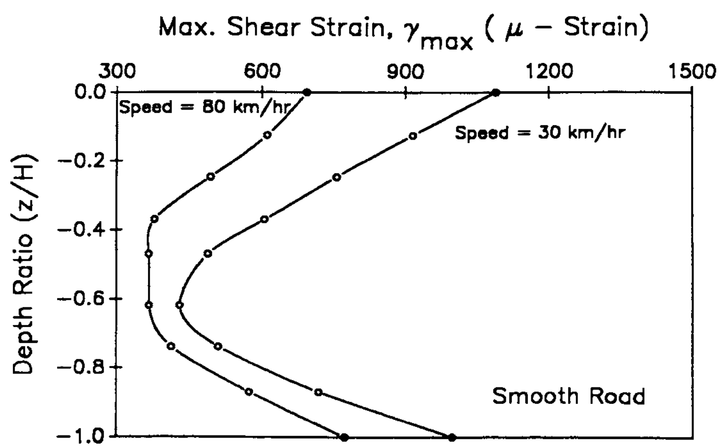

Fig. 8 : Maximum Shear Strain Induced by the Moving Semi-Trailer