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Dynamic simulation of a flexible pavement layers considering shakedown effects and soil-asphalt interaction

Behzad Ghadimi *, Hamid Nikraz, Michele Rosano

Curtin University, Australia

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ABSTRACT

This research evaluates the effects of shakedown and soil asphalt interaction on the dynamic simulation of flexible layered pavement structure. In a newly developed assessment methodology the shakedown concept is implemented for the granular layer under asphalt concrete. Under this assessment granular material behaviour changes from plastic to elastic as a function of the number of loading cycles. Interactional forces are considered through contact elements placed between the base and the asphalt layer. A nonlinear stress dependent model in the elastic domain and the Mohr–Coulomb constitutive model in the plastic domain are utilised to simulate the behaviour of granular layers and the results of the simulation are validated with previously published literature. One static simulation and three different dynamic simulations under cyclic Haversine loading of a single tyre dual axle are then compared with each other. The first dynamic simulation assumes Mohr–Coulomb plasticity, the second simulation considers the shakedown effects and the third simulation calculates soil asphalt interactional forces.

Introduction

In flexible pavement engineering the significant role of the granular layers in rutting failure is well known. The investigation of the contribution of granular materials in rutting and surface deflection in accelerated pavement tests has been previously examined (Little, 1993; Pidwerbesky, 1996; Arnold et al., 2001; Korkiala-Tanttu et al., 2003). Based on this research, the layers containing granular materials have been considered responsible for 30–70% of the rutting deflection occurring at the surface of flexible pavements. The rutting itself is governed by the permanent deformation and the residual plastic strains induced inside the granular body in each loading cycle. This is why the investigation of unbound granular materials (UGM) and their reaction to the cycles of traffic loading is considered critical.

The behaviour of granular materials can be divided into two parts: elastic range and plastic range performance. Whilst induced stress remains in the elastic domain, material behaviour can be modelled as linear elastic or nonlinear elastic. For UGM it is more realistic to consider a stress dependent elastic modulus where elastic modulus (or resilient modulus) is not constant during the increments of loading. Such an approach has been widely used in previous research (Cho et al., 1996; Kim and Tutumluer, 2006; Kim et al., 2009; Lee et al., 2009; Cortes et al., 2012; Ghadimi et al., 2013a,b,c). There is a variety of nonlinear constitutive models developed especially for granular material assessment in flexible pavement. Nonlinearity of granular material can be considered through the dependency of the resilient modulus to the strain tensor (Hjelmstad and Taciroglu, 2000; Taciroglu and Hjelmstad, 2002) to the bulk stress (Seed et al., 1962; Hicks and Monismith, 1971) or to the stress invariants representing deviatoric and bulk stress conditions (Uzan, 1985; Witczak and Uzan, 1988). Amongst

* Corresponding author. Tel.: +61 8 9266 4521; fax: +61 8 9266 4811.
E-mail address: bghadimy@gmail.com (B. Ghadimi).

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forms of nonlinearity, the latter has found more interest amongst flexible pavement researchers where UGM behaviour is largely defined as a function of deviatoric and bulk stress conditions simultaneously.

If no cap is defined for the UGM, the stress–strain path will remain the same in the loading and unloading scenarios. However, in reality there is some residual strain in the UGM layers after each loading cycle which necessitates the usage of elastoplastic constitutive models in the numerical simulation of the granular layers. There are various constitutive models to represent plastic behaviour of UGM. Among them Drucker–Prager criterion and Mohr–Coulomb criterion have been used commonly in the simulation of granular materials in flexible pavement (Zaghloul and White, 1993; Shen and Kirkner, 2001; Saad et al., 2005; Ghadimi et al., 2014). The two criteria are compared in Fig. 1 where $\sigma 1$, $\sigma 2$ and $\sigma 3$ are the three principle stresses. The main disadvantage of the Moher–Coulomb criterion when compare to the Drucker–Prager criterion is in the numerical simulation where the failure surface is not a smooth differentiable surface and may cause some inconsistency during incremental analysis. However, Clausen et al. (2007) introduced a method to include Mohr–Coulomb criterion in the ABAQUS programme through a piece-wise function and return algorithm and this same methodology is employed in this study.

The goal of numerical simulation of pavement structure is to evaluate the mechanical responses to a given traffic load. The usage of a general purpose finite element programme made this approach more feasible in the field of pavement engineering. ABAQUS programme is used by many researchers who have conducted numerical simulations (Zaghloul and White, 1993; Uddin et al., 1994; Kim and Tutumluer, 2006, 2010; Cortes et al., 2012; Ghadimi et al., 2013a,b,c, 2014). This software programme permits researchers to define new constitutive models for the materials in the simulation of different types of loading and boundary conditions. The accuracy of finite element simulation can be adjusted through geometrical dimension (two dimensional or three dimensional), assumed materials behaviour (linear, nonlinear, elastic or plastic), boundary conditions (rollers, clamped or infinite elements) and loading conditions (static or dynamic).

Static loading provides the advantage of simplifying computing efforts when a complex material model is used.

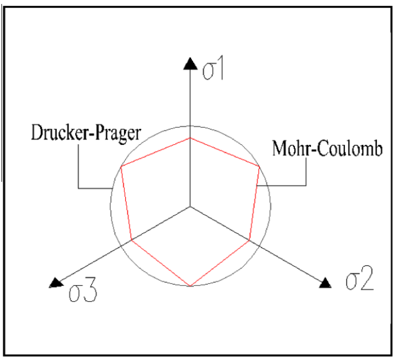

Fig. 1. Yield criteria used for granular materials.

Many researchers have investigated the effects of material behaviour in layered flexible pavement under static loading (Cho et al., 1996; Myers et al., 2001; Holanda et al., 2006; Kim and Tutumluer, 2006; Kim et al., 2009; Ghadimi et al., 2013a,b,c). However, the assumption of static loading overlooks some important aspects. For example the effects of damping and body forces are ignored in static analysis. This may result in the calculation of larger deformation in static loading than actual experiments. Such effects have been reported in previous studies (Zaghloul and White, 1993; Uddin et al., 1994; Saad et al., 2005). Furthermore, under the assumption of static conditions, the effects of the unloading path cannot be investigated. This is especially important if material behaviour is dependent on loading path (elastoplastic).

The numerical analysis of pavement layers subjected to dynamic loading provides more accurate insight into the actual mechanical responses of the pavement structure. This, however, necessitates more complex computation. One of the earliest studies considering dynamic loading in numerical simulation was conducted by Zaghloul and White (1993) where ABAQUS software was employed to simulate the responses of layered flexible pavement. After this study, dynamic simulation has continued to grow amongst pavement researchers (Uddin and Pan, 1995; Saad et al., 2005; Bodhinayake, 2008; Al-Qadi et al., 2010; Ghadimi et al., 2014). In dynamic simulation major points which need to be considered include the effects of boundary conditions, layer interactions, the wave function of loading pluses and any materials change due to loading cycles. Boundary conditions can be simulated as rollers and pins (Zaghloul and White, 1993; Uddin and Pan, 1995; Bodhinayake, 2008) or infinite elements (Al-Qadi et al., 2010; Ghadimi et al., 2014). The latter may reduce the effects of reflective stress waves in the simulated medium. In terms of layers interaction, there are only a few studies that consider this effect in flexible pavements (Pan et al., 1994; Baek et al., 2010; Ozer et al., 2012), but have been considered in the other similar layered structure assessment (Mishra and Tutumluer, 2012). Loading pulses from tyres may also be simulated to have a triangular (Saad et al., 2005; Bodhinayake, 2008), trapezoidal (Zaghloul and White, 1993), sinusoidal (Al-Qadi et al., 2010) or Haversine (Ghadimi et al., 2014) function varying in the time span of the stress pulse. The behaviour of the granular layers is assumed to be modified in each of the loading cycles.

In the case that applied load exceeds yield criterion of the UGM, the response of the granular material may change according to the cycles of loading. To study this phenomenon the shakedown theory was developed (Melan, 1938; Zarka and Casier, 1979). This theory was applied through limit analysis in flexible pavement layers by Sharp and Booker, 1984, 1985. Other approaches to calculate the analytical shakedown limit in a layered flexible pavement subjected to tyre pressure can be via the upper-bound solution (Collins and Boulbibane, 1998) or the lower-bound solution (Yu and Hossain, 1998). Researchers have also tried to investigate the shakedown limits of UGM in laboratory experiments (Barksdale, 1972; Siripun et al., 2010; Cerni et al., 2012). The experimental approaches