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Dynamic Behavior of Flexible Pavement Under Moving Wheel Load

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Abstract

Due to the rapid growth of heavy vehicles in many countries around the world, new challenges and problems relating to the performance of road foundations may arise. The heavily loaded vehicles apply huge tire pressure on pavement that causes extra stresses and excessive displacements leading to possible pavement damages. This unwanted scenario makes it important to investigate the dynamic behavior of flexible pavement foundations under moving wheel load. In the current paper, a sophisticated three-dimensional (3D) finite element (FE) modelling is developed to simulate the dynamic response of flexible pavement subjected to moving wheel loads. The dynamic responses of the pavement are evaluated under various influencing factors such as different subgrade stiffness and different loading amplitudes. The results are analyzed and presented in details in this paper. These results obtained from this paper provide key parameters for flexible pavement optimization and support for damage control technologies.

Keywords: *Stress deformation behavior; Dynamic response; Flexible pavement; Midas GTS NX; Moving wheel load.*

1 Introduction

The road network plays a crucial role in the communication system by providing an effective method for transporting goods and services. Typically, roads are constructed using two main types of pavements, namely rigid pavement and flexible pavement. Among them, the majority of roads worldwide are built using flexible pavement. Flexible pavement refers to the type of pavement that can bend or deform under the weight of heavy traffic loads. It is typically composed of several layers designed to distribute the load and provide structural support. The typical layers found in a flexible pavement system, from the top down, are: surface course, binder course, base, sub-base, improved subgrade and subgrade.

The prevalence of heavily loaded vehicles is increasing at a rapid pace globally, driven by the rising need for transporting goods and services. The growing vehicular load presents new challenges and potential issues regarding the performance of road foundations. The passage of heavily loaded vehicles over the pavement can lead to additional stresses in various layers of the pavement and causes excessive deformations. The increased stresses and deformations could shorten the lifespan of road foundations, leading to higher maintenance costs. Therefore, it becomes crucial to precisely forecast the dynamic response of road pavement and subgrade when subjected to moving wheel loads.

There are several ways to estimate the dynamic response of road pavement e.g. empirical method, analytical approach and numerical method. The numerical techniques, including Finite Element Method (FEM), Boundary Element Method (BEM), and the combination of FEM/BEM (Andersen and Nielsen, 2003; Duncan et al.,1968; Beskou et al., 2016; Pan and Atluri, 1995), are used in addressing pavement-related issues. Due to recent advancement of high-speed computing, the FEM has emerged as the predominant numerical approach for calculating stresses and strains. Several computer programs based on FEM have been developed for pavement analysis. A number of authors (Al-Qadi et al., 2008; Beskou et al., 2016; Castillo et al., 2019; Djellali et al., 2017; Jiang et al., 2019; Khavassefat et al., 2012; Lee et al., 2013; Mamlouk and Davies, 1984; Sousa et al., 1988; Siddharthan et al., 1998; Yoo and Al-Qadi, 2007; Vale, 2008; Zheng et al., 2012;) have modeled the flexible pavements were modelled under static or dynamic stationary or moving loads. The combination of FEM/BEM is also utilized to calculate stresses and strains in flexible pavements.

Nevertheless, when a wheel load moves along a flexible pavement, the pavement layers experience intricate loading conditions, including the rotation of principal stresses (Powrie, Yang, and Clayton 2007; Brown 1996). Consequently, moving wheel loads (i.e., cyclic loading with principal stress rotation) have the potential to influence the material stiffness (Inam, Ishikawa, and Miura 2012; Lekarp, Isacsson, and Dawson 2000b; Lekarp, Isacsson, and Dawson 2000a). Unfortunately, as most of the available studies considerer static or cyclic loading in 2D or 3D medium, they cannot fully account for the dynamic effects of moving loads, representing a significant limitation of the studies. Accordingly, a sophisticated three-dimensional (3D) FE numerical modelling can be used to determine the induced stresses in the pavement layers to analyze the dynamic effects of roads. Hence, the main focus of this study is investigating the pavement behavior under true wheel moving loads.

2 Numerical Modelling of Flexible Pavement

Among different numerical solutions, the advanced finite element (FE) modelling is adapted for conducting this study. A typical Bangladeshi Department of Roads & Highway (RHD) road section profile (RHD Design type 4) which is a flexible pavement, is selected to develop the FE model. The FE model is simulated in 3D medium using a numerical modelling-based software GTS-NX (MIDAS IT. Co. Ltd. 2013), as it can simulate more practical situations compared to two dimensional and axisymmetric modelling. Figure 1 represents the 3D FE model that is used to analyze the dynamic responses of the flexible pavement profile. The dimensions of the modelled pavement in X-, Y- and Z- directions are 50m, 9.8m, and 9m, respectively.

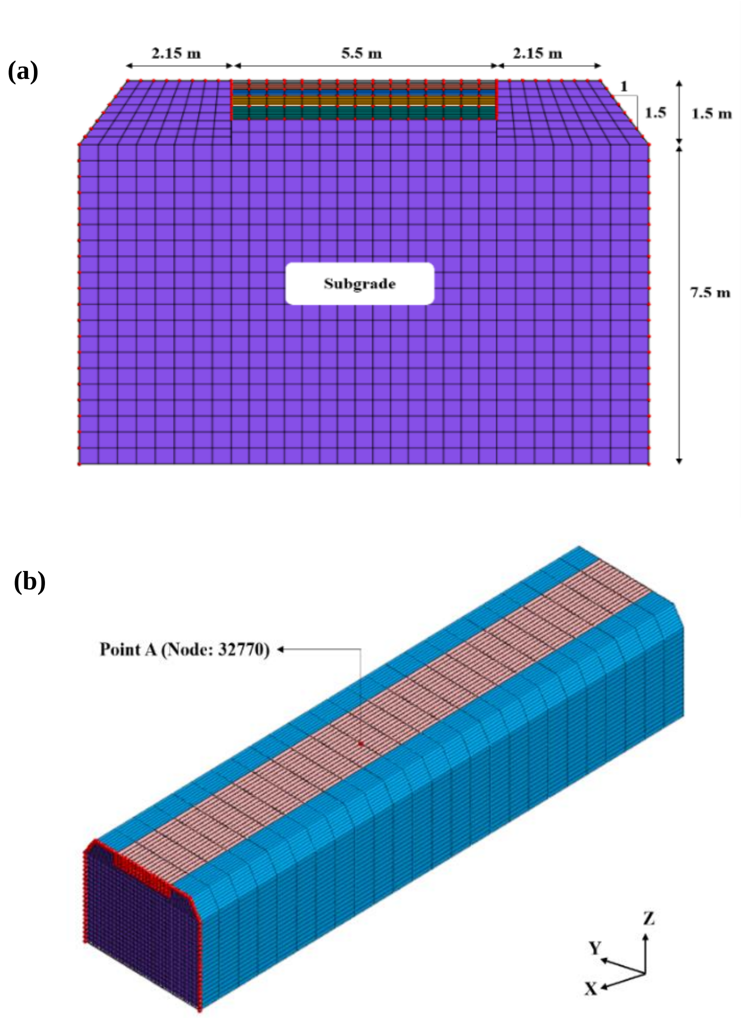


Figure 1. Three-dimensional FE model of flexible pavement (a) cross section of the model; (b) 3D view of the model

The material characteristics of different pavement layers, the contact conditions and the magnitude, frequency and configuration of wheel loads are chosen based on practical conditions. All the pavement components (i.e., surface, base, sub-base and subgrade) are modelled using 3D solid elements. They are modelled as linear elastic material.

The properties of all materials considered for nominal model are summarized in Table 1. These data are taken from several researchers (Ibrahim et al., 2014; Asim et al., 2021; Rahman et al., 2011; Mwanza et al., 2016).

Table 1. Material properties

Materials	Thickness (mm)	Modulus of elasticity, E (MPa)	Poisson's ratio	Unit weight (kN/m³)
Surface (Asphalt concrete)	52	2000	0.30	22
Base (Crushed stone)	150	500	0.35	16
Sub-base (Lime stabilized soil)	150	400	0.20	14
Subgrade #1 (Improved subgrade)	250	100	0.40	16
Subgrade #2 (Improved subgrade)	300	100	0.40	16
Subgrade #3 (Natural subgrade)	8098	100	0.40	16

3. Dynamic responses of pavement

The dynamic responses of flexible pavement under moving wheel loads for different parameters are investigated in terms of the stress-deformation behavior of surface course with respect to time and vertical stresses at different depth of the pavement profile. The subgrade stiffness and loading amplitude are the parameters which are varied for investigating the stress-deformation responses of the flexible pavement. The subgrade stiffness for nominal model is considered to be 100 MPa. The pavement responses of nominal model are assessed based on Tata LPT 2516 truck's wheel load at a speed of 25.28 m/s. The configuration of wheel load of Tata LPT 2516 truck is presented in Figure 2.
The point A (Node: 32770) which is located at surface course (Figure 1b), is considered to assess all the time history stress-deformation responses for different conditions. Below point A, the stresses at various depth of the pavement profile are also evaluated for various pavement conditions.

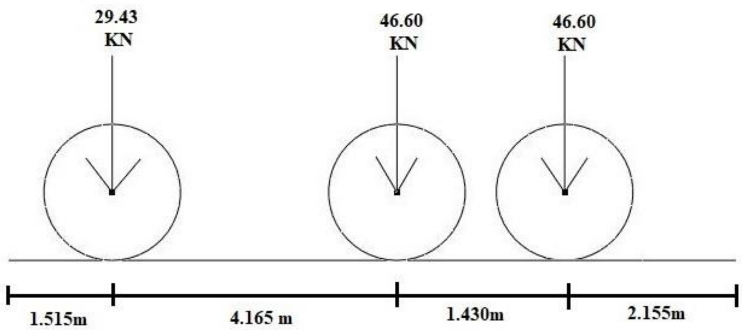


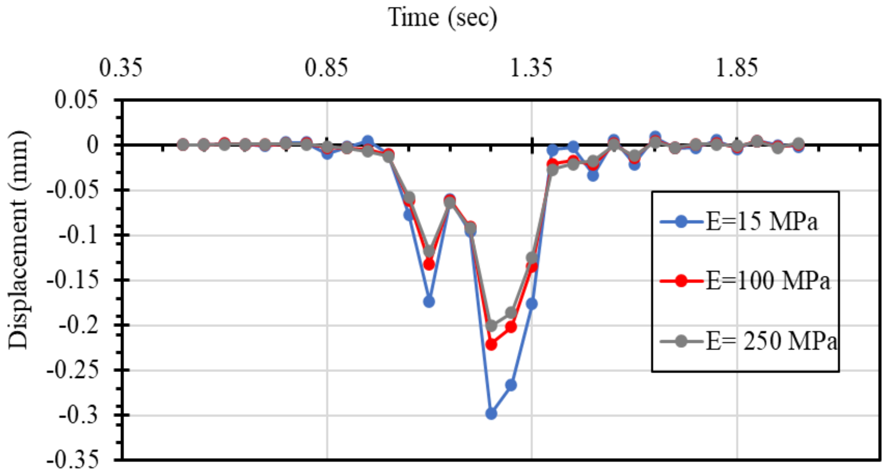
Figure 2: Configuration of wheel load of Tata LPT 2516 truck is presented in Figure 2.

3.1 Impact of different subgrade stiffness

In this section, the impact of different subgrade stiffness (i.e., modulus of elasticity) on the stress-deformation behavior of flexible pavement is investigated under nominal truck loading (Tata LPT 2516 Truck). There are five layers in the nominal pavement profile- surface, base, sub-base, improved subgrade layer #1 and improved subgrade layer #2. The modulus of elasticity of improved subgrade layer #1 is considered 100 MPa in the nominal model. For the evaluation of impact of different subgrade stiffness, changes in stiffness of improved subgrade layer #1 is performed but the other properties of the pavement layers are kept the same as defined by the Table 1. In Table 2, a variety range of modulus of elasticity of improved subgrade layer #1 which is considered for the parametric study, is defined. In case 1, the modulus of elasticity is taken as 15 MPa which represents a soft subgrade whereas, in case 3, the modulus of elasticity is taken as 250 MPa which denotes a stiff subgrade.

Subgrade #1 layer	Modulus of elasticity, E (MPa)
Case 1	15
Case 2 (nominal case)	100
Case 3	250

The stress-deformation behavior of flexible pavement under moving wheel load for different values of modulus of elasticity of improved subgrade layer #1 is represented by time history graphs. The behavior is assessed for surface course for a specific nodal point. The stresses at different depths of pavement profile are also evaluated for that point.
Figure 3 represents the impact of different subgrade stiffness on stress-deformation behavior of flexible pavement under nominal loading. It can be seen that with the increase of modulus of elasticity of subgrade the deformation of the flexible pavement decreases. It is also noted that with the vertical stress developed at the measurement point 'A' decreases with the increase of subgrade modulus.



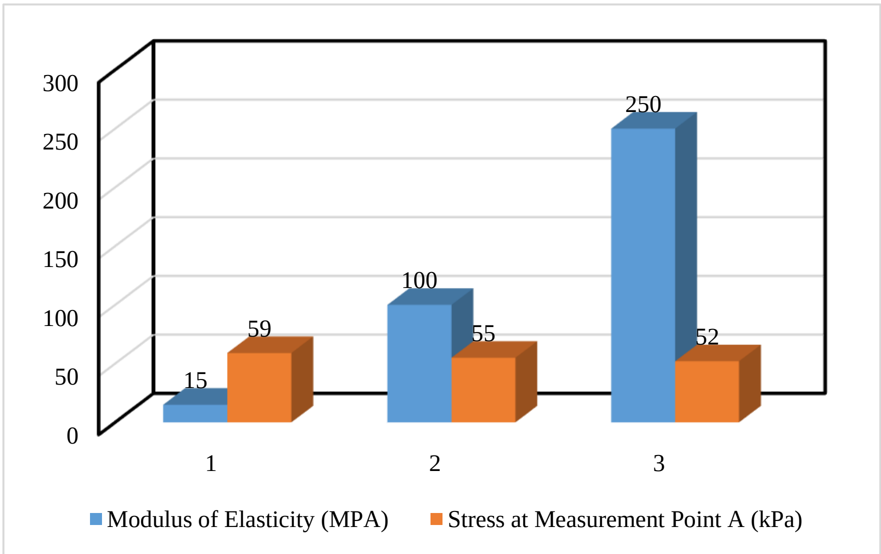


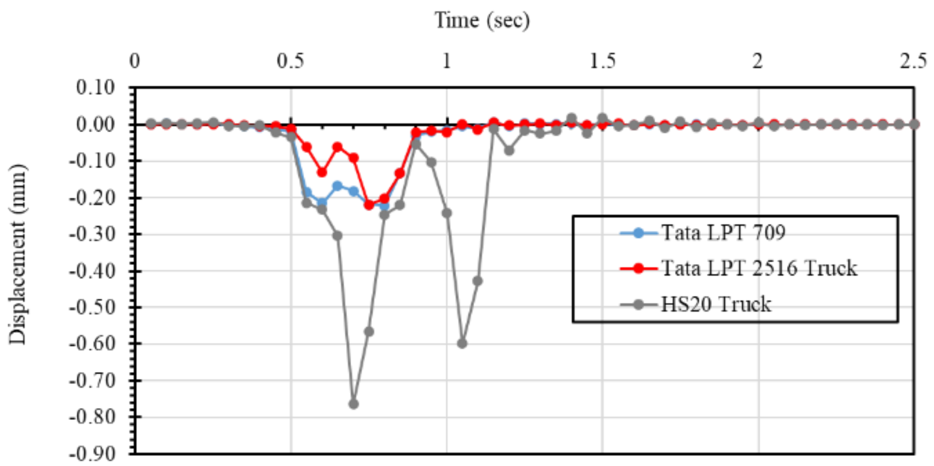
Figure 3: Impact of subgrade stiffness: (a) Time history deformation responses at point 'A'; (b) Stress verses modulus of elasticity at point 'A'

3.2 Impact of different loading amplitudes

The influence of amplitude of moving wheel loads on the flexible pavement is investigated using three different loading values denoted here in as standard, light and heavy. Tata LPT 2516 truck is chosen for nominal loading which is taken as standard loading. HS 20-44 truck as heavy loading and Tata LPT 759 truck as light loading are chosen for parametric study. The properties of different materials of pavement layers are assigned as defined in Table 1 for light and heavy loading conditions. The velocity for the light and heavy loading conditions is considered to be same as the nominal condition which is 25.28 m/s.

The stress-deformation behavior for a specific nodal point A with respect to time for the three loading amplitudes considered are shown in Figure 4. As expected, the deformation of surface course increases with the increasing wheel load. The red marked line in each graph represents the pavement responses for the nominal case. It can also be seen that maximum stress developed for HS-20 loading, whereas similar stress developed in the measurement point A for Tata LPT 700 and Tata LPT 2516 Truck.

a)



b)

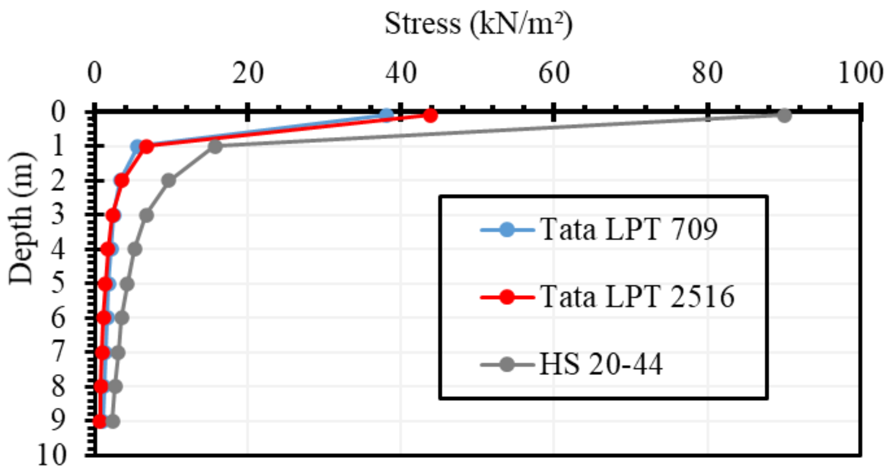


Figure 4. For different loading amplitudes (a) Time history deformation responses for point A; (b) Time history stress responses for point A; (c) Stress with depth below point A

4. Conclusions

In the current paper, an advanced level 3D finite element model is developed for simulation the dynamic response of the flexible pavement. It can be summarized that the developed model can simulate qualitatively the behavior of the flexible pavement. The following conclusions are observed.

- The deformation of the flexible pavement decreases with the increase of modulus of elasticity of subgrade. The vertical stress developed at the surface course also decreases with the increase of subgrade modulus.

- The loading amplitudes largely affect the pavement behaviors under moving wheel loads. For a heavier vehicle, the pavement experiences excessive stresses and displacements. So, pavement which experiences heavier loads from vehicles should have a good and stiff flexible pavement layer.

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