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AN IDEALIZED DISCRETE ELEMENT MODEL FOR PAVEMENT-WHEEL INTERACTION

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Key words: pavement engineering, discrete element method, wheel-pavement interaction, traffic loading.

ABSTRACT

In order to design a longer-lasting pavement, it is important for pavement designers to understand the mechanism of the vehicular loading. The main objective of this paper is to present an idealized discrete element modeling of pavement-wheel interaction for better understanding traffic loading conditions. The idealized model consists of three parts: a smooth surface, a wheel, and a mass. The smooth surface simulates the pavement surface, while the wheel and mass represent a vehicle wheel and its corresponding mass, respectively. The mechanical behaviors at the interaction surface are simulated through an elastic contact model, a slip model, and a viscous contact damping model. Discrete Element simulation was performed through loading the wheel with a vertical force and a torsion moment at its center. As a result, the wheel was rotated and moved forward to simulate a vehicle rolling on the pavement surface. Through analyzing the simulation results, it was found that findings of this research were comparable with theoretical solutions and those of the finite element modeling in a previous study.

I. INTRODUCTION

Traffic loading generated through pavement-wheel interaction is one of the most important key aspects in pavement design. In order to build longer-lasting pavements, it is necessary to interpret pavement-wheel interactions for better understanding traffic loading conditions. In the past decades, plenty of research efforts were made in this area. Hegmon (1987) presented an overview of the interactions between vehicle tires and the pavement with the emphasis on highway safety. He pointed out that tire-pavement friction is important for traction and braking as well as directional stability of running vehicles. Markow et al. (1988) analyzed the interactions between dynamic vehicle loads and highway pavements by developing analytic models. They concluded that the vehicle itself was very important in influencing dynamic pavement loads and recommended that the policies governing the maintenance and rehabilitation of highway infrastructure might need to look at the vehicle as well as the pavement or bridges. Papagiannakis and Gujarathi (1995) presented a roughness model to investigate the influences of the pavement roughness on the interactions between the pavement and heavy vehicles. Both experimental and numerical results were analyzed. Mamlouk (1996) performed both computer modeling and experimental tests to study effect of vehicle-pavement interaction. Sun and Deng (1998) considered dynamic loads caused by vehicle-pavement interaction as two parts: moving loads or random loads. Liu et al. (2000) presented a unified analytic framework to study responses of rigid pavements due to the vehicle-road interaction under a moving vehicle load. They concluded that the surface roughness could significantly impact the dynamic responses of concrete slab. Saleh et al. (2000) proposed a mechanistic roughness model based on the vehicle-pavement interaction. The model was developed for flexible pavement design or evaluation with considering the relation between roughness and number of load repetitions, axle load, and asphalt layer thickness. Papagiannakis et al. (2007) utilized a wavelet approach to interpret the interaction between truck dynamic axle loads and pavement roughness profile. Sun and Luo (2007) studied nonstationary dynamic pavement loads resulted from vibration of vehicles traveling at varying speed using a quarter-vehicle and a half-vehicle models. It was found that compressive tire-pavement interaction forces were significantly impacted by vehicle motion features (acceleration, steadily moving, and deceleration). Kim and Tutumluer (2008) performed finite element analysis to study the multiple wheel-load interaction in flexible pavement. They concluded that pavement responses under multiple wheel loads were somewhat different from those obtained from the single wheel-load response superposition approach. Li and Yang (2009) investigated dynamic interactions between

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heavy vehicle and road pavement with a three dimensional finite element method. It was concluded that the coupling action of vehicle acceleration, suspension deformations, tire forces, and pavement responses could not be neglected and dynamics of vehicle and pavement should be considered simultaneously. Sawant (2009) and Sawant et al. (2010) performed dynamic analysis of rigid pavement with vehicle-pavement interaction considered and concluded that velocities of aircraft had a significant effect on the pavement responses. Shi and Cai (2009) presented a three-dimensional (3D) vehicle-pavement coupled model to simulate the pavement dynamic loads induced by the vehicle-pavement interaction where both the vehicle vibration and pavement deformation were considered. It was observed that the dynamic loads of vehicles under rough road conditions were significantly higher than those under the static loads. Li et al. (2009) performed dynamic analysis of an asphalt pavement due to vehicle-road interaction with a commercial finite element code (ANSYS program). It was observed that pavement dynamic responses were impacted by vehicle speeds, tire stiffness, suspension stiffness, and suspension damping values. Xia (2010) proposed a fully tire-pavement interaction finite element model and concluded that the tire/pavement interaction model could be used to predict pavement response and pavement damage due to fatigue cracking and rutting in the field of pavement engineering. Yang et al. (2010) presented a three-dimensional model based on Galerkin method and quick direct integral method to investigate the dynamic interaction between a heavy vehicle and road pavement. They pointed out that emphasis should be put on the dynamics of both vehicle and pavement simultaneously.

In summary of the existing research efforts, it was found that:

(1) In terms of methodologies, there were three kinds of methods in the literatures to study the pavement-vehicle interaction, namely the experimental measurement, the analytical analysis, and the computer simulation. The majority of the literatures utilized computer simulation techniques to simulate the pavement-vehicle interaction and validated their simulation results with experimental data. Analytical equations were usually integrated into the computer models and few literatures utilized pure analytical analysis. Finite element codes, such as ANSYS and ABAQUS, were typically utilized to perform computer simulations.
(2) In terms of research focuses, most studies was started from the model development, followed by prediction of the parameters of interest, and ended up with comparison between modeling results and those from experimental tests. Few attentions were paid to fundamental understanding of pavement-vehicle interactions.
(3) Additionally, the majority of research efforts were developed based on the continuum mechanics. However, the pavement-vehicle interaction is a contacting problem whose contacting position keeps changing from one time to another. Therefore, the existing continuum mechanical methods solved the pavement-vehicle interaction in an indirect manner instead of direct approach.

II. OBJECTIVES AND SCOPES

The main objective of this study is to develop an idealized model for quantitatively studying pavement-wheel interaction with the discrete element method (DEM). Different from the existing finite element models (FEM) and analytical methods, the discrete element method is a discontinuum-based approach which is much suitable for solving interaction problems of individual entities. In other words, a DEM simulation is direct and intuitional compared with the existing continuum-based approaches (a FEM simulation for instance). It should be noted that a DEM simulation usually means longer computing time and sensitivity to input variables. Therefore, this paper was mainly focused on development of the idealized model and demonstration of its application through examples. Experimental tests were not directly involved in this study due to the following reasons:

(1) The accuracy of DEM in simulating contacting problems has been validated by many existing studies (Cundall and Strack, 1979; Hart et al., 1985; Taylor et al., 1985; Huang et al., 2008; Kim and Choi, 2008; Kim, 2008). Based on DEM simulation, granular flow, sand behaviors, grinding mechanism, a large basalt bock property, and asphalt concrete viscoelastic properties were evaluated or predicted. The simulation results were validated through comparing with experimental testing data.
(2) This research effort is presented herein not for prediction purposes, but for improving fundamental understanding of the wheel-pavement interactions through discrete element simulation as demonstrated in the previous research efforts(Yao et al. 2012; Liu and You 2013). The improved fundamental understanding may help practitioners or researchers make a better decision in further evaluation or analysis with more comprehensive experimental or virtual testing programs. Therefore, the model inputs of this research were selected through analyzing existing testing data.

III. DISCRETE ELEMENT MODEL FOR PAVEMENT-WHEEL INTERACTION

A commercial discrete element code, Particle Flow Code in three-dimension (PFC3D), was employed in this study. Fig. 1 shows the idealized discrete element model which consists of a pavement surface, a vehicle mass, and a moving wheel. The smooth surface represents the pavement surface and was modeled with an infinite wall. The vehicle mass represents the mass which the wheel can carry, while the wheel is a truck steering wheel. Both the mass and the wheel were modeled

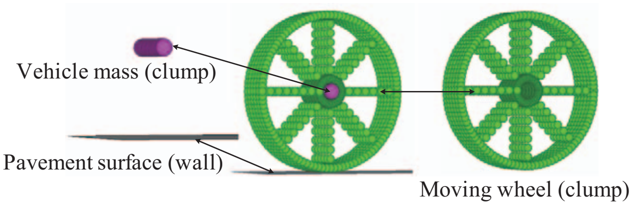


Fig. 1. Illustration of the idealized discrete element model.

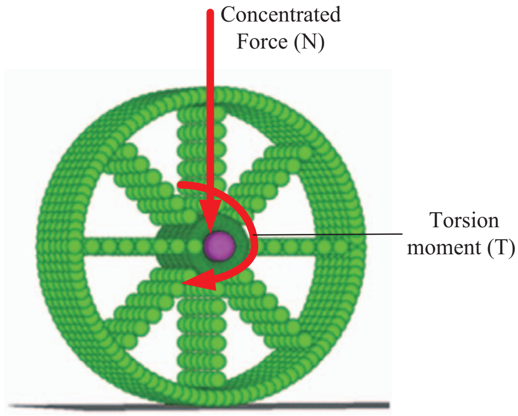


Fig. 2. Loading conditions on the wheel.

with clumps which consist of balls glued with contact-bond models as shown in the Figure. As shown in the PFC3D manual, the "wall" has the infinite dimension and can be characterized with the friction coefficient, while a "clump" can be considered a special element with a user-defined shape. Details about "wall" and "clump" logics can be found in the manual of PFC3D.

The interactions between adjacent discrete elements were simulated with three contact models: a linear elastic contact stiffness model was employed to simulate the force-displacement relationships; a slip model was used to simulate the frictional properties at the interaction surface; and a viscoelastic contact damping model was used to simulate the mechanical damping behavior. Readers may refer to the previous research (Liu et al., 2009) and PFC3D manuals for dtailed descriptions of those three models (definitions, parameters, etc.).

In the reality, the direct loads on the wheel include weights of the truck and the wheel itself as well as the torsion from the truck engine. As shown in the Fig. 2, the weights were simulated with a concentrated force (N) and the torsion was represented by a moment (T).

IV. DISCRETE ELEMENT SIMULATION RESULTS

Based on the idealized discrete element model, a PFC3D program was developed to simulate the wheel-pavement interaction with the inputs as listed in Table 1. As shown in the table, the wheel geometry was determined through dividing dimension of tire 265/45R16 with a ratio of 2 in order to save computation time. Additionally, a large value of 7,600,000 kg/m^3 was selected as the unit vehicle mass to simulate the inertia effects of a car. It should be noted herein that the controlled angular velocity was set for controlling velocity in the stage of steadily moving.

Table 1. Inputs for DEM simulation under different damping ratios.

Category	Input Variable	Meaning	Value
Geometry	whl_R (mm)	Wheel radius	150
	whl_W (mm)	Wheel width	120
	whl_brad (mm)	Radius of discrete elements	15
Mechanics	whl_Ec (GPa)	Modulus of wheel	55
	whl_knos	Ratio of shear stiffness over normal stiffness	1
	whl_fric	Friction coefficient of the wheel	1
	wal_fric	Frictional coefficient of the infinite wall (pavement surface)	1
	wb_kratio	Ratio of wall stiffness over ball stiffness	1.2
	dmp_xvis	Shear critical damping ratio	0
	dmp_yvis	Normal critical damping ratio	0.5
Loading	whl_dens (kg/m^3)	Density of the running wheel	2,600
	cwhl_dens (kg/m^3)	Unit vehicle mass	7,600,000
	whl_yfmax (kN)	Concentrated force	100
	whl_zspc (rad/s)	Controlled angular velocity	10

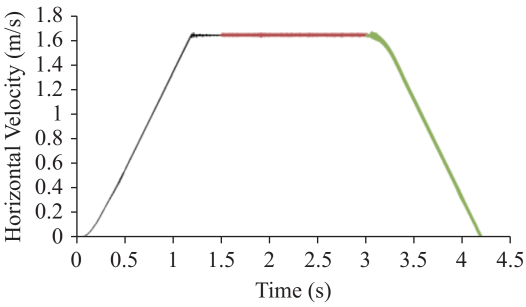
1. Wheel Motion Features

During the simulation, the horizontal and rotational velocities of the wheel was recorded and plotted in Fig. 3. Clearly, the wheel accelerated at the beginning, then steadily moved, and decelerated.

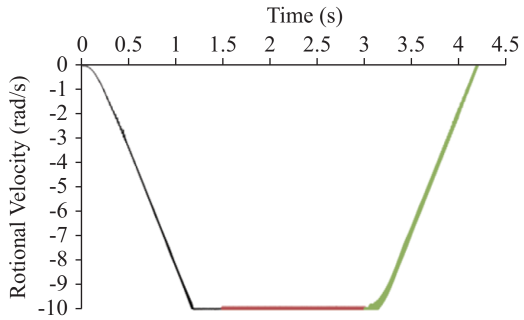
2. Compressive Forces at the Interaction Surface

During the wheel moving on the pavement surface, the interaction contact forces were developed and recorded. Fig. 4 shows the contact compressive forces when the wheel accelerated, steadily moving, and decelerated. From this figure, it was observed that

(1) The vertical compressive force was not equal to its corresponding static vertical load of 100 kN, but fluctuated around 100 kN.
(2) Motion features significantly impacted the fluctuating compressive forces as shown in the figure.



(a) Horizontal velocity *vs.* time



(b) Rotational velocity *vs.* time

Fig. 3. Typical motion feature of the rolling wheel (the different colors of the curves indicate that different motion features: acceleration, steadily moving, and deceleration).

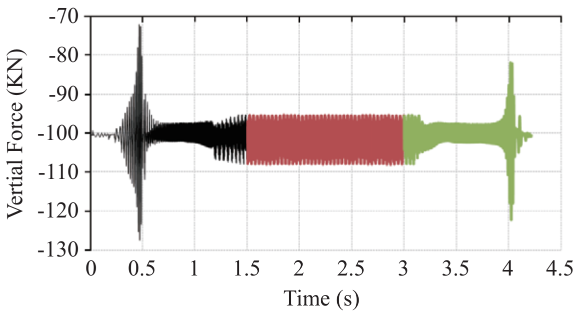


Fig. 4. Vertical contact compressive force during the wheel acceleration, steadily moving, and deceleration.

(a) The amplitudes during the wheel accelerating and decelerating were significantly larger than the amplitude during the wheel steadily moving.
(b) During the wheel accelerating or decelerating, the amplitudes varied significantly, but the amplitudes during the wheel steadily moving were close to a constant.

From the findings above, it could be concluded that trucks may have larger vibrations during acceleration and deceleration compared with steadily moving. Therefore, it was recommended that acceleration and deceleration should be minimized for safe and comfortable driving.

3. Contact Frictional Forces at the Interaction Surface

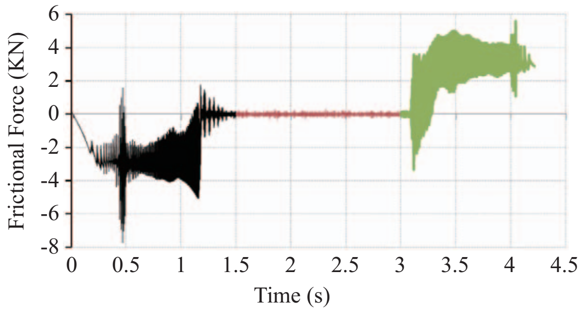


Fig. 5. Contact frictional force during the wheel acceleration, steadily moving, and deceleration.

In addition to the contact compressive forces, the frictional force at pavement wheel interface is one of the most important factors in road pavement and vehicle engineering as mentioned in the previous study (Cao et al., 2013). Therefore, frictional forces were also recorded during the simulation as shown in Fig. 5. The similar findings were observed that the wheel motion features significantly impacted the frictional force:

(1) As shown in the figure, the average frictional force was close to zero during the wheel steadily moving along the pavement surface while it was non-zero value due to the inertia force during the wheel acceleration or deceleration.
(2) During the wheel acceleration and deceleration, the frictional force varied significantly and the force directions were opposite to each other.

Based on the observations, it was concluded that smoothly driving could save energy since less frictional force was developed between the pavement and the truck.

V. SUMMARY AND CONCLUSION

In order to study dynamic wheel-pavement interaction and better understand traffic loading, this paper has developed an idealized model which consists of a wheel, a smooth surface, and a mass. Discrete element simulations were performed with this newly developed model. Through analyzing the simulation results, it was observed that:

(1) During the wheel moving along pavement surface, the contact forces (normal compressive force and the frictional forces) were not constant but oscillating around their average values.
(2) The wheel motion features significantly impacted the simulation results:
   (a) During acceleration and deceleration, both the compressive and frictional forces varied significantly.
   (b) During the wheel steadily moving, the vertical compressive force was very close to the static load of 100 kN and the frictional force was close to zero.

As mentioned at the beginning of this paper, it is very important but very challenging to fully understand the mechanism underlying the pavement-wheel interaction. This paper presented a simplified discrete element modeling approach. More complex and realistic modeling approaches are desired in the future research through considering more realistic pavement surface roughness, contact models, and wheel configuration.

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