# Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 13 (12): 2146-2150, 2013
ISSN 1812-5654 / DOI: 10.3923/jas.2013.2146.2150


# Finite Deformation Analysis of Layered Asphalt Pavement

[1]Ming-Jian Li, [2]Xu-Dong Wang and [1]Nian-Mei Zhang
[1]School of Physics, University of Chinese Academy of Sciences, Beijing, China
[2]Research Institute of Highway, Ministry of Transport of China, Beijing, China

**Abstract:** Layered asphalt pavement structures are usually analyzed applying small deformation theory. In this study, finite deformation theory was employed to achieve more accurate results. The response of pavement structure under vertical and horizontal loads was investigated by three-dimensional finite element method. The calculating results, especially for deflection, on the basis of finite deformation theory are very different from that according to the small deformation theory. And the difference will increase while the stiffness of pavement structure decrease. With only vertical loads, asphalt layer is mainly under compressive stress in three directions. With horizontal loads and vertical loads, shear stress contributes to accumulated plastic deformation in the asphalt layer. Sliding between layers could occur due to the shear stress. Tensile strain can cause fatigue cracking in asphalt layer under low temperature. Due to a small modulus of resilience, there exists a large compressive strain and visible deflection in soil base.

**Key words:** Finite deformation, layered structure, asphalt pavement, FEM

## INTRODUCTION

Asphalt pavement is widely used due to its construction rapidity and easy maintenance. For the recent years, many scholars have studied its mechanical responses under traffic loads.

Hu *et al*. (2007) analyzed shear stress of decks with different structure combination under non-uniform loads and in different interlayer conditions with 3D finite element method. Liu *et al*. (2011) investigated asphalt concrete pavement with subgrade based on cross-anisotropy under moving load. Wei *et al*. (2011) calculated maximum principal tensile stress and maximum shear stress on different layers by the changes of partial bonding condition between layers. Xu and Sun (2012) calculated the shear stress distribution along the depth of the asphalt layer and established a shear stress curve functional equation.

However, most of these approaches were based on the small deformation theory. Second order terms of displacement were neglected in such methods and linear superposition principle was applied. However, large deformation can be seen in some pavements due to the viscoelasticity of asphalt mixture. Viscous flow of asphalt is considerable especially under high temperature in summer. Rutting depth can be 5-10 cm in some highway under heavy traffic loads. Deformation in these cases can no longer be neglected since the average thickness of the asphalt layer is approximately 15 cm. Thus, finite deformation theory should be applied to achieve more accuracy. This study presents a finite deformation FEM approach to responses of layered pavements under traffic loads and provides a reference to large deformation issue in this field.

## MATERIALS AND METHODS

Geometric model is shown in Fig. 1. In this model, x, y and z axes are respectively the driving direction of vehicles, the width and depth of the road. The length is respectively 10, 10 and 9.8 m. According to calculation by Zaghloul and White (1993), a larger model would make little contribution to accuracy in simulating actual roads. Six continuous layers have been considered. Tire print is simplified as a 0.25×0.25 m square area. The top surface is free from constraint while all other boundaries are constrained by fixed support.

Table 1 displays properties of each layer in the pavements based on a typical highway structure.

Considering geometric nonlinear characteristics of this problem, finite deformation theory was applied. Here, Lagrange description and Green strain tensor has been used:

$$E_{JK} = \frac{1}{2}\left(U_{J,K} + U_{K,J} + U_{I,J}U_{I,K}\right) \tag{1}$$

with $S_{ij}$ as Kronecker symbol and $U_j$ as displacement. Constitutive relations can be described by strain energy density function W ($E_{ij}$) and written as the following Eq:

**Corresponding Author:** Ming-Jian Li, School of Physics, University of Chinese Academy of Sciences, Beijing, China

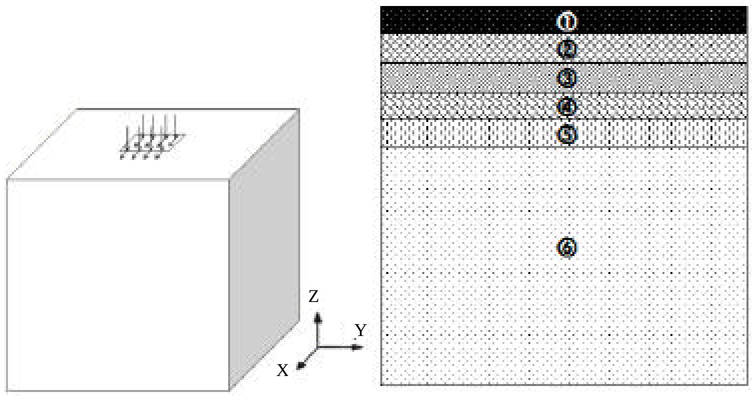


Fig. 1: Geometry model of the pavements system

Table 1: Material properties of layered pavements

| Material | h (mm) | E (Mpa) | μ |
|---|---|---|---|
| Asphalt concrete | 0.15 | 1200 | 0.2 |
| Cement with gravel | 0.20 | 1700 | 0.2 |
| Lime and cement fly-ash | 0.15 | 1400 | 0.2 |
| Limestone soil 12% | 0.15 | 600 | 0.2 |
| Limestone soil 8% | 0.15 | 300 | 0.2 |
| Soil with 80% compaction | 9.00 | 17 | 0.3 |

$$S_{ij} = \frac{\partial W(E_{ij})}{\partial E_{ij}} \quad (2)$$

where, W ($E_{ij}$) presents strain energy density and $S_{ij}$ is the Kirchhoff stress tensor. According to the virtual work Eq:

$$\int_{V_0} S_{ij}\delta E_{ij} dV = \int_{V_0} F_{bi}\delta u_i dV + \int_A F_{Ai}\delta u_i dA \quad (3)$$

Nonlinear finite element equations have been established as (K) (δ) = (R). These equations can be solved by the Newton-Raphson iteration method in FEM code.

Considering FEA accuracy and material property, higher order 20-nodes hexahedral elements were applied. And layers are continuous on all interfaces.

In order to verify the accuracy of FEM code, a validation example has been calculated. Figure 2 shows a half-infinite three-dimensional body. Uniform pressure p(r) with its radius δ is applied on the surface. The elastic modulus and Poisson's ratio are respectively E, μ. According to linear elasticity theory, deflection w and vertical stress $\sigma_z$ in cylindrical coordinate system r-z are presented with Bessel functions:

$$\begin{cases} \sigma_z = -p\int_0^\infty (1+\frac{z}{\delta}x)e^{-\frac{z}{\delta}x} J_1(x) J_0(\frac{r}{\delta}x)dx \\ w = \frac{(1+\mu)p\delta}{E}\int_0^\infty (2-2\mu+\frac{z}{\delta}x)e^{-\frac{z}{\delta}x}\frac{J_1(x)J_0(\frac{r}{\delta}x)}{x}dx \end{cases} \quad (4)$$

Comparison between elasticity and FEM has been presented. Results suggest good agreement to elasticity theory in both deflection and vertical stress. Maximum relative error is within 5% in this case. This verified the calculation model and FEM code, which is a foundation for further investigation.

## RESULTS

Here, we presents only the most dangerous situation. In this case, 1 MPa vertical load was uniformly applied on the rectangular area of the surface. Additional horizontal friction force was applied and adhesion coefficient is 0.7 to simulate emergency braking. For comparison, we also calculated case under only vertical loads. Both cases were calculated by non-linear FEM using finite deformation theory.

Figure 3 presents distribution of vertical displacement along the diagonal line of the model. Displacement of different layers has been marked. As can be seen, displacement and its gradient are rather small at the edges of the model, which indicates the model is large enough for analyzing. Maximum vertical displacement is about 0.8 mm on the surface of the road. Horizontal force causes 1% increase of vertical displacement. Displacement decreases when the road gets deeper and tend to be zero when deep enough.

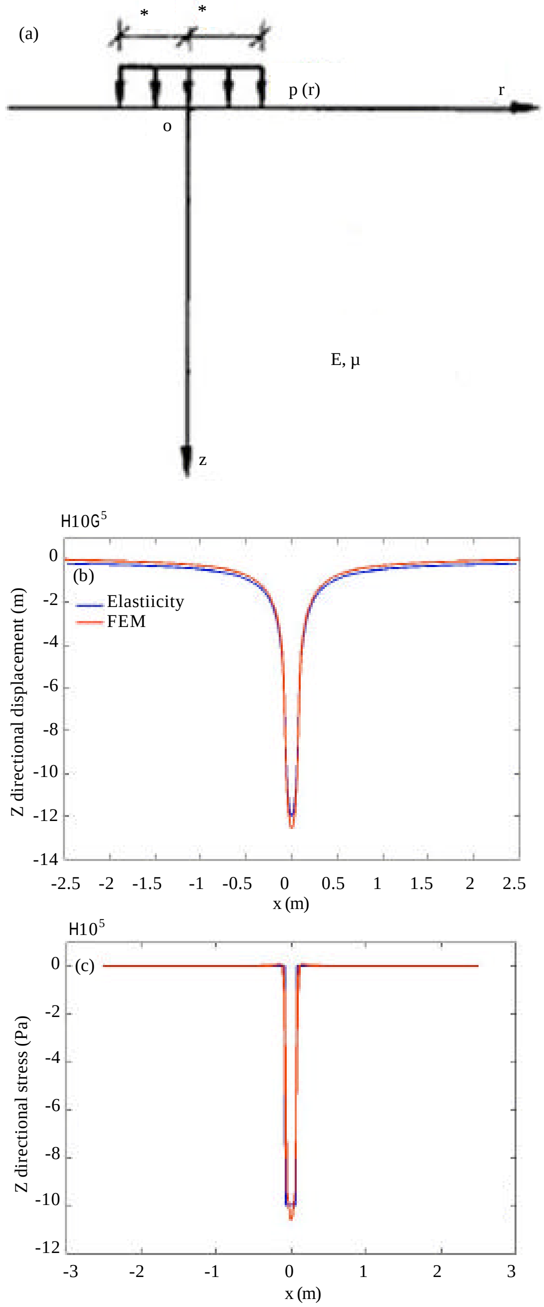


Fig. 2(a-c): Comparison between FEM and elasticity theory

Figure 4a presents vertical stress distribution along x axis. Layers are mainly subjected to compressive stress in z axis. Maximum stress occurs on the surface of the asphalt layer. Stresses decrease rapidly as depth increases. And in this weakening process asphalt and cement layer make major contribution. Stresses also decrease rapidly as it gets further to the center of wheel.

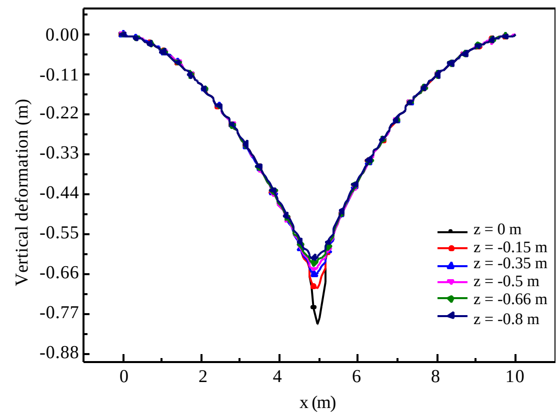


Fig. 3: Distribution of vertical displacement

Little stresses can be seen beyond 1m to the print. Horizontal force causes 4% increase in maximum vertical compressive stress.

Considering maximum principle stress in Fig. 4b, compressive stress occurs mainly in asphalt layer. When it gets deeper, compressive turns to be tensile. Maximum von-Mises stress in Fig. 4c is 1.5 MPa while maximum Tresca stress in Fig. 4d is about 0.8 MPa. In this case, horizontal force causes about 100% increase in both Mises and Tresca stresses. This indicates that braking of vehicles would lead to considerable shear stress. And this mainly affects the first layer, which means shearing strength of asphalt is particularly important.

Maximum principle strain along x axis is displayed in Fig. 4e. Tensile strain can be seen on the asphalt surface. Horizontal tensile strain in this layer may cause fatigue fracture in low temperature. Maximum equivalent strain in Fig. 4f is $1\times10^{-3}$ and maximum vertical compressive strain is $7\times10^{-4}$. Both compressive and tensile strain occurs around the wheel, which indicates that horizontal fraction force may lead to separation and rutting in asphalt layer. Figure 4h displays distribution of vertical strain along z axis in the center of the wheel. Compressive strain tend to decrease as the depth increases. However, a relative large strain can be found in the upper part of the soil base, which has a small resilient modulus. Maximum strain in soil is $1\times10^{-4}$, which can cause considerable deflection under repeated traffic loads.

Horizontal force causes about 150% increase in maximum equivalent strain. Additionally, asphalt layer is in three direction compressive state without horizontal force. However, tensile strain can be seen in braking state. From these calculations, we can see quite large strain. This suggests finite deformation analysis tend to be necessary.

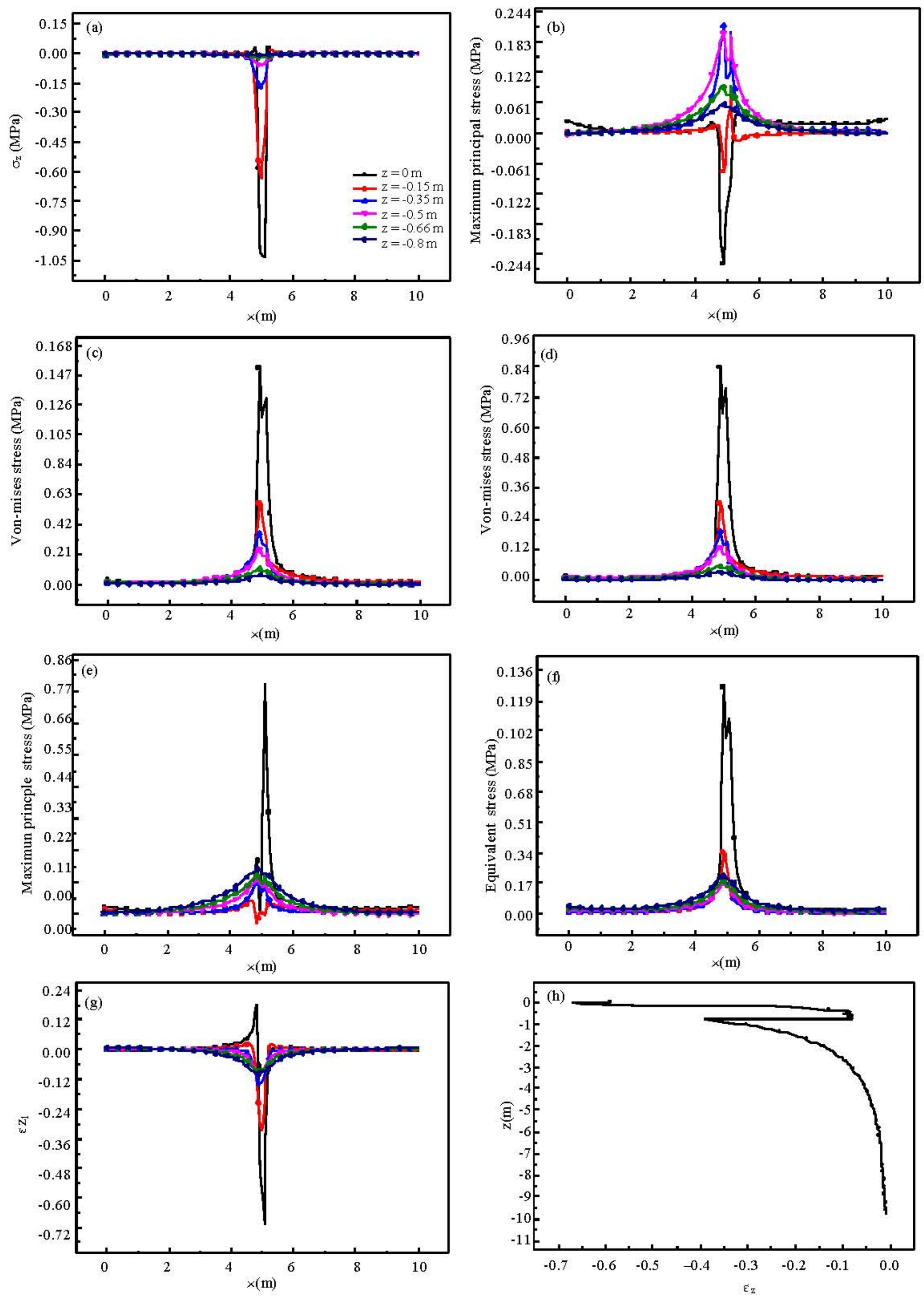


Fig. 4: Distribution of stress and strain under both vertical and horizontal loads

Table 2: Comparison between linear and non-linear analysis

| Model | | $u_z$ (mm) | $\sigma_{Mises}$ (Mpa) | $\varepsilon_{eq}$ ($1\times10^{-3}$) | $\sigma_{Tresca}$ (MPa) |
|---|---|---|---|---|---|
| I | SD[1] | 0.602 | 0.776 | 0.646 | 0.391 |
| | FD[2] | 0.663 | 0.804 | 0.804 | 0.407 |
| | δ | 10.130 | 3.610 | 3.720 | 4.000 |
| II | SD[1] | 0.710 | 0.698 | 0.582 | 0.370 |
| | FD[2] | 0.792 | 0.724 | 0.603 | 0.380 |
| | δ | 11.550 | 3.720 | 3.610 | 2.700 |
| III | SD[1] | 1.110 | 0.640 | 0.846 | 0.352 |
| | FD[2] | 1.250 | 0.660 | 0.834 | 0.352 |
| | δ | 11.870 | 3.730 | -1.420 | 0.030 |

SD: Small deformation theory, FD: Finite deformation theory

Horizontal displacements were also calculated. Maximum horizontal displacement is 0.2 mm, which is in front of the wheel center. In asphalt and concrete layer, backward displacement occurs behind the wheel center while forward displacement occurs in front of it. In other layers, situations are reversed. This indicates that horizontal load tend to separate asphalt layer in x axis and separate layers from each other on interface. As a result, repeated traffic loads can cause sliding between layers and upheaval on the surface.

In order to demonstrate the differences between finite deformation theory and small deformation theory, more cases were calculated. Three models of different materials under vertical loads were considered. Differences of deflection, vertical strain, Mises stress and Tresca stress are presented in Table 2. In Model I, the elastic modulus of the 2nd layer becomes 8940 MPa while other layers remain unchanged. In Model II, all materials remain unchanged. In Model III, elastic moduli of the 2nd and 3rd layer are 1500 and 600 MPa, respectively, while elastic modulus of 4th, 5th and 6th is 17 MPa and Poisson's ratio is 0.3.

From the calculations we can see the differences of defection is very obvious. Result from finite deformation theory is about 10% larger than result from small deformation theory. This suggests the necessity of finite deformation analysis. When the overall stiffness of pavements decreases, this difference tend to be larger. Equivalent stress calculated by finite deformation theory is also larger. Maximum shear stress from finite deformation theory is slightly larger.

## CONCLUSION

Deflections of the road calculated by small deformation and finite deformation theory are very different. Additionally, material property of pavements can affect these differences.

Stress and strain state of the road can be changed when horizontal force is applied. In some area, great increase of stress and state can be found.

Horizontal load can cause obvious Tresca stress. Shear stresses in opposite directions among layers are also considerable in this case.

Due to small elastic modulus, subgrade is under large vertical compressive strain while vertical load is applied. Repeated traffic loads may cause large deflection in soil base.

Horizontal displacement in opposite directions occurs around the center of the loads. This can cause sliding, rutting and upheaval in pavements.

## ACKNOWLEDGMENTS

This study was supported by Research Institute of Highway, Ministry of Transport of China (Western project Numerical simulation and experimental verification of the dynamic behavior of the full scale pavement structure).

## REFERENCES

Hu, X., K. Su, X. Hu and L. Sun, 2007. Shear stress response analysis of asphalt concrete pavement for concrete bridge deck. J. Highway Eng., 32: 136-141.

Liu, J.Q., B.S. Wang, C.C. Chen and Y.Y. Chao, 2011. Dynamic response analysis of stress in asphalt concrete pavement structure under vehicle load. Highway, 6: 13-18.

Wei, S., Q.G. Yang and J.Y. Gu, 2011. Stress analysis on different partial bonding condition between base course and surface course of asphalt pavement. J. Chongqing Jiaotong Univ. (Nat. Sci.), 30: 403-406.

Xu, Y. and L.J. Sun, 2012. Research on simplified model for variation of shear stress of asphalt layers in asphalt pavements. J. Tongji Univ. (Nat. Sci.), 40: 211-216.

Zaghloul, S.M. and T.D. White, 1993. Use of a Three-Dimensional, Dynamic Finite Element Program for Analysis of Flexible Pavement. National Research Council, Washington, DC., ISBN: 0309054575, pp: 60-69.